Sweet Corrosion in Large Diameter, Inclined Multiphase Pipelines

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ABSTRACT

There is little knowledge on flow characteristics and their subsequent effect on corrosion in inclined flowlines. This information is essential for the proper design and operation of subsea and hilly terrain multiphase pipelines.

Experiments have been carried out to determine the effect of multiphase flows on sweet corrosion in 10 cm diameter, inclined, oil/water/gas pipelines that can operated up to pressures of 150 bar. Carbon dioxide partial pressures up to 0.79 MPa have been studied at inclinations of 0, 2, 5, and 15 degrees at a temperature of 40 C. Water cuts of 100, 80, and 40% were used with a light condensate type oil having a density of 800 kg/m^3 and viscosity of 2 cP at 40 C. The liquid and gas superficial velocities ranged from 0.2 to 3 m/s and 2 to 10 m/s respectively.

A new, nonintrusive technique to determine flow regime and slug characteristics has been developed using differential pressure transducers. These detect the presence of slugs and are used to measure

the slug frequency and slug velocity.

The results indicate that, in upward flow, the slug frequency increases with increase in inclination and there is significant backflow in the film region between slugs. This leads to an increase in the film Froude number and consequently higher turbulence levels and higher corrosion rates. However, at the lower water cuts, increasing the inclination angle does increase the mixing of the oil and water. This leads to the oil contacting the wall at the bottom of the pipe which helps reduce the corrosion rate.

The corrosion rate increases with increase in slug frequency up to a value of approximately 40 slugs per minute. Above this, the corrosion rate does not change with further increase in slug frequency.

From the above results, a model relating the flow characteristics and chemistry to corrosion rate has been compiled.

1. INTRODUCTION

Much of the work done on flow and corrosion has been based on experiments using single phase water or two phase water/gas systems. The application of these results are limited in the area of multiphase flow and corrosion. Not only is there limited data on three phase flow, there is practically no data available on multiphase flow in high pressure inclined pipelines. This also limits the application of previous work due to the fact that pressure and inclination effects the flow characteristics in a multiphase flowline which can further enhance the corrosion process.

De Waard and Milliams[2] (1975) and De Waard and Lotz[3] (1993) investigated the mechanism of carbon dioxide corrosion on carbon steel under different conditions. They also proposed various models to predict carbon dioxide corrosion of carbon steel. Different corrosion products are formed on the pipe wall depending upon the experimental conditions. According to De Waard and Milliams (1975)[2], the undissociated carbonic acid molecule is directly absorbed on the metal surface and then reduced. This is the rate determining step and the corrosion rate is directly related to the concentration of undissociated carbonic acid in the solution. Bockris[1] et al. (1962) showed that the rate controlling step depended upon the pH. De Waard and Milliams[2] (1975) further showed that the solubility of $FeCO_3$ is low and decreases with increasing temperature. They also showed that $Fe(HCO_3)_2$ forms the main component of the dissolved species. Iron carbonate is usually the main corrosion product.The iron carbonate dissolves in the solution until its solubility limit is reached. Thereafter the solution becomes supersaturated and the iron carbonate precipitates on the metal wall. Depending upon various conditions like the solution chemistry, temperature, pressure and flow rate, iron carbonate may form a protective film on the metal surface.

Lee[10] (1993) demonstrated both that the introduction of a third phase can seriously affect the applicability of the Taitel and Dukler[13] (1976) model and that it improperly predicts the annular flow transition. Lee's experiments were low-pressure, large diameter, horizontal studies. It was observed that the oil composition affected the slug - annular transition, making the transition occur at lower gas velocities with increasing oil composition.

Limited mapping data exists for inclined pipeline effects. Gould[4], *et al.*, (1974) introduced +45 and +90° flow pattern maps. Stanislav[11], *et al.*, (1986) reported inclined flow pattern data as compared with a modified Taitel and Dukler model in small diameter pipes. Kokal and Stanislav[8] (1986) have characterized extensively the upflow and downflow patterns. However, all of these studies involved two phase flow. Additionally, large diameter and high pressure flow has not been studied. They did find that even a slight inclination results in stratified flow being eliminated and the flow regime map begins to be dominated by slug flow. Wilkens[15] et al. (1998) have shown that slug flow dominates the flow regime map at an inclination of even 2°.

Jepson and Kouba[9] (1989) showed that there are different kinds of slugs and that the strength of the slug is proportional to the Froude number calculated in the liquid film ahead of the slug. Sun and Jepson[12] (1992) carried out corrosion rate measurement in oil/water/gas slug flow. They were able to show that within the slug there were areas of high turbulence and high shearing forces which are more than capable of removing any films of corrosion products formed at the wall. They were also able to show that the shearing forces of the slug did not allow stable inhibitor films to form on the wall surface.

Jepson and Taylor[5] (1988) studied slug flow and its transitions in air/water two phase flow in 30 cm diameter horizontal pipelines. It was shown that the transitions differ substantially from smaller diameter pipes and that no theoretical model accurately predicted the transitions. They also attempted to incorporate the effect of pipe diameter on slug frequency plotting the non-dimensional group $(f D) / V_{sl}$ against the mixture velocity, V_m. The mixture velocity is defined as the sum of the superficial gas and liquid velocities. They showed that there was a good correlation between the non-dimensional group and the mixture velocity which is given as follows:

$$\frac{f D}{V_{sl}} = 4.76 \times 10^{-3} * V_m + 0.035 \qquad (1)$$

where:

v	=	slug frequency, s^{-1}
D	=	pipe diameter, m
V_{sl}	=	superficial liquid velocity, m/s
V_m	=	mixture velocity, m/s

Two previous papers, Jepson[7] et al. (1996) and Jepson[6] et al. (1997) have described a predictive model for corrosion rate in oil/water/gas flow in horizontal pipes that incorporates the effect of carbon dioxide partial pressure, temperature, pressure gradient across the slug and water cut, as well as the effect of slug frequency and crude oil type.

This paper shows the effect of inclination on corrosion rate in multiphase slug flow and correlations for slug flow in inclined pipes are proposed that can be added to the existing corrosion rate model.

2. EXPERIMENTAL SETUP AND PROCEDURE

The experiments are performed in an 18-m long, 10-cm diameter, high pressure, high temperature, inclinable flow loop shown in Figure 1. The entire system is manufactured from 316 stainless steel.

A brine/oil solution is stored within a 1.4 m^3 mixing tank. The liquid is moved through the system by a 3 - 15 kW variable speed centrifugal pump and the flow rate is adjusted from 0 -100 m^3/hr by means of a recycle line. The recycle stream stream also serves to agitate the liquid in the mixing tank. Flow rate is metered with a GH-Flow Automation TMTR510 Frequency Analyzer coupled with an in-line turbine meter.

A feed line at 2 MPa pressure supplies carbon dioxide gas from a 20,000 kg storage tank. After passing through a pressure regulator, the gas flow rate is metered with an HEDLAND variable area flow meter where the pressure and temperature are also measured. The gas then passes through a check valve and into the liquid flow which then enters the test loop. The pipe inclination can be set at any angle from 0° to 90°. Both upward and downward flows are studied simultaneously.

Measurements are made in the test section illustrated in Figure 2. Temperature is determined with a type-K thermocouple wired to an OMEGA DP3200-TC electronic display. The total pressure is measured with a 0.1 to 2.9 MPa pressure gauge. The pressure drop across the test section is measured between two sets of taps (one set 132 cm apart and the other 10 cm apart). These pressure taps are connected to two 0 to 35 kPa OMEGA PX-750 heavy duty differential pressure transducers. A QuickBASIC program was written on a 75 MHz Pentium to import the data from both channels at a combined rate of 12 kHz. Each output value is then an average of 100 samples for an effective sampling rate of 60 Hz.

Upon leaving the test section, the multiphase flow then passes through a separator to prevent siphoning due to the 18 meter downward flow return and back to the mixing tank. The gas passes through a de-entrainment plate allowing the liquid to separate from the gas, through a separator and back pressure regulator where it is vented to the atmosphere.

