CORROSION IN THREE-PHASE OIL/WATER/GAS SLUG FLOW IN HORIZONTAL PIPES.

X. ZHOU AND W. P. JEPSON
NSF, I/UCRC CORROSION IN MULTIPHASE SYSTEMS CENTER
DEPARTMENT OF CHEMICAL ENGINEERING
OHIO UNIVERSITY
ATHENS, OHIO 45701
USA

ABSTRACT

A study of corrosion in the mixing zone at the front of slugs has been carried out in a 10 cm internal diameter, horizontal, three-phase flow system using a light condensate oil and saltwater as liquids and carbon dioxide as the gas phase. Visual observations show that stratified water layers are apparent at the bottom of the pipe at oil compositions up to 60%. Pulses of gas bubbles are formed at high Froude numbers which impinge on the lower surfaces of the pipe. The corrosion rate increased with an increase in Froude number. This is due to the increases in wall shear stress, turbulence, and gas present at the bottom of the pipe as the Froude number increases. The presence of gas at the bottom of the pipe has a significant effect on the corrosion rate. It provides an erosion component to the corrosion processes. The corrosion rate can be related to pressure drop across the slug but average wall shear stress does not seem to be appropriate.

INTRODUCTION.

In remote oil and gas producing sites, such as subsea or Alaska, it is usually impracticable to separate the liquid and gas phases. Often, the flow from several wells are combined and passed into a large diameter pipeline where the multiphase flow is transported to a platform or central gathering station. Separation takes place here.

With age and the use of some enhanced oil recovery techniques, the amount of water produced increases greatly. Water cuts as high as 80% are common. The combination of high water cuts and increasing carbon dioxide partial pressures lead to very corrosive environments.

In these multiphase flowlines, several flow regimes exist which include stratified, slug, and annular flows. At high production rates, the pipeline operates under slug flow conditions.

A typical slug is depicted in Figure 1. The flow characteristics in slug flow have been described by several workers, eg. Dukler and Hubbard (1975). When a slug forms in a pipe, it is accelerated to a velocity near to that of the gas. The front of the slug rolls over the liquid film ahead of the slug and a violent mixing zone is formed. This scoops up the liquid film and assimilates it into the slug body. The mixing zone also entrains large amounts of gas. Some of this is returned to the gas pocket ahead of the slug and most is passed through into the slug body.

Sun and Jepson (1992) showed that slug flow greatly increases the corrosion rate. This was substantiated by Green at al (1990). The corrosion rates are much higher than any predicted values, eg. de Waard and Milliams (1991), or from most experimental data obtained from rotating cylinder electrodes, single phase full pipe flow, or from vertical two phase flows. Many studies on corrosion in oil and gas pipelines have been carried out by these methods. None of them can account for the turbulent nature of the multiphase flow and caution should be used if data is extrapolated to field situations. Gross underestimates of the corrosion rates can occur. Sun and Jepson (1992) also mentioned that there existed regions of high wall shear stresses and turbulence that may contribute to the corrosion but no attempt was made to describe the mechanisms involved in the corrosion processes.

In previous corrosion studies, Ellison and Wen (1981) proposed three mechanisms for corrosion. These were convective mass transfer, phase transport, and erosion-corrosion. Phase transport depends on the wetting properties of the fluids. Mass transfer effects involve the movement of the corrosive materials and products to and from the metal surface. Erosion-corrosion often occurs at high velocity, turbulent flow or when solids are present. The turbulent nature of the flow can remove corrosion products from the surface and simultaneously enhance the mass transfer processes.

Efird et al (1993) showed that, for full pipe flow, the corrosion rate can be expressed in terms of wall shear stress. Further, they showed that corrosion measurements from rotating cylinder electrodes were much lower than those obtained from pipe flow.

The study of fast moving slugs in a pipeline is very difficult and involves the use of fast response instruments to capture the transient nature of the slugs. There are presently no corrosion instruments that can identify the effects of the passage of a slug on the corrosion mechanisms. Jepson (1987) and (1989) showed that slugs were propagating hydraulic jumps and these could be formed in a pipe and made stationary by the application of a back pressure to the flow. This allows the study of the mixing zone within the slug to be much easier. It was shown that the mechanisms and measurements in the stationary hydraulic jump and the front of moving slugs are identical at the same Froude number.

This work closely examines the nature of the flow within the mixing zone of the slug and identifies possible mechanisms that contribute to the corrosion processes.

EXPERIMENTAL SETUP.

The test facility is outlined in Figure 2. Oil and water in their designated proportions are pumped from the 1.2 m^3 storage tank into a 7.5 cm internal diameter PVC pipe where the liquid flowrate is measured by an orifice plate. The flow is allowed to expand into a 10 cm internal diameter PVC pipe and then forced under the gate G opened to a height of 4 cm. The liquid then issues into a 10 m long, 10 cm internal diameter plexiglass pipeline.

Carbon dioxide is used for the gas phase and this is injected into the system at point H, just downstream of the gate. The multiphase mixture then flows along the pipeline and into the liquid storage tank. The tank is fitted with specially designed, high efficiency, gas/liquid de-entrainer internals which separates the gas from the liquid. The gas is vented to atmosphere and the liquid falls to the lower section of the tank for re-circulation.

Initially, the system is pressurized using the gas from high pressure cylinders and the pressure maintained using a back pressure regulator fitted to the tank. For these experiments, the pressure was fixed at 0.137 MPa. Heaters are fixed into the storage tank and the temperature regulated to the desired operating conditions. A temperature of 40 C was used for these experiments.

As the flow moves down the pipe, a hydraulic jump is formed. This phenomenon has been proven to represent the front of a fast moving slug in horizontal flowlines. Here, the mixing regions of the slug produce high levels of instantaneous wall shear forces and turbulence. This can contribute to greatly enhanced corrosion/erosion rates. It is extremely difficult to monitor the characteristics in rapidly moving slug flow since very fast response instruments are needed due to the transient nature of the slugs. Few existing instruments for measuring corrosion, wall shear stress, oil/water/gas fractions are available. These only provide an average over the several slugs and cannot identify the mechanisms in each part of a slug.

By controlling the flow of gas into the pipeline, the hydraulic jump is moved to the test section where it is made stationary. The mechanics of the mixing region at the front of the jump can be readily examined. It should be noted that the flow properties downstream of the mixing zone are not the same as in moving slug flow. Only measurements from the front of the mixing jump are reported here.