The test section shown in Figure 2 is 2 m long, 10.16 cm diameter stainless steel pipe. Port A is used for *in situ* void fraction and oil/water composition measurements. These are carried out by withdrawing an isokinetic sample of the multiphase mixture and allowing the phases to separate in a calibrated tube at the system pressure and temperature.

Tap B is the thermocouple port which contains a type K thermocouple for temperature monitoring. The two sets of taps labeled C are the ports for the pressure taps. One set of taps are 10 cm apart with the other set of taps being separated by 132 cm. These two sets of taps are connected to the two pressure transducers which are used to make pressure drop measurements. A novel, nonvisual technique for determining flow regimes using two simultaneous differential pressure measurements has been developed. Port D is the system pressure tapping which allows system pressure measurements to be made in the test section. The two larger 2 inch ports labeled E are the corrosion probe insertion ports where the electrical resistance probes are inserted for corrosion measurements.

3. TEST MATRIX

The test matrix is shown in Table 1. A mixture of ASTM substitute seawater and a light condensate type oil with density 800 kg/m^3 and viscosity 2 cP are used in the liquid phase.

Table 1: Test matrix for flow characteristics and corrosion at high pressures

Gas	Carbon Dioxide
Oil Composition, %	0, 20, 60
Pressure, MPa	0.27, 0.45, 0.79
Temperature, °C	40
Superficial Gas Velocity, m/s	0, 1, 3, 5, 7, 9
Superficial Liquid Velocity, m/s	0.1, 0.5, 1.0, 1.5
Inclination, degrees	+2°, +5°

4. RESULTS AND DISCUSSION

In order to characterize flow in the system, the dual differential pressure method of Wilkens and Maley[14] (1995) is utilized. This is a nonvisual technique which was made necessary by the material of construction for the system(316 stainless steel). It was shown that using pressure transducers, which was validated using high speed video, each of the flow regimes had a characteristic differential pressure trace. Figure 3 is a sample for slug flow. The use of a second pressure transducer in series allows the calculation of a velocity for the flow regimes. The technique has been patented and is awaiting publication.

4.1 Slug Frequency

The slug frequency was found to increase with increasing gas velocity for liquid velocities of 0.5 m/s and greater and decrease with increasing gas velocity for the lower liquid velocity of 0.1 m/s. The slug frequency was also found to increase with increasing liquid velocity. It was also observed that saltwater composition and pressure had little apparent effect on the slug frequency results. Slug frequency is seen to increase when increasing the inclination from 2° to 5°. Figure 4 is a plot of slug frequency versus gas velocity for an inclination of 2° for all pressures and oil compositions at each of the liquid velocities of 0.1 to 1.5 m/s. It can be seen that the slug frequency increases with increasing gas velocity increasing from values of approximately 52 to 76 slugs per minute when the gas velocity increases from 3 to 8 m/s at a liquid velocity of 1.5 m/s. Similar trends can be seen for liquid velocities of 1.0 and 5.0 m/s. It is again observed that the slug frequency decreases for the liquid velocity of 0.1 m/s, decreasing from 8 to 0 slugs per minute as the gas velocity increases from 3 to 8 m/s. Figure 5 is a similar graph for slug frequency results at an inclination of 5°. The results are very similar for both angles. Comparing Figures 4 and 5, it can be seen that the slug frequencies obtained at an inclination of 5° are slightly higher than the results obtained at an inclination of 2° at similar conditions.

A correlation of mixture velocity and slug frequency can be made if a plot of slug frequency in slugs per second multiplied by the pipe diameter in meters divided by the superficial liquid velocity in m/s, which becomes a dimensionless number, is plotted on the Y-axis with the mixture velocity plotted on the X-axis as in Figures 6 and 7 Looking at Figure 6, which is a plot for an inclination of 2° for all pressures and saltwater compositions, it can be seen that for the higher liquid velocities of 0.5 to 1.5 m/s that a correlation can be drawn. The liquid velocity of 0.1 m/s yields interesting results due to the fact that the low liquid volume produces a localized slug frequency. These often change with distance along the pipe. Often slug flow is assumed not to exist in this case. However, turbulent slugs are present and do cause corrosion. Looking at Figure 7, similar conclusions can be drawn.

Performing a linear regression through the data points, with the exception of the data collected at a liquid velocity of 0.1 m/s, the following correlations were made:

For an inclination of 2° $\text{Log}(f * D)/Vsl = 3.36 \times 10^{-2} * V_m - 1.40$ **(2)**
For an inclination of 5° $\text{Log}(f * D)/Vsl = 2.37 \times 10^{-2} * V_m - 1.28$ **(3)**

The results of the correlations are illustrated in Figures 6 and 7.

Jepson and Taylor(1988) collected some data on slug frequency in horizontal, 30 cm diameter air saltwater flow. They attempted to incorporate the effect of pipe diameter plotting the non-dimensional group $f * D / V_{sl}$ versus the mixture velocity (V_m). Figure 8 is a plot of the results found by Jepson and Taylor (1988) with the correlations developed in this study. Jepson and Taylor's correlation (Equation 1) can be seen to fit the data points where the 2° and 5° correlations (Equations 2 and 3) predict a higher slug frequency at the lower superficial gas velocities than what was actually obtained in Jepson and Taylor's study. It is also seen that all three correlations come to unity at the higher superficial gas velocities now that the turbulence in the slug has become sufficient enough to overcome the effects of inclination.

4.2 Film Velocity

The effect of inclination on film velocity for a superficial gas velocity of 4 m/s and at 80% water cut for upward inclinations of 2, 5, and 15 degrees is shown in Figure 9. It is observed that the film velocity decreases with an increase in inclination. It is seen that at a superficial liquid velocity of 1.0 m/s, the average film velocity decreases from 1.5 to 1.3 and then to 1 m/s with increase in inclination from 2° to 5° and then to 15°. The effect of inclination can be clearly observed at low gas and liquid velocities. For instance at a liquid velocity of 0.5 m/s, the film velocity decreased from 1.3 to -0.7 with increase in inclination from 2° to 15° at 80% water cut. The decrease in film velocity to values less than zero indicates back flow. This causes the film Froude number ahead of the slug to increase and thereby cause an increase in corrosion rates.

4.3 Corrosion Rates

Effect of Slug Frequency

The effect of slug frequency on corrosion in multi phase flow pipelines can be seen in Figures 10 and 11. It was found that with the increase of slug frequency at constant pressure, Froude number, oil composition and inclination, that the corrosion rate increased. An example of this can be seen in Figure 10. Here is a plot of corrosion rate versus slug frequency at an inclination of 2° and a pressure of 0.27 MPa. For an oil composition of 60% and a Froude number of 12, the corrosion rate increases form 1.6 mm/yr to 5.6 mm/yr at slug frequencies of 8 to 44 slugs/min. It is observed that above 40 slugs/min, the corrosion rate begins to level off. This is predicted by the corrosion rate model proposed by Jepson et al. (1997). This same trend was evident with the increases in inclination from 2° to 5°, which can be seen in Figure 11. On this plot of corrosion rate versus slug frequency at 5° and 0.27 MPa, we again see that the corrosion rate increases with increasing slug frequency. At an oil composition of 60% and a Froude number of 6, the corrosion rate increases from 1.3 mm/yr to 2.6 mm/yr at slug frequencies of 18 to 42 slug/min, respectfully.

Effect of Froude Number

The corrosion rate increases with increasing Froude numbers for all conditions tested. An example of this result is seen in Figure 12, which shows the corrosion rate in 5° upward flow at a carbon dioxide partial pressure of 0.27 MPa for both 80% and 40% water cuts. It is seen that in both cases, the corrosion rate increases with Froude number. For example, for 80% water cut, the corrosion rate increases from about 3.8 mm/yr to 6 mm/yr at a slug frequency of 16/min, as the Froude number is increased from 6 to 12. For the 40% water cut the corresponding results are about 1.2 and 2.8 mm/yr respectively.