Details of the test section are provided in Figure 3. The wall shear stress and turbulent intensity are measured at positions E using flush mounted, hot film sensors. The signals from these probes are passed to an anemometer system for processing and storage. The distribution of the oil/water/gas phases is determined using the sampling tube C. Iso-kinetic samples of the flow are taken along the vertical diameter of the pipe. From these, the oil, water, and gas fractions are calculated.

The pressure drop across the mixing zone is found from the pressure tappings D. To measure the corrosion rate, combinations of electrical resistance (ER) and linear polarization resistance (LPR) probes, and metal coupons are placed flush mounted at the top and bottom of the pipe at positions A and B which are 15 cm apart. The LPR probes were only used for the high water cuts. These are the only methods that can be readily used for monitoring corrosion in multiphase flows.

The fluids used in this study were ASTM saltwater, a light condensate oil, and carbon dioxide as the gas. The oil was chosen by the member companies of the Corrosion in Multiphase Systems Center as it is commonly used as a test fluid for simulating gas/condensate type flows. The density and viscosity of the oil at 40 C is 825 kg/m**3 and 2 cp respectively.

The liquid comprised mixtures of oil and water ranging from 100% water to 100% oil. Slug flow was studied at Froude numbers of 6, 9, and 12. These correspond to slugs moving at approximate translational velocities of 3, 4.5, and 6 m/s respectively.

For each of the experiments, the system was monitored carefully for oxygen content, iron concentration, and pH. Before each run, the system was purged to ensure the oxygen level was below 20 ppb in both the liquid and gas phases. The iron content was measured, and for all runs, the iron content was maintained mostly below 1 ppm and always below 10 ppm.

RESULTS.

During each experiment, visual observations were made of the flow within the front of the stationary slug. These observations indicated that the oil and water do separate and form stratified layers with water being at the bottom of the pipe. This would not be true for vertical flows.

It was also noted that at a Froude number of 6, there was some turbulence with gas being entrained. Most of this gas seemed to be returned to the gas pocket ahead of the slug with only relatively small amounts being passed into the slug body. This gas did not reach the bottom of the pipe. As the Froude number was increased, the turbulence levels increased dramatically and the amount of gas entrained increased substantially. Further, the bubbles of entrained gas were shot towards the bottom of the pipe in pulses. Some of these bubbles impacted on the wall at the bottom of the pipe. This is clearly seen in Figure 4. As the Froude number increased, the frequency of the pulses of bubbles also increased and more were seen to impinge on the pipe wall.

The void fraction data is presented in Table 1. The fraction of the gas at the bottom of the pipe and fraction averaged over the vertical diameter are given for each Froude number. It can be seen that the amount of gas within the slug increases substantially with increase in Froude number. Further, at the bottom of the pipe, the amount of gas present increases with Froude number. This is consistent with the observed pulses of bubbles.

The above could have serious consequences in the corrosion processes since an erosion component may now be present. This was substantiated when the wall shear stress and void fraction data were analyzed. Figure 5 shows the average wall shear stress and turbulent intensity for 80% saltwater and 20% oil at Froude numbers of 6, 10, and 12 where the Froude number is defined as:

$$Fr_f = \frac{(v_t - v_s)}{(g \cdot h_{eff})^{0.5}}$$

where: v_t = the translational velocity of the slug,
v_s = mixture velocity of the slug,
g = acceleration due to gravity,
h_{eff} = effective height of the liquid film calculated from the area of flow divided by the width of the gas/liquid interface.

It shows that there is a large change in the shear stress across the front of the slug. The greatest changes occur at the high Froude numbers. At a Froude number of 6, the wall shear changes from 8 N/m^2 just within the slug, to only 2 N/m^2 at 60 cm into the slug. For the Froude number of 12, the respective shear stresses are 26 and 9 N/m^2. The turbulence levels, which give a measure of the fluctuations in the shear stress, increase from very low levels at a Froude number of 6, to greater than 25% at the Froude number of 12. It is also noted that the turbulence exists over much longer distances into the slug at the high Froude numbers.

Instantaneous values of wall shear were very high at the high Froude numbers. Values greater than 100 N/m^2 were recorded at a Froude number of 12.

As the oil composition was increased, the wall shear stress increased at the same Froude number but the turbulence levels decreased. This is shown in Figure 6.

The corrosion rate data is provided in Figures 7 and 8. Figure 7 shows the variation of corrosion rate with Froude number for 20%, 40%, 60% and 80% oil. It can be seen that, at each oil composition, the corrosion rate increases with Froude number with the largest changes being at the highest Froude number. The high corrosion rates occur at the regions of high wall shear stress, high levels of turbulence, and gas bubble impingement.

Figure 8 shows the effect of increasing oil composition on corrosion rate. For the 20%, 40% and 60% oil, the corrosion rates are similar at each Froude number. However, above 60% oil, the corrosion rate decreases substantially but at the Froude number of 12, the corrosion rates are still relatively high at 1 mm/yr. The sudden decrease is attributed to the oil becoming the continuous phase at the bottom of the pipe. However, due to the turbulence and bubble impacts, the water can still contact the wall on an intermittent basis.

The equation developed by De Waard and Milliams (1991) gives a corrosion rate of 1.1 mm/year for these conditions. Adding in a velocity correction factor is very difficult since the pipe is not full and the phases move with different velocities. It does provide reasonable estimates of the corrosion rate at low velocities corresponding to low Froude numbers, but can severely underestimate the corrosion at high Froude numbers.

The effect of entrained gas on the corrosion rate is shown in Figures 9 and 10. The void fraction averaged over a vertical diameter at 60 cm into the mixing zone is plotted against corrosion rate in Figure 9. This shows that the corrosion rate increases with increase in average void fraction at each oil composition.

Due to the bubble impingement shown in Figure 4, a more important parameter may be the amount of gas present at the bottom of the pipe. This is illustrated in Figure 10. At each oil composition, the corrosion rate increases virtually linearly with amount of gas present at the bottom of the pipe. The gradients are similar at each oil composition. The amount of gas at the bottom of the pipe is dependent on the Froude number and is greatest at the high Froude numbers.

It has been suggested by Efird et al. (1993) that the corrosion rate is related to the wall shear stress. For slug flow, this is examined in Figure 11. The averaged maximum wall shear stress, which occurs close to the front of the of the mixing zone, is plotted with corrosion rate. It shows that, at each oil composition, the corrosion rate does increase with wall shear stress. However, no clear relation is noticed. Similar plots of wall shear stress at different distances into the mixing zone were examined and again no apparent fixed relation was found. The wall shear stress is calculated from the average of many readings from the hot film sensor. The fluctuations in the readings due to turbulence and bubble impingement are not accounted for. The turbulence intensity does account for some of this and can involve the bubble impacts.