It is also seen from Figure 12 that increasing the water cut at the same Froude number has increased the corrosion rate. This is because, with inclination, in slug flow, the oil and water are well-mixed due to increased turbulence causing oil-wetting of the pipe wall. This in turn decreases the corrosion rate.

5. CONCLUSIONS

It was observed that inclination eliminated the stratified flow regimes which are normally encountered in horizontal flow. The slug flow regime was now seen to dominate the range of flows studied.

The slug frequency was found to increase with both increasing gas and liquid velocities. This was seen at both inclinations of 2° and 5°, for all pressure and oil/water compositions. Pressure and oil/water composition were found to have little effect on the frequency of slug flow. Correlations are proposed for slug frequencies for inclinations of both 2° and 5° and these can be used for corrosion rate prediction.

For a given carbon dioxide partial pressure, Froude number and slug frequency, the corrosion rate was observed to decrease with increasing oil compositions. Inclination results in better mixing of oil and water, leading to oil-wetting of the wall. This results in lower corrosion rates.

For water cuts of 80 and 60%, the corrosion rate was found to increases with increasing Froude number at a given carbon dioxide partial pressure, slug frequency and oil composition. An increase in Froude number gives an increases in the void fraction resulting in higher levels of turbulence within the slug. The increase in intensity of the turbulence results in higher corrosion product removal which in turn increases the corrosion rate.

The corrosion rate was found to increase with increasing slug frequency at a given carbon dioxide partial pressure, Froude number and oil composition. Increasing the slug frequency increases the total amount of time that an area of the pipeline is exposed to the turbulent nature of a slug. Increasing the time of exposure again results in higher corrosion product removal producing higher corrosion rates.

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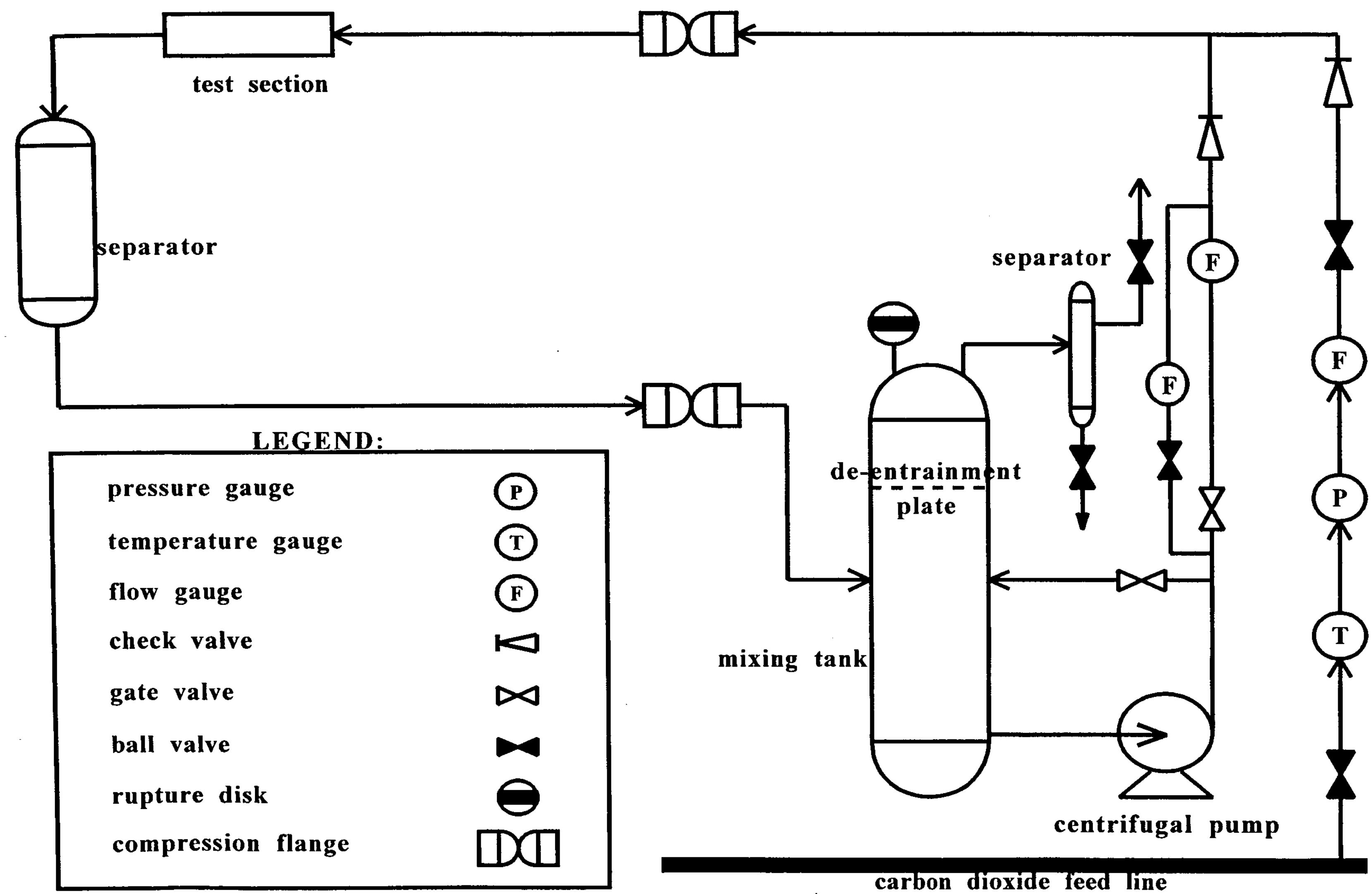
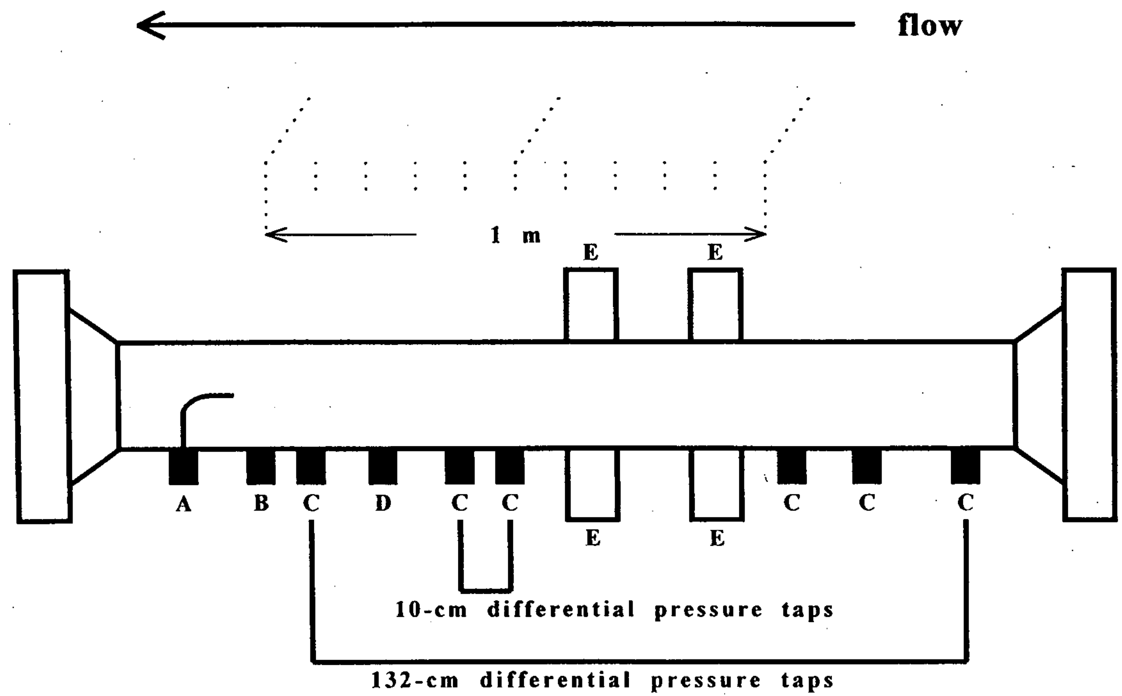


Figure 1: High-pressure, inclinable flow system process flowsheet.



LEGEND:

void fraction port	A
thermocouple port	B
differential pressure tap	C
system pressure/shear stress port	D
corrosion probe insertion port	E

Figure 2: Test section diagram.

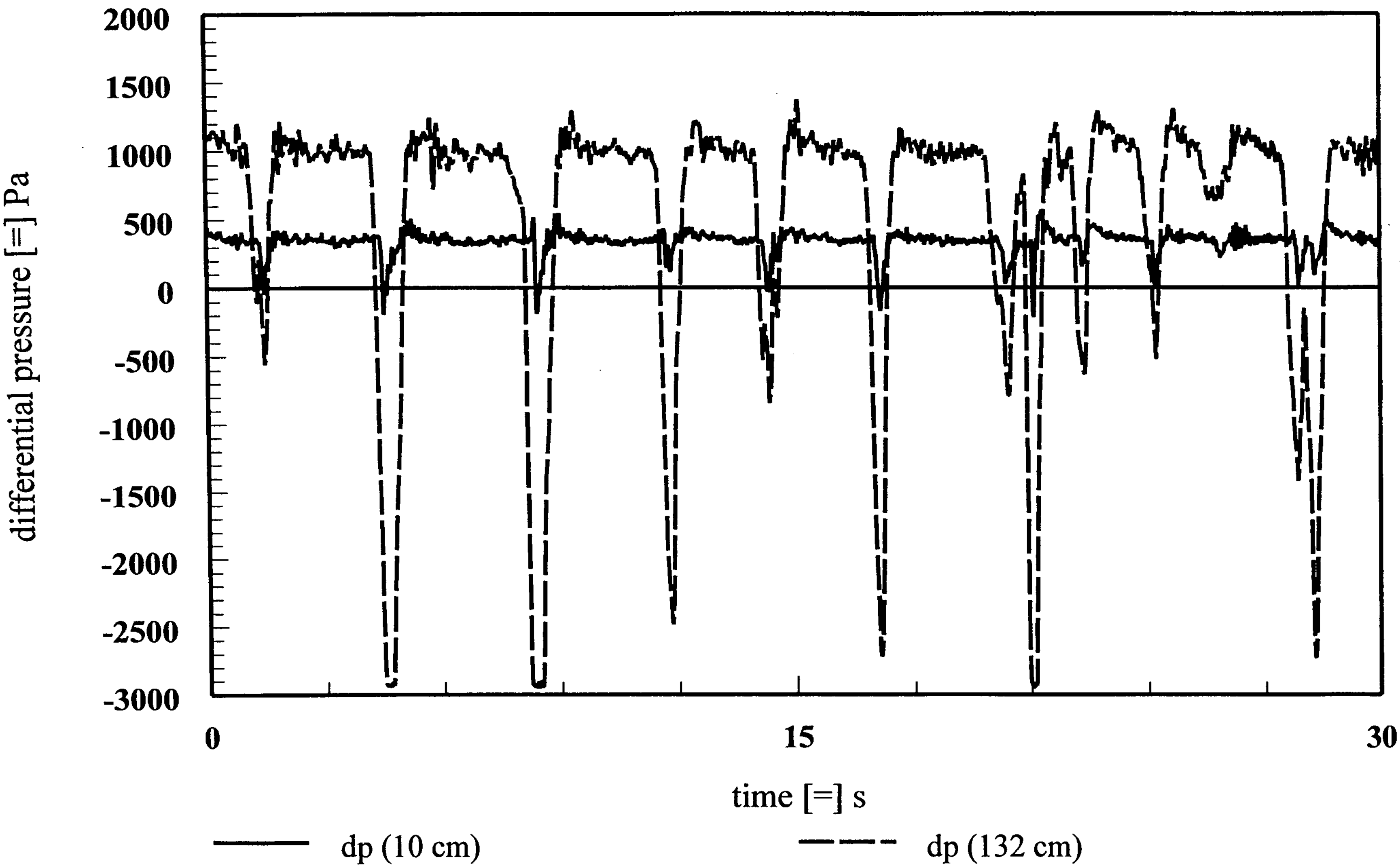


Figure 3: Sample Differential Pressure Trace for Slug Flow

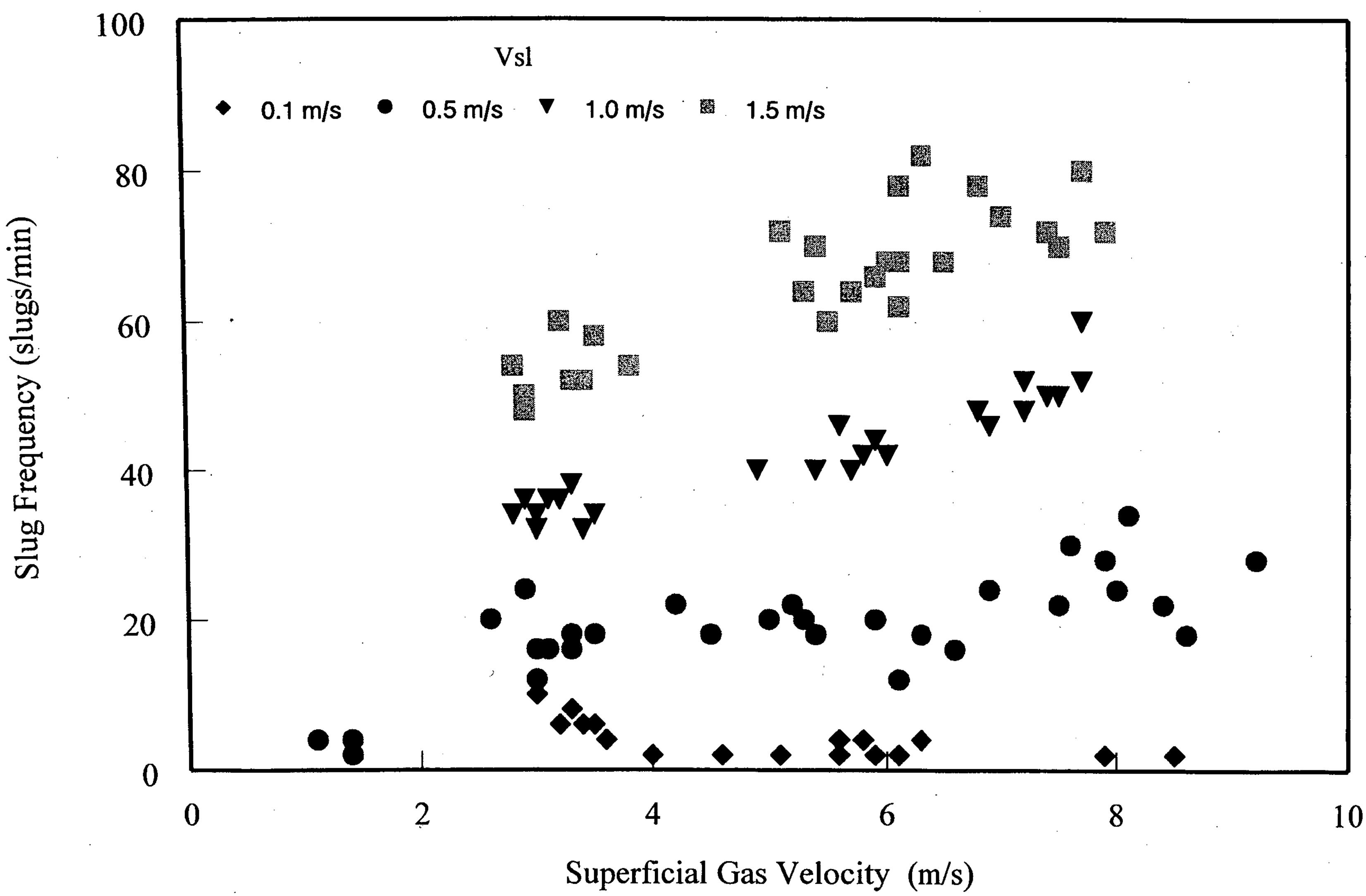