The pressure drop across the slug front incorporates the shear stresses and losses due to turbulence. This is plotted against corrosion rate in Figure 12. For oil compositions of 20% 40% and 60%, there is only a small effect of oil composition. There is a good correlation between corrosion rate and pressure drop. At 80% oil, a similar relation exists but falls below that of the lower oil compositions. This is probably due to the oil becoming the continuous at the high oil percentages.

CONCLUSIONS.

Experiments have been carried out to examine the effects flow parameters on corrosion in horizontal slug flow. An oil similar to that in gas condensate systems, and saltwater at compositions of 20%, 40%, 60%, and 80% were studied using carbon dioxide as the gas. The experiments were carried out at 0.137 MPa and a temperature of 40 C.

Visual observations indicate the presence of water layers in the lower section of the pipe up to 60% oil. At higher oil percentages, the oil becomes the continuous phase at the bottom of the pipe. Further, pulses of gas bubbles within the mixing zone of the slug were present. These impact on the bottom of the pipe at high Froude numbers which correspond to high gas velocities. These produce regions of high wall shear forces and turbulence. These forces change substantially with position in the slug.

The corrosion rate increases with increase in Froude number at all oil compositions. Up to 60% oil, there is little effect of oil composition on corrosion rate. Above 60% oil, the corrosion rate decreases rapidly.

The presence of gas at the bottom of the pipe is an important parameter in the corrosion processes. The more gas that is present, the higher the corrosion rate. This is due to the bubbles of gas impacting on the wall and producing an erosion component to the processes.

The corrosion rate does not seem to be directly related to the wall shear stress as for full pipe flow since it is an averaged value and this does not account for the large fluctuations due to the turbulence and bubble impacts.

The pressure drop, which does include the shear forces and losses due to turbulence, is a more suitable parameter for correlating corrosion rate in slug flows.

5. REFERENCES.

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Table 1. Void Fraction data.

	Oil Composition.											
	20%			40%			60%			80%		
Froude number	6	10	12	6	10	12	6	10	12	6	10	12
average void fraction	.12	.17	.36	.17	.28	.33	.17	.40	-	.23	.30	.39
void at bottom of pipe	.06	.11	.22	.09	.22	.25	.10	.25	-	.10	.24	.32

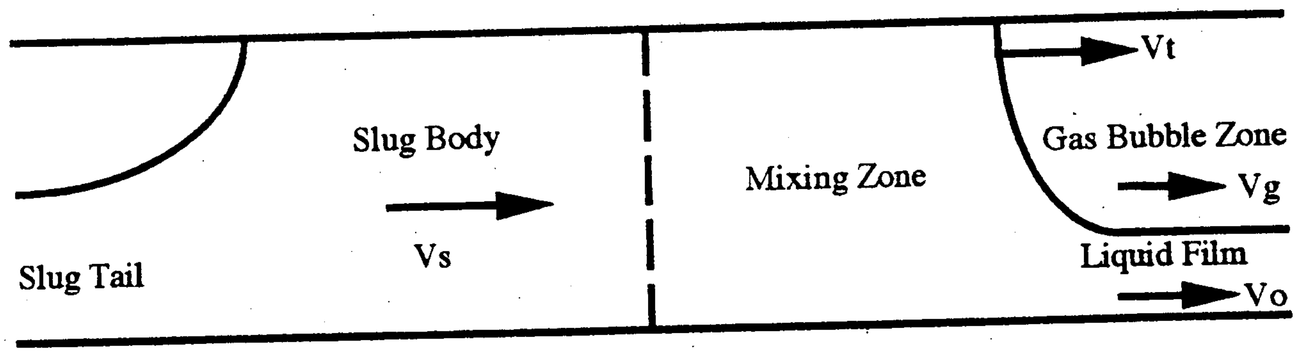
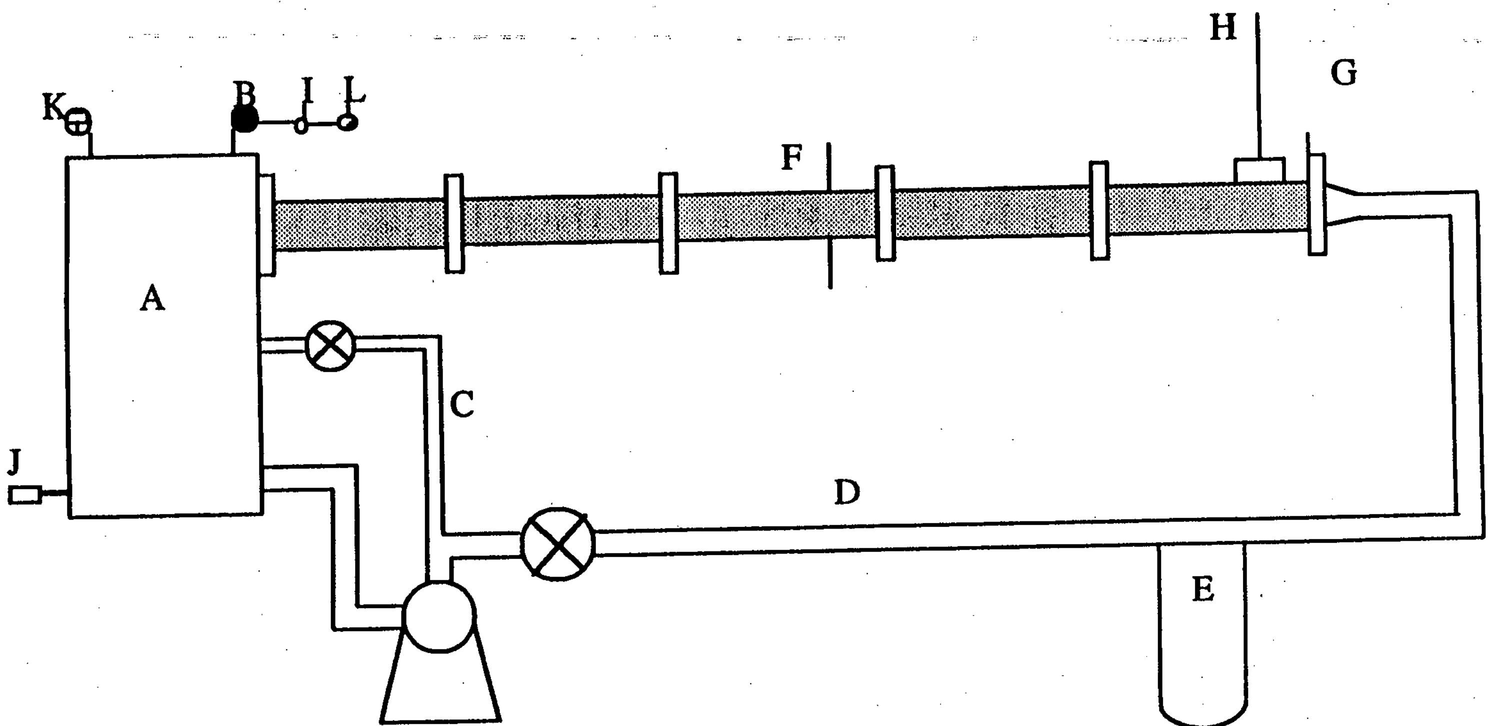
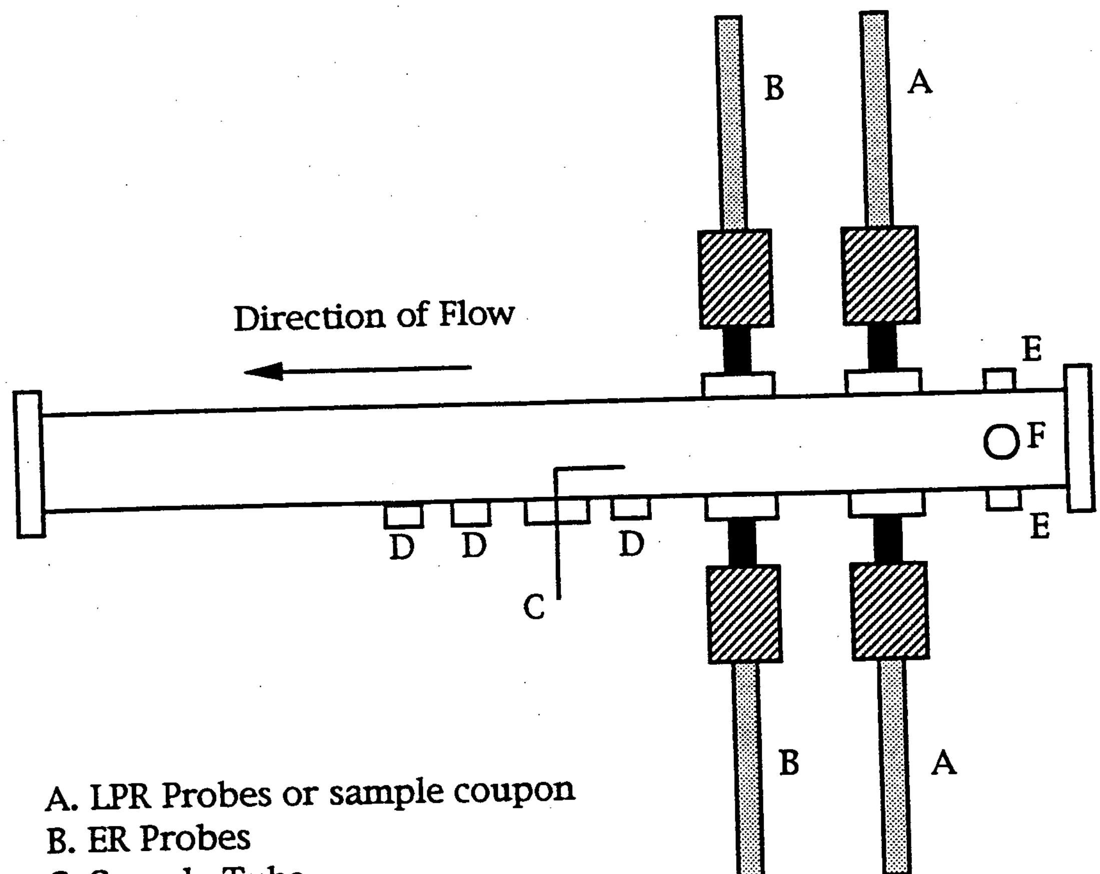