Figure 4: Slug frequency results @ 2° for all pressure and compositions

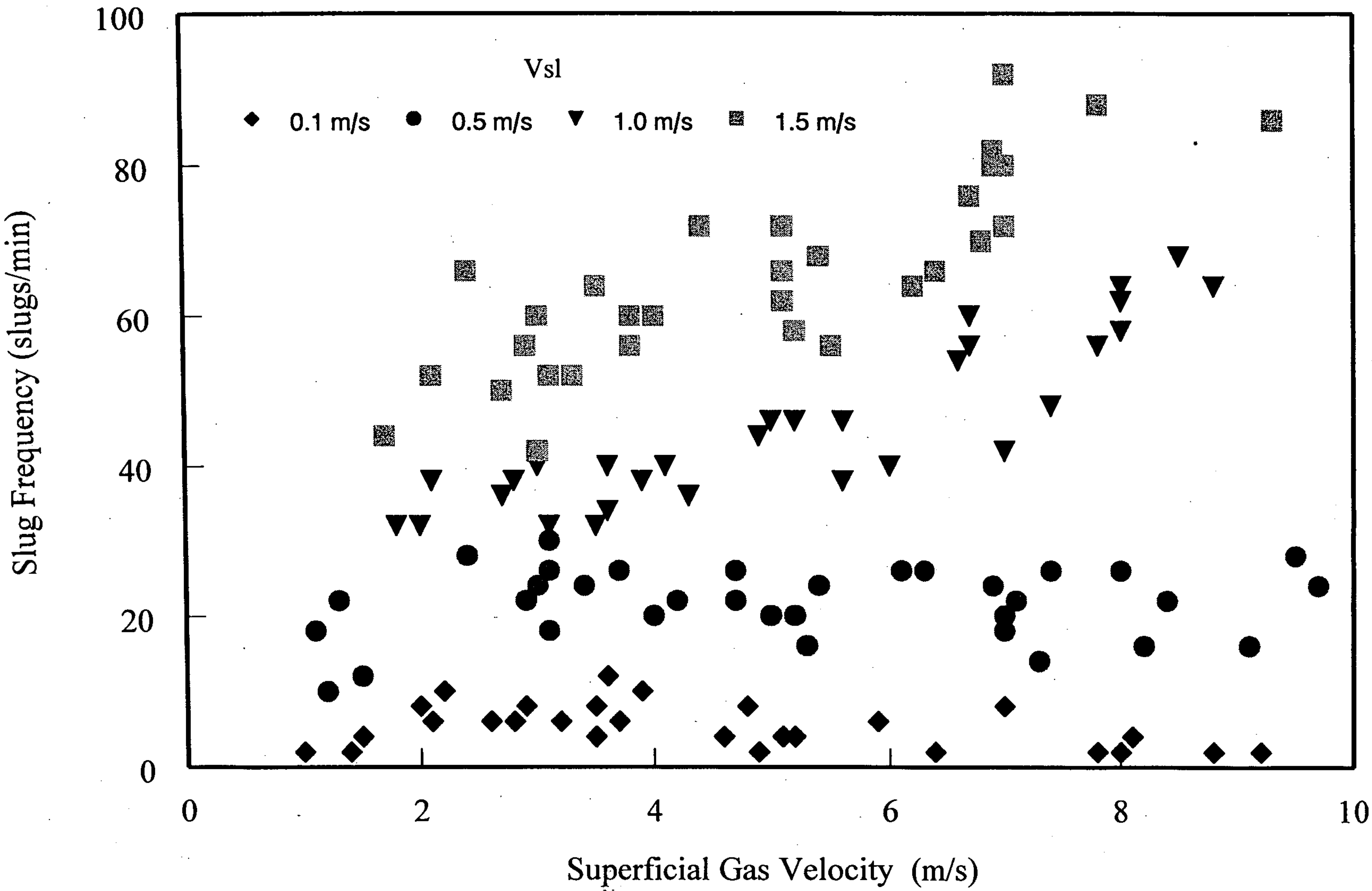


Figure 5: Slug frequency results @ 5° for all pressure and compositions

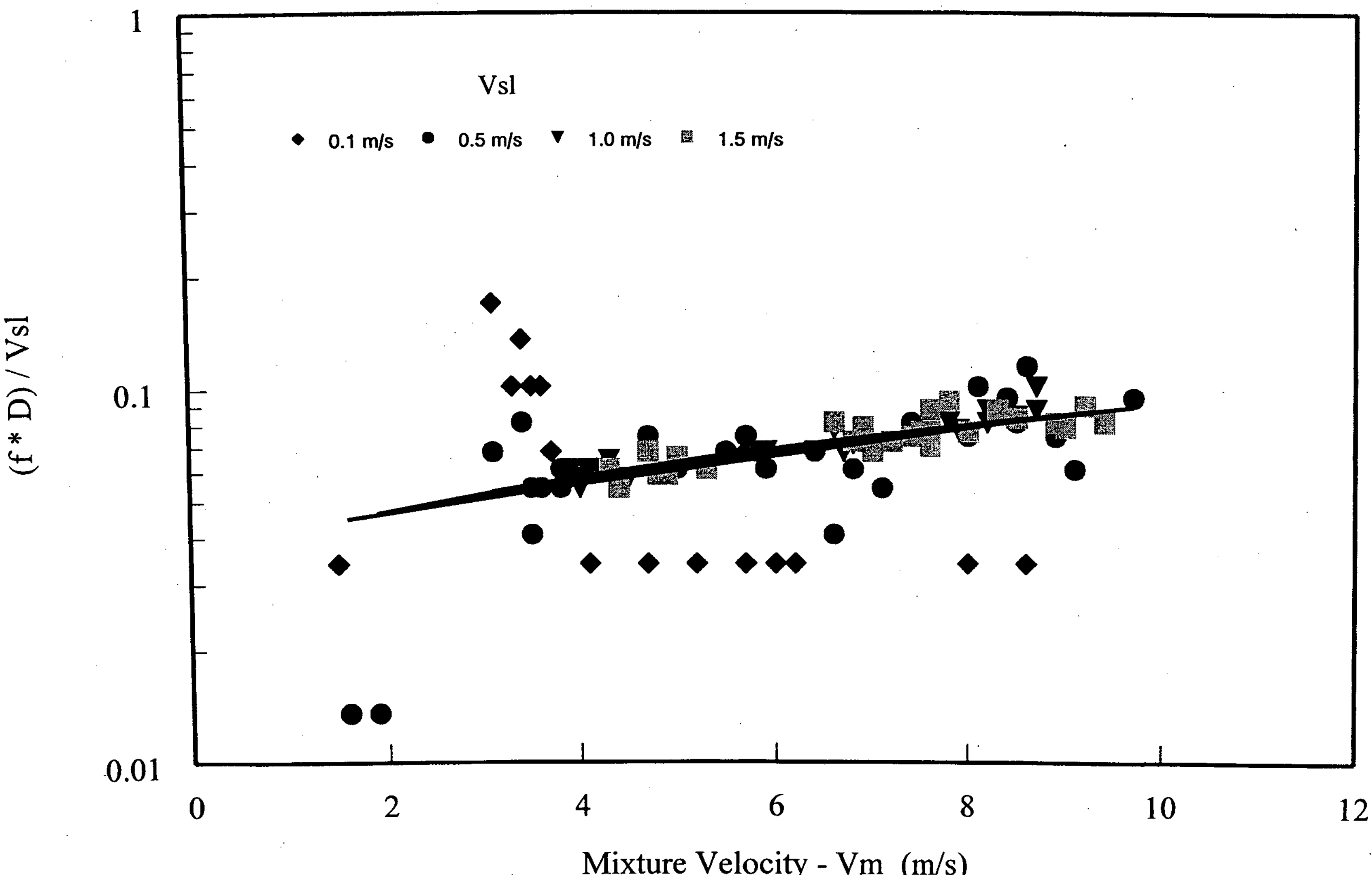


Figure 6: (f * D) / Vsl vs. mixture velocity @ 2° for all pressure and compositions

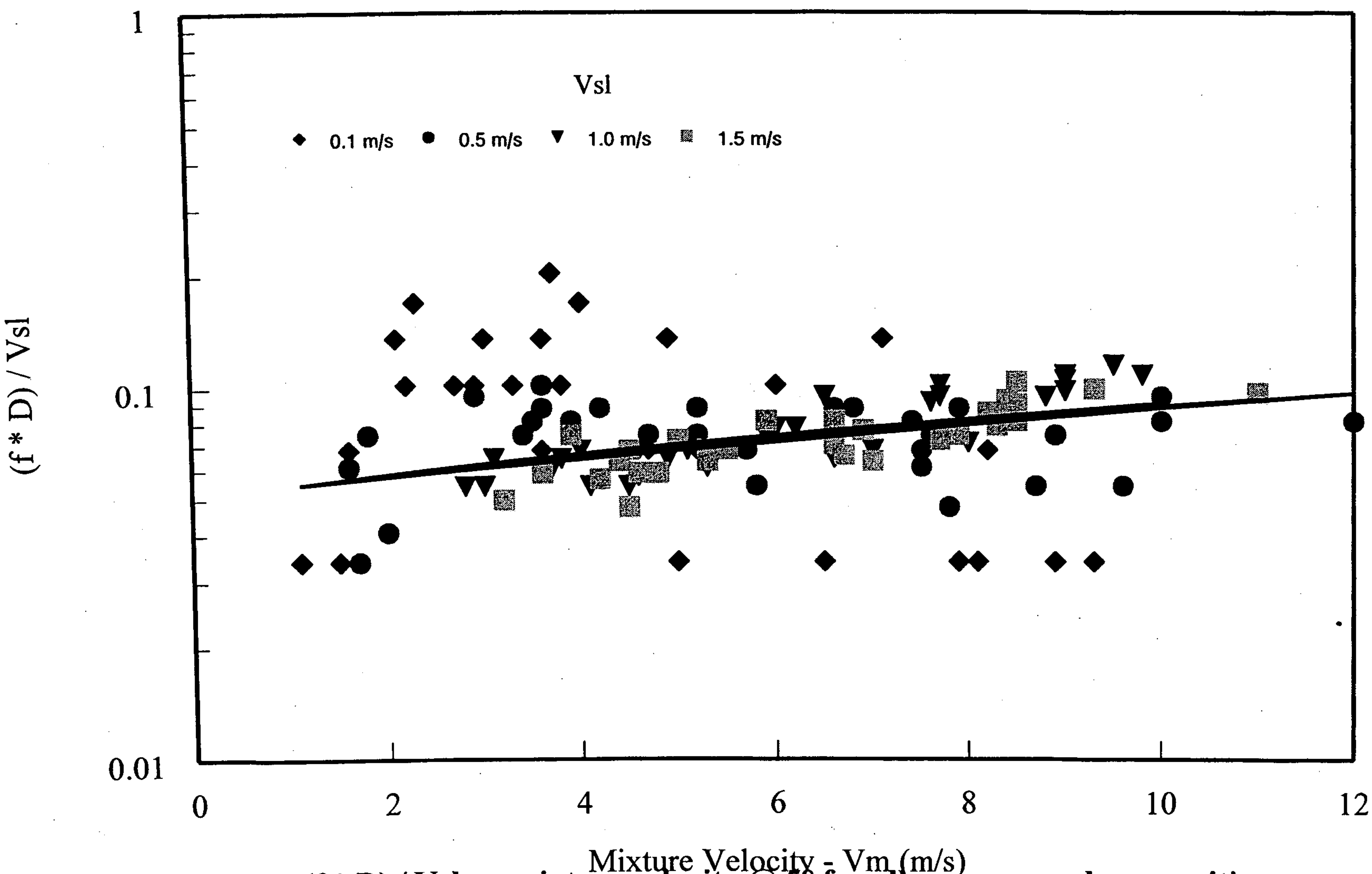


Figure 7: (f * D) / Vsl vs. mixture velocity @ 5° for all pressure and compositions

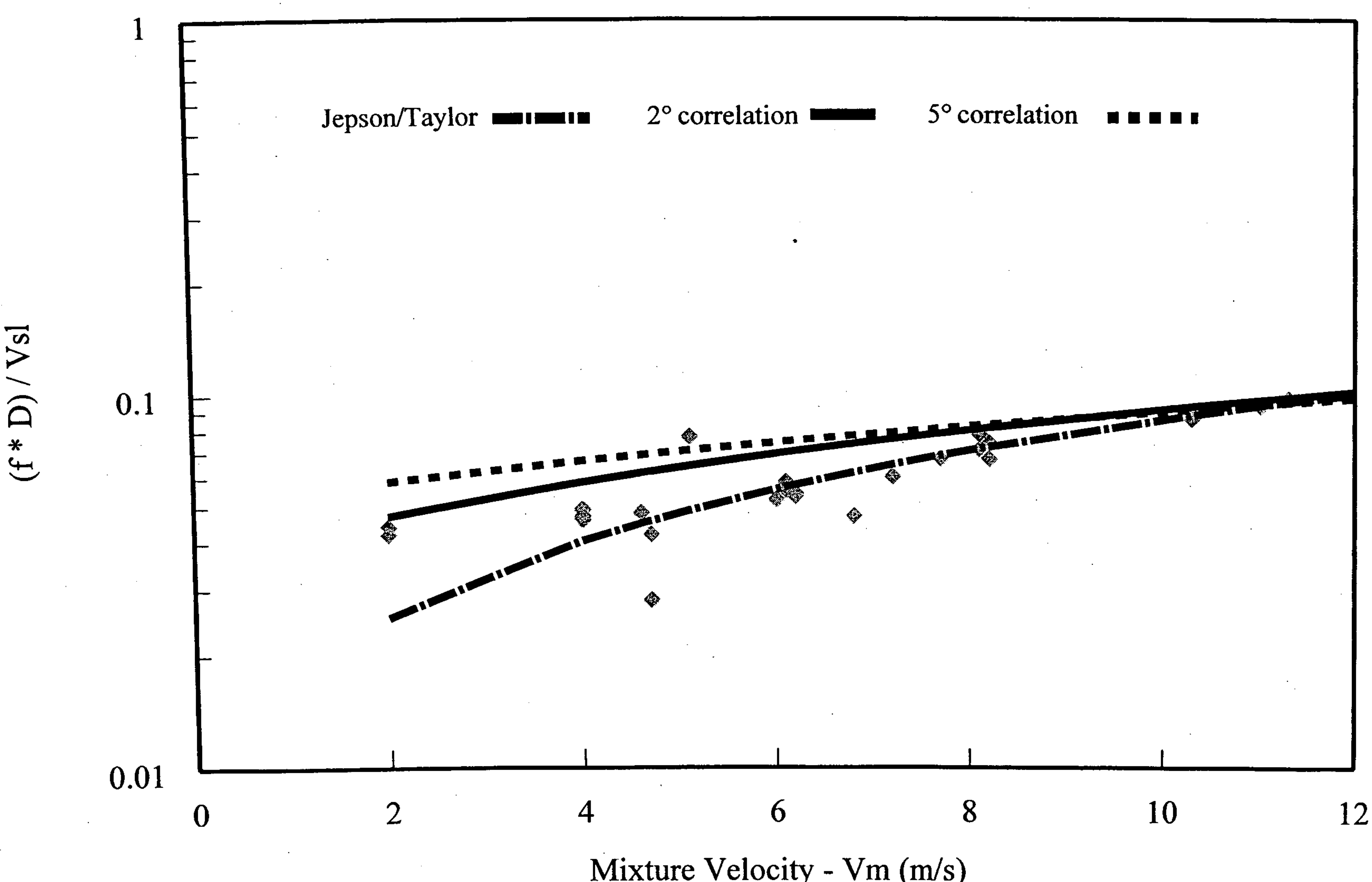


Figure 8: Jepson/Taylors(1989) results compared with the correlations developed in this study