Figure 1 Slug Flow Unit



A. Liquid Tank
B. Pressure Gauges
C. Liquid Recycle
D. Liquid Feed - 3"PVC
E. Orifice Plate Manometer
F. Test Section - 4" Plexiglass
G. Flow Height Control Gate
H. CO_2 Feed Line
I. VENT w/valve
J. Heater
K. Safety Valve
L. Back Pressure Regulator

Figure 2. Layout of experimental system.



A. LPR Probes or sample coupon
B. ER Probes
C. Sample Tube
D. Pressure Tappings
E. Shear Probe Mountings
F. Temperature Probe

Overall Length - 6 ft.

Figure 3. Test section.

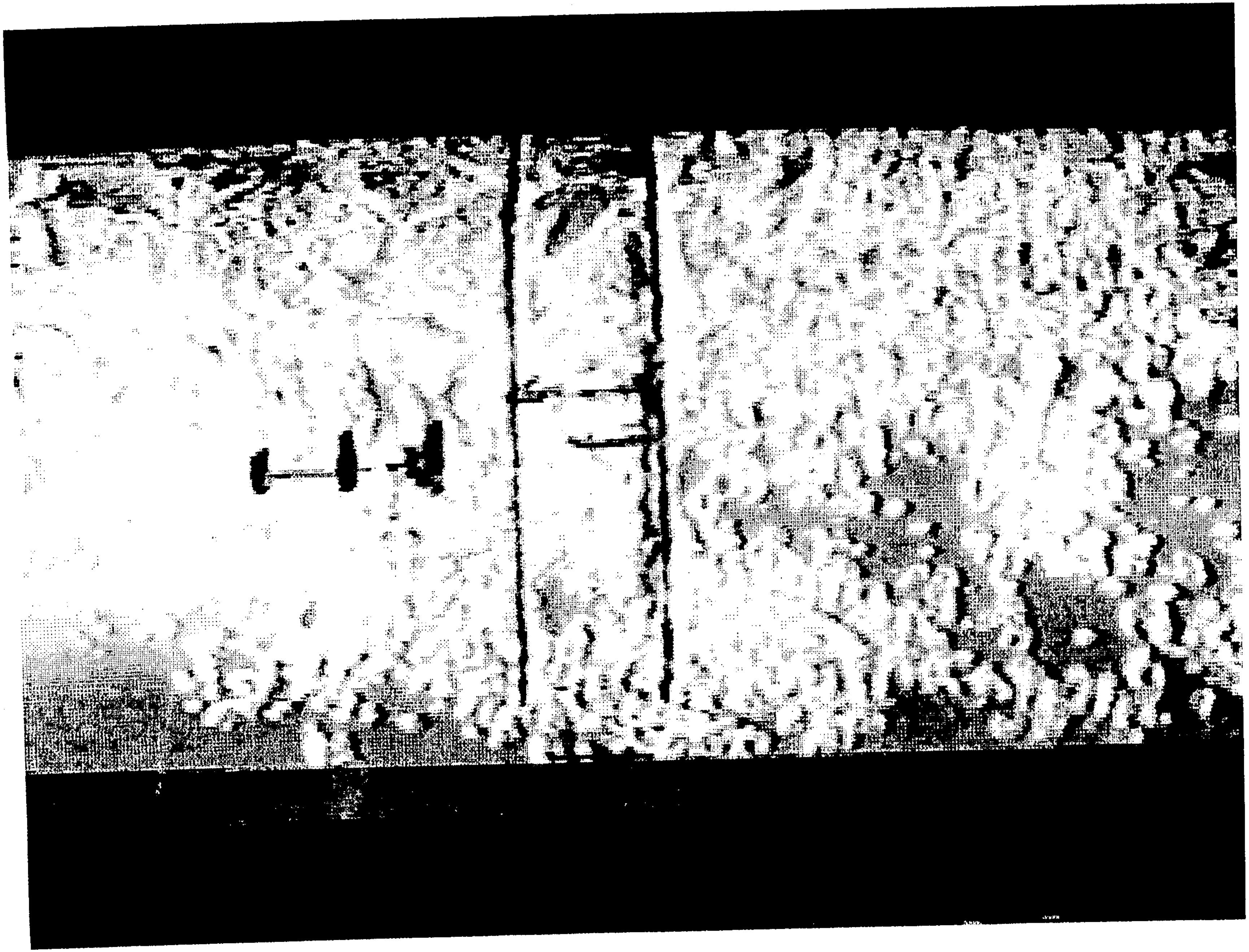
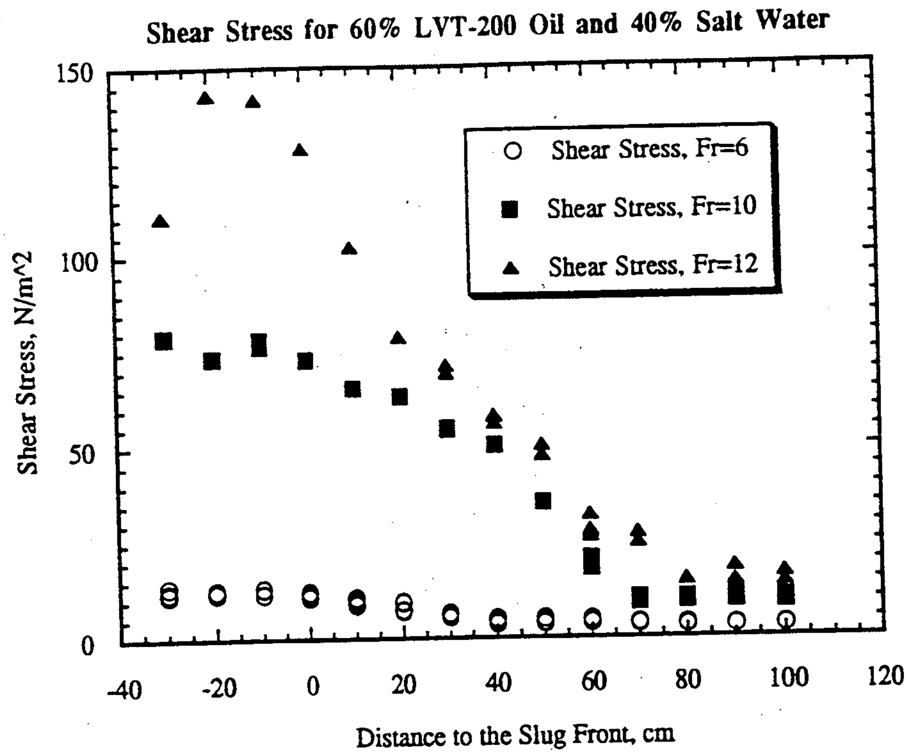


Figure 4. Video image of gas bubble impact in mixing zone of slug



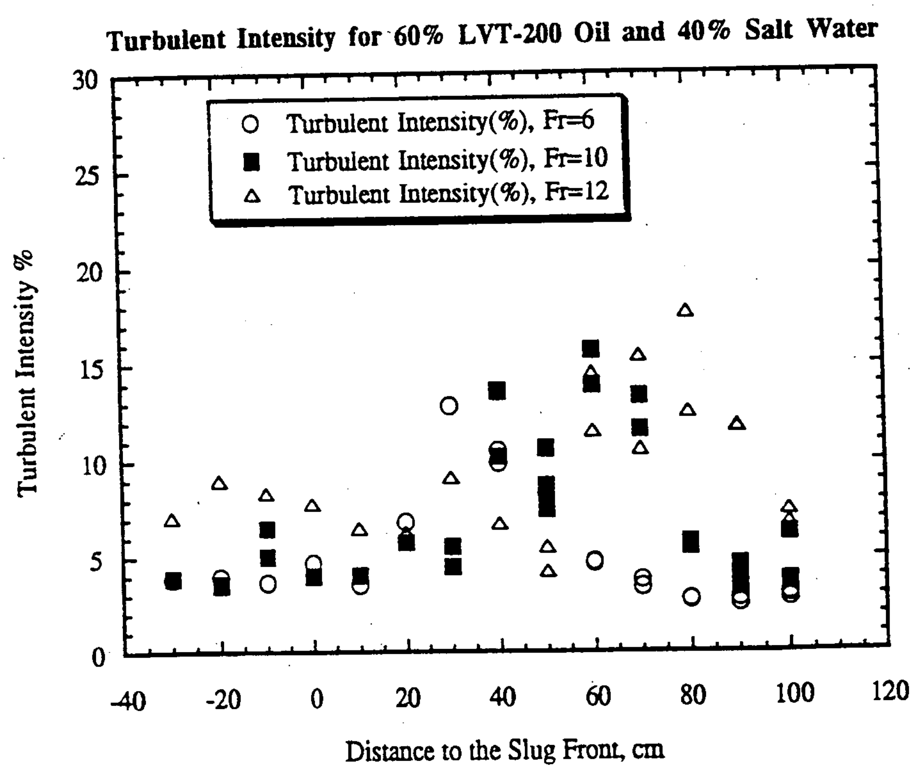


Figure 5. Shear stress and turbulence variation in the slug front.

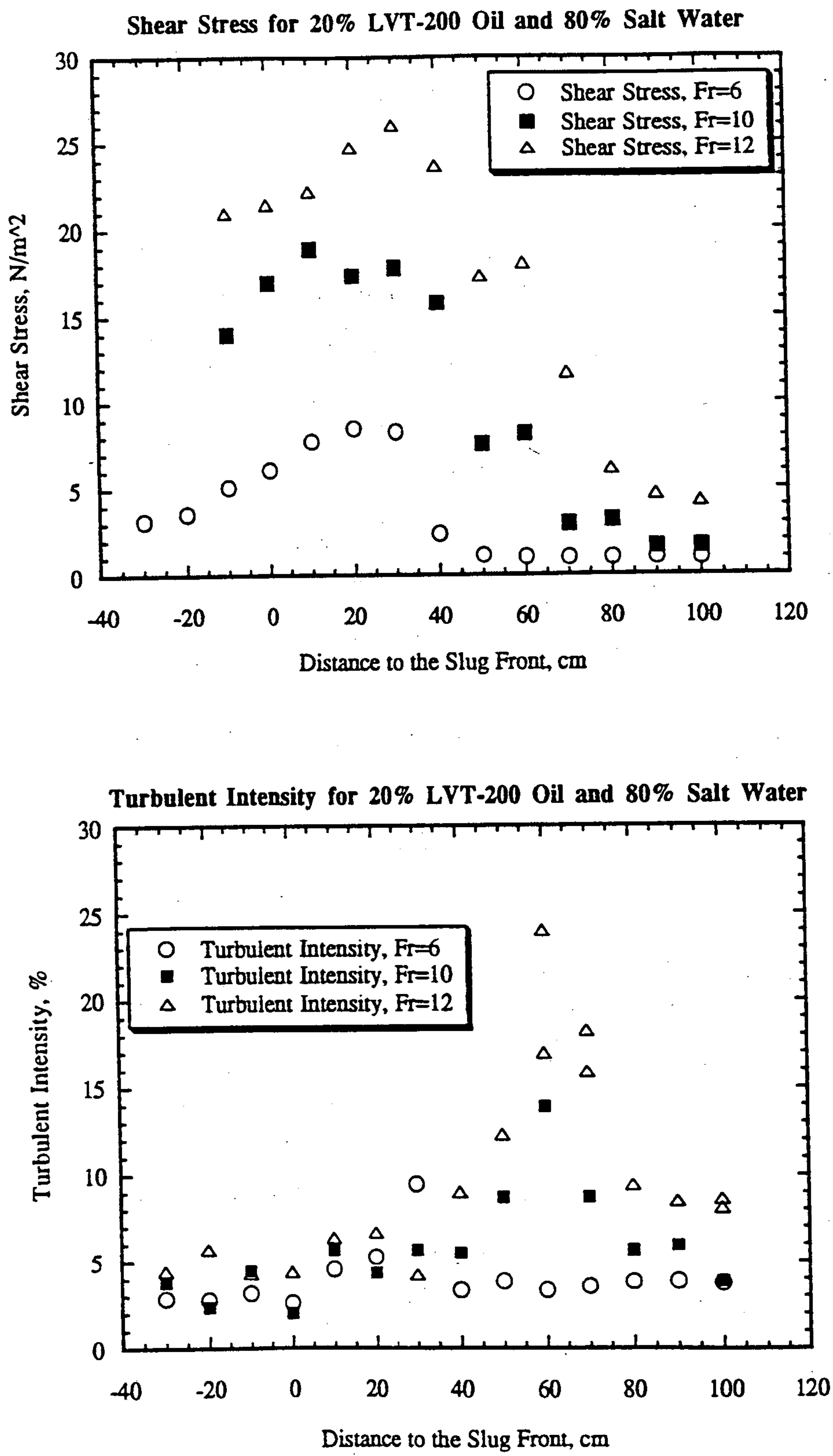


Figure 6. Shear stress and turbulence variation in the slug front.