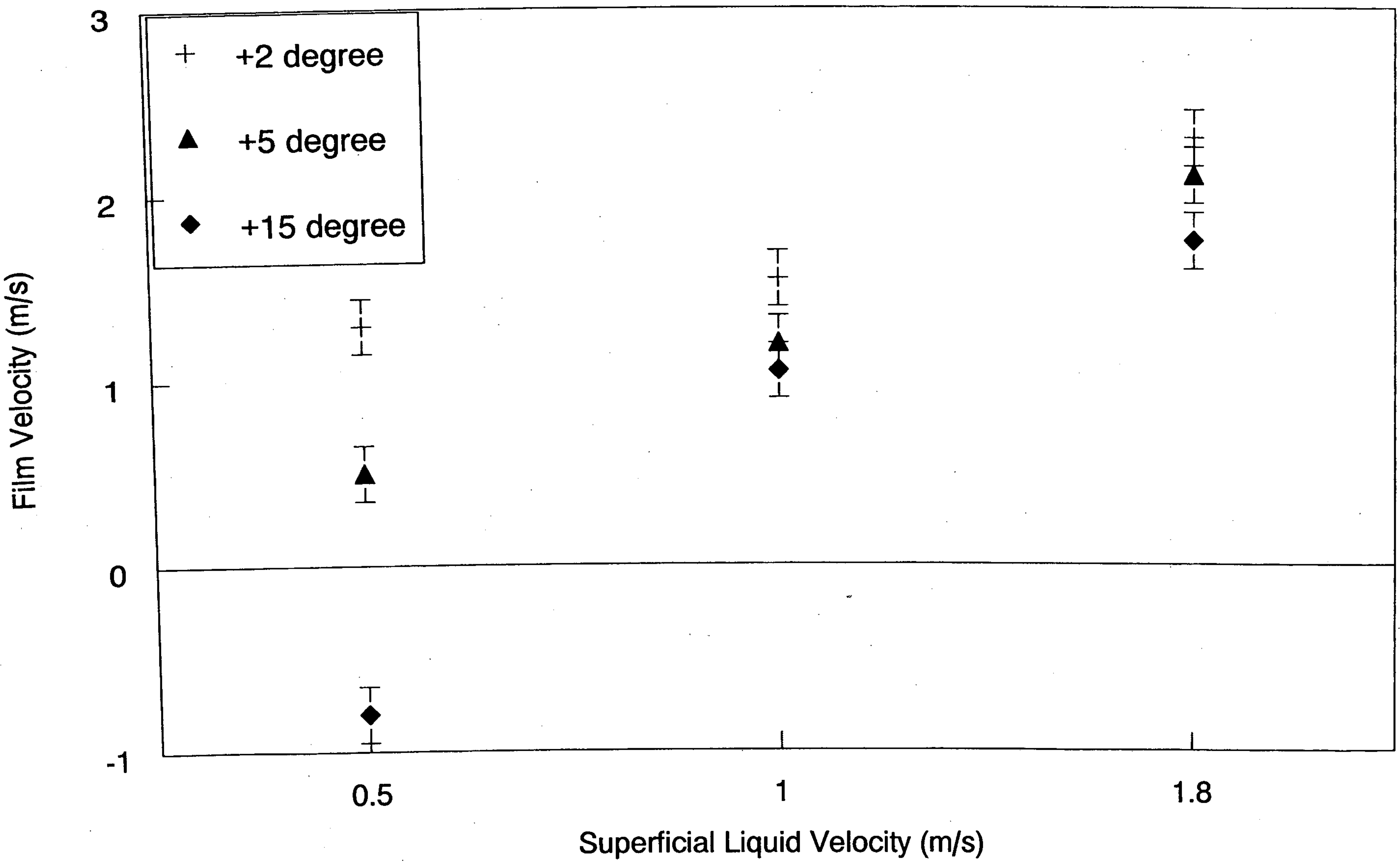


Figure 9: Effect of Inclination on Film Velocity
at 80% Water Cut, Vsg = 4 m/s

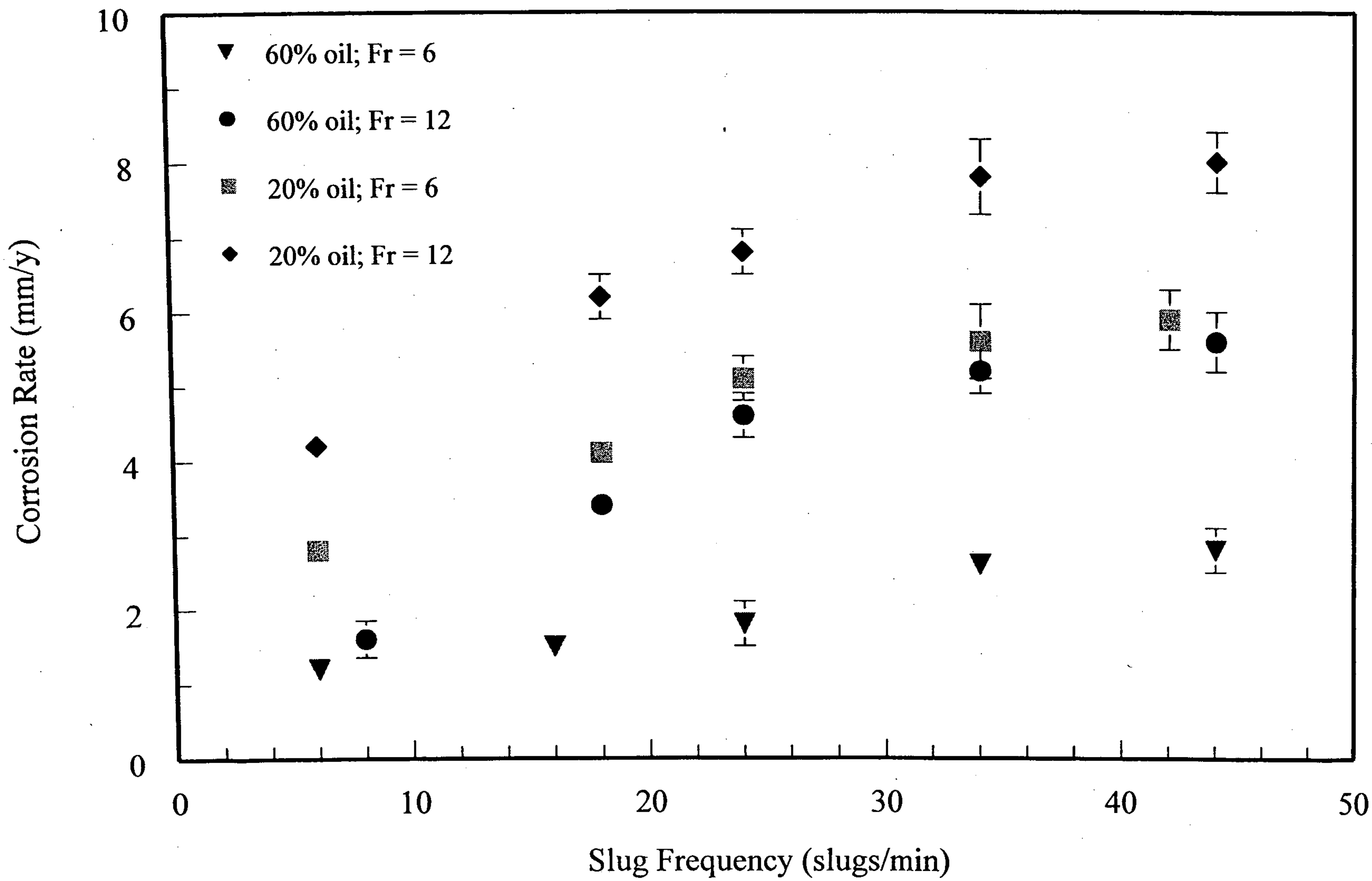


Figure 10: Corrosion Rate vs. Slug Frequency for 2°; 0.27 MPa