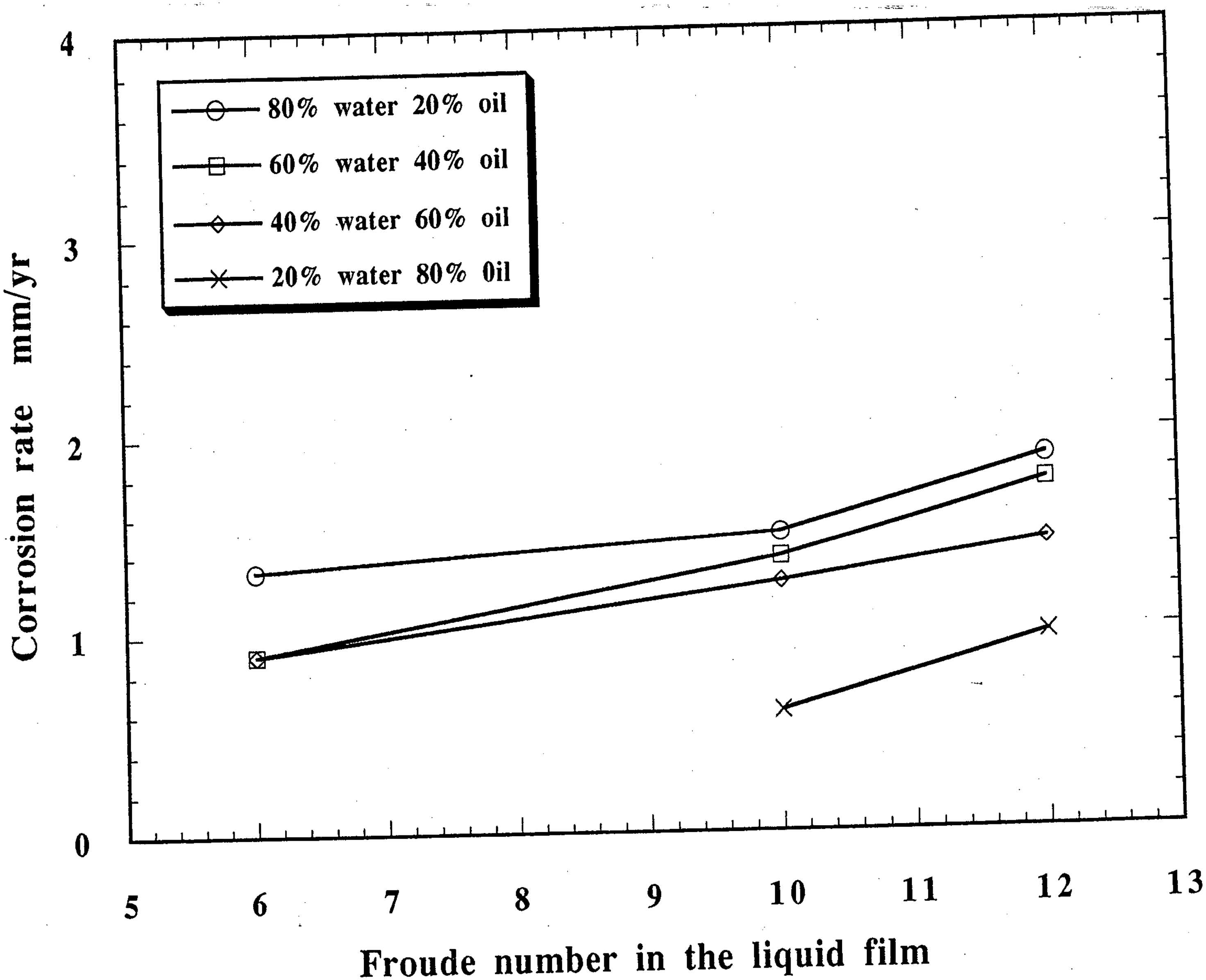


Figure 7. Variation of corrosion rate with Froude number.

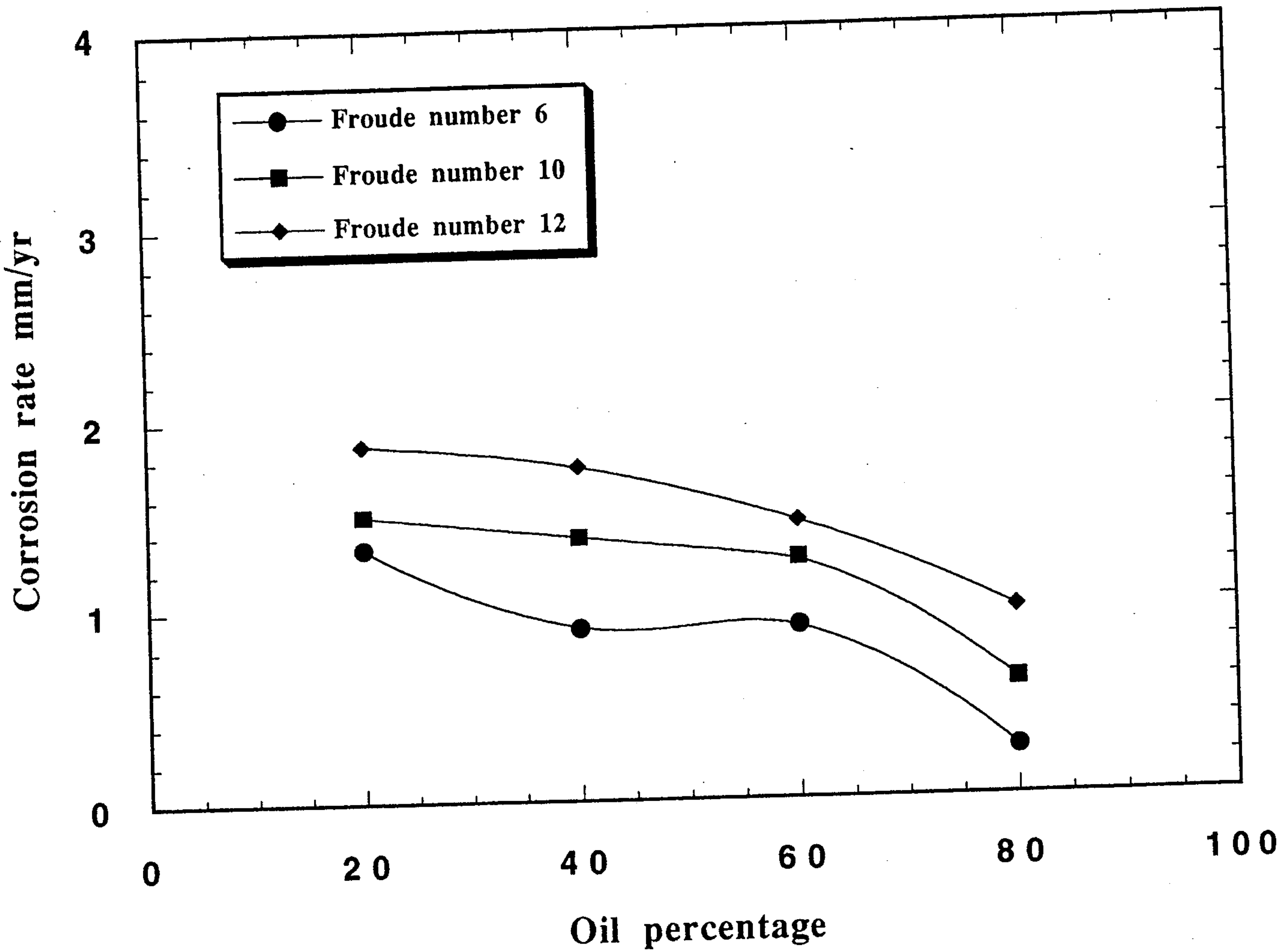


Figure 8. Effect of oil composition on corrosion rate.