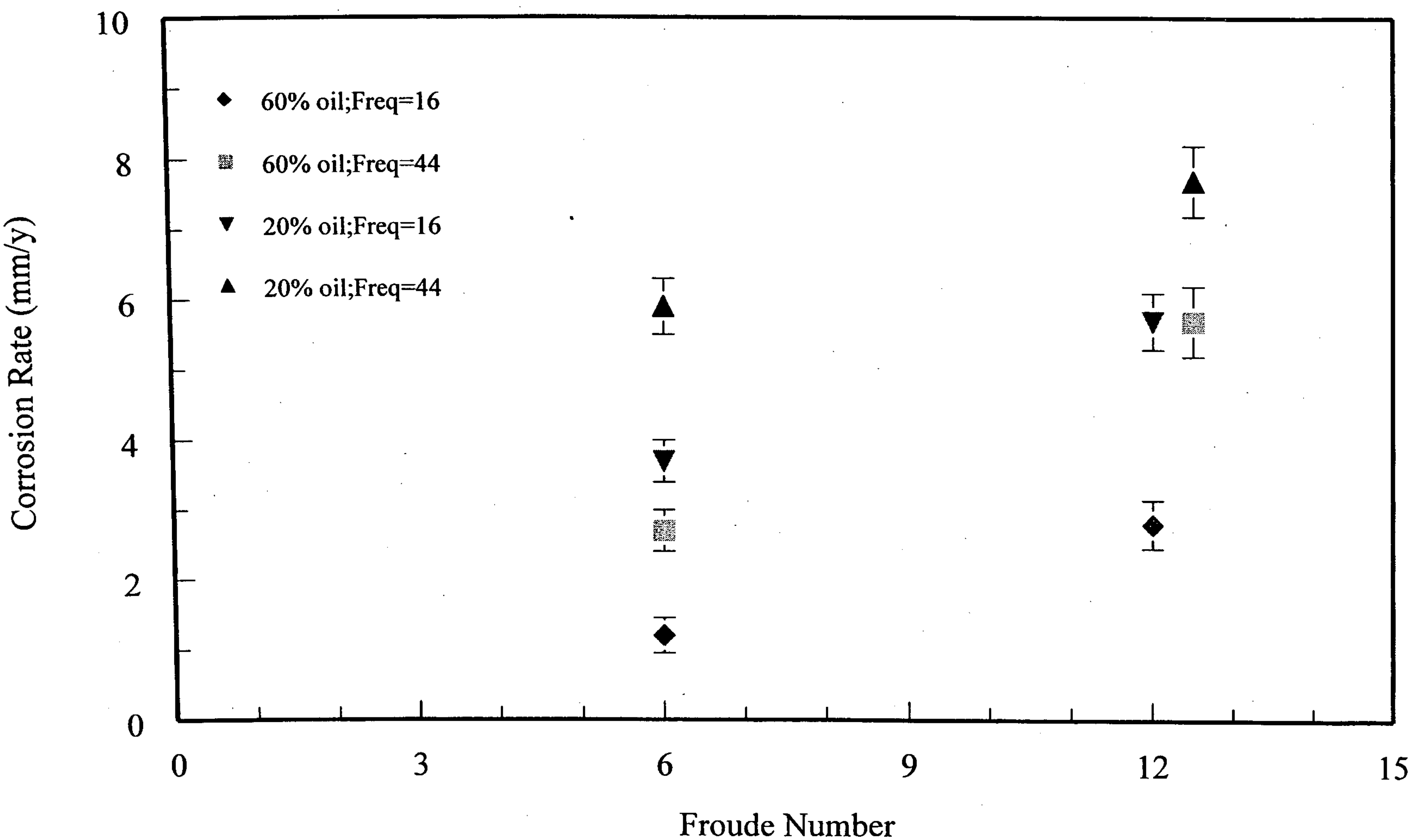


Figure 11: Corrosion Rate vs. Froude Number for 5°, 0.27 MPa; 80 & 40% saltwater

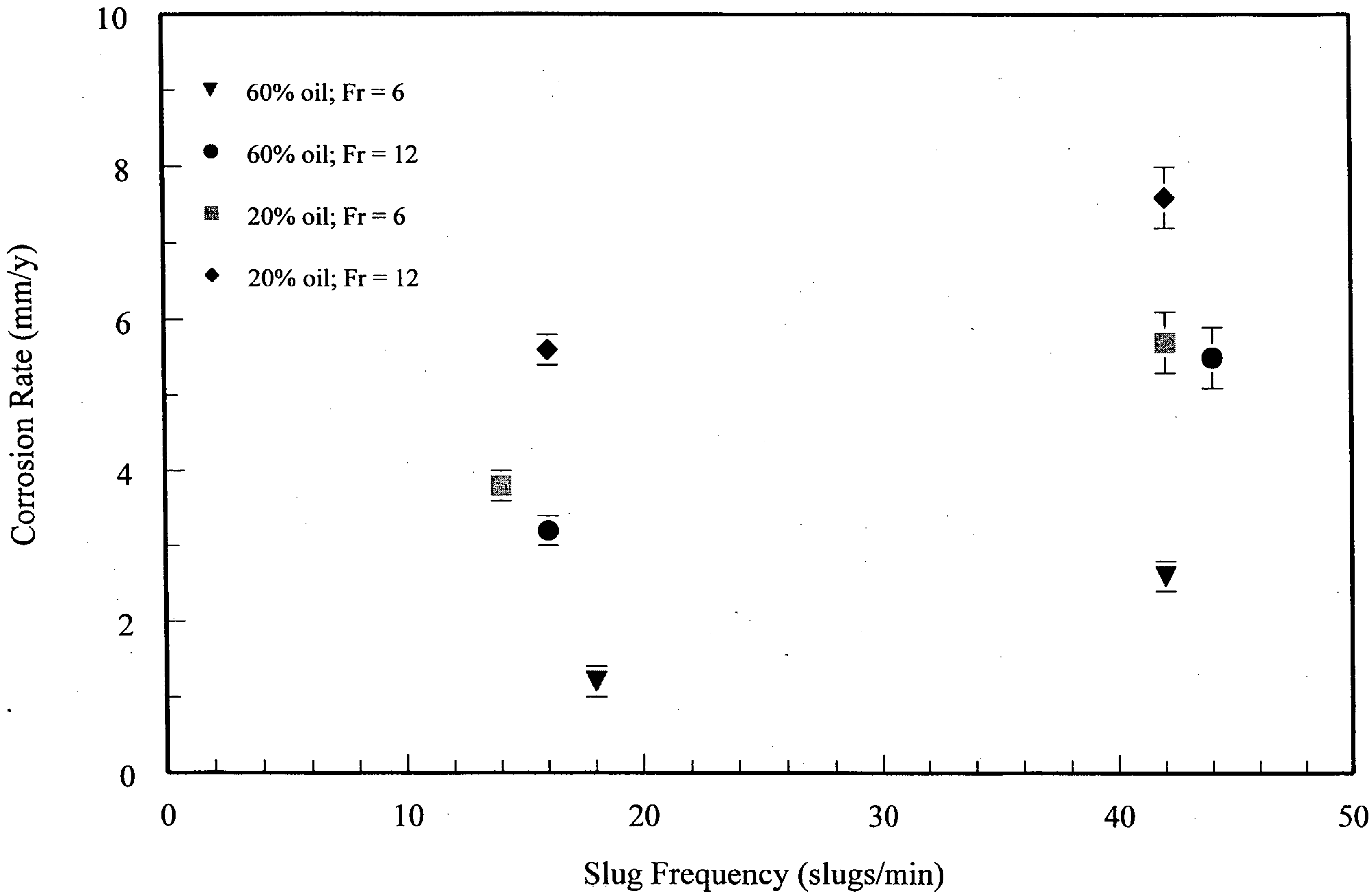


Figure 12: Corrosion Rate vs. Slug Frequency for 5°; 0.27 MPa