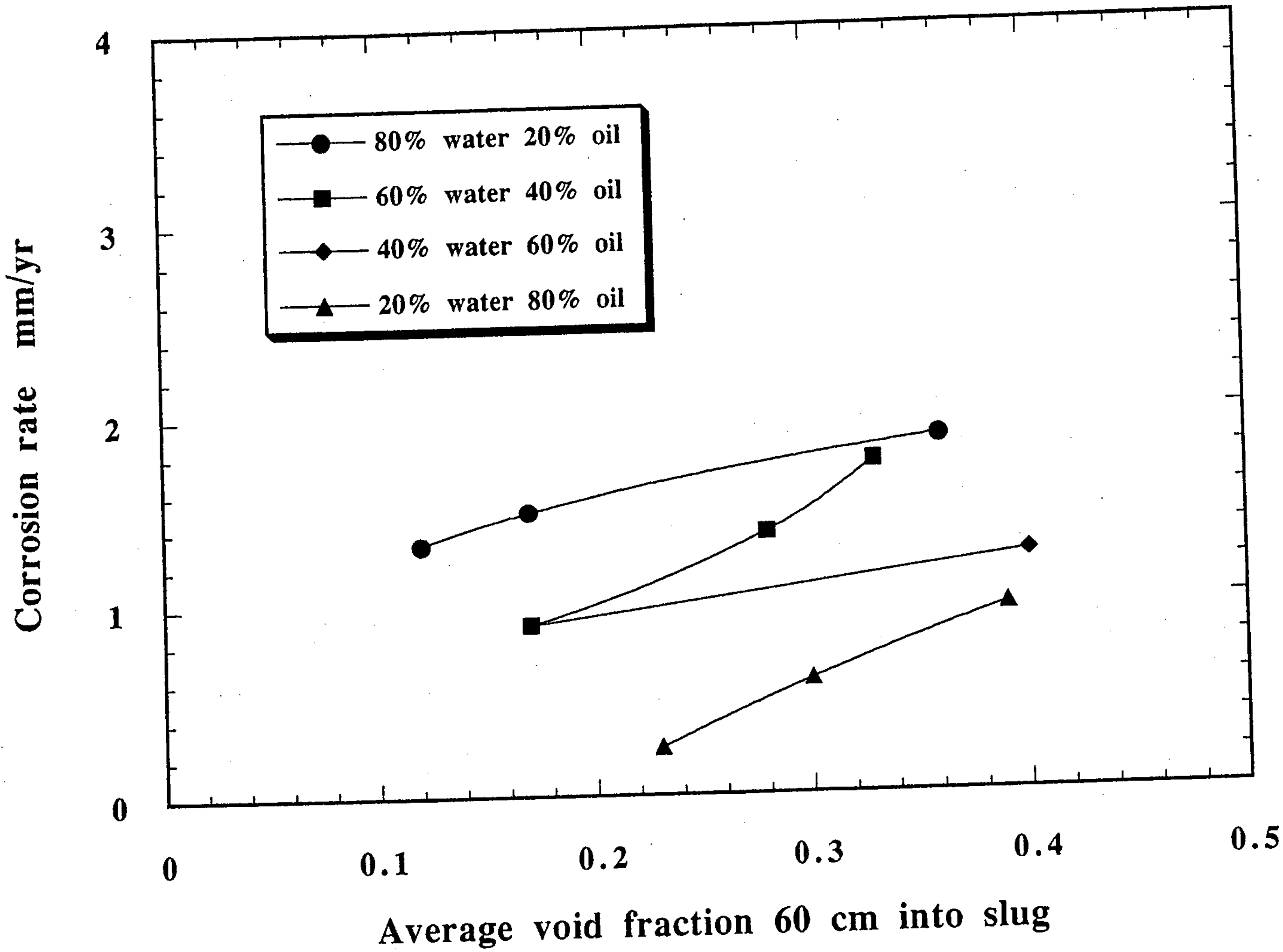


Figure 9. Effect of average slug void fraction on corrosion rate.

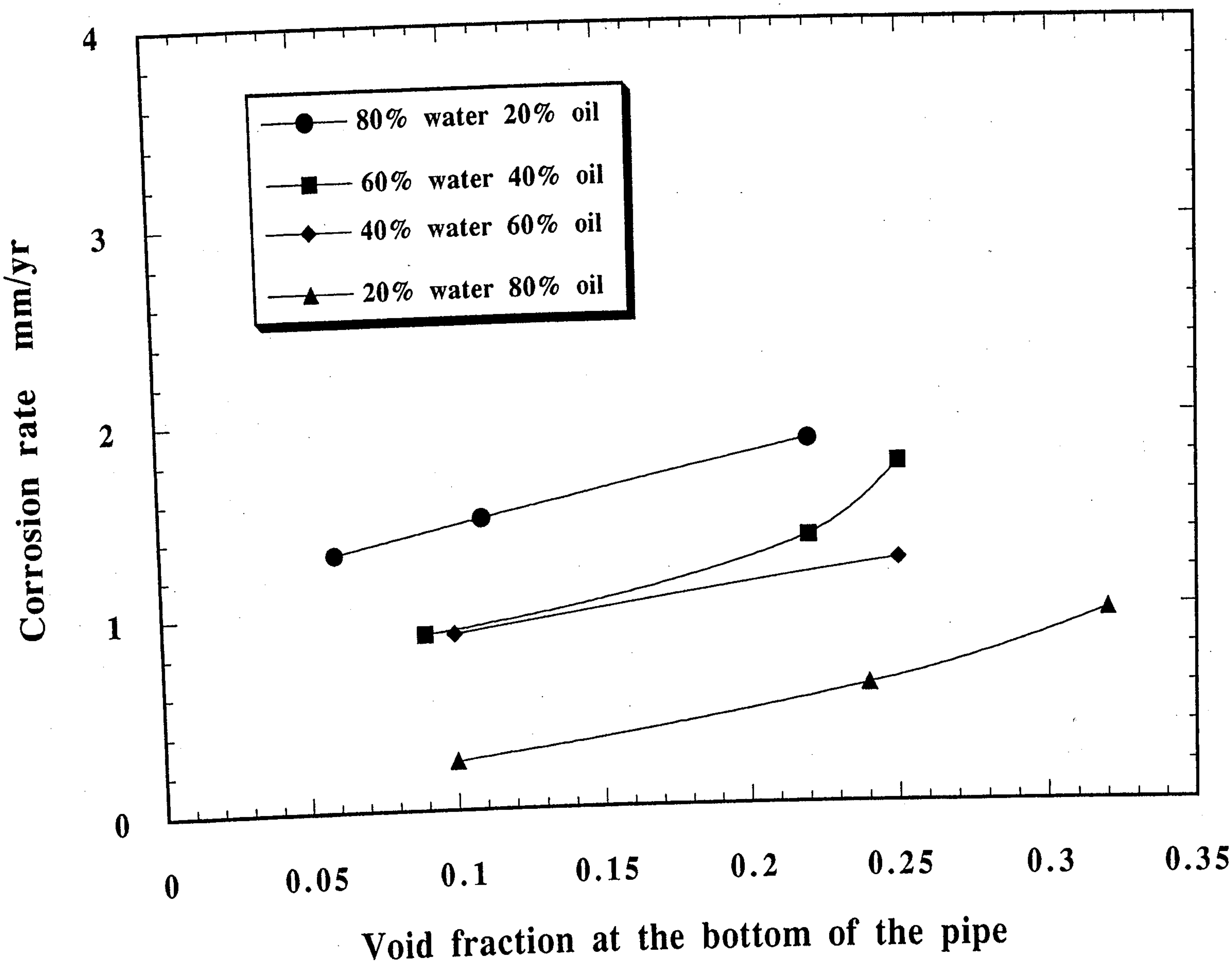


Figure 10 . Effect of void fraction at the bottom of the pipe on corrosion rate .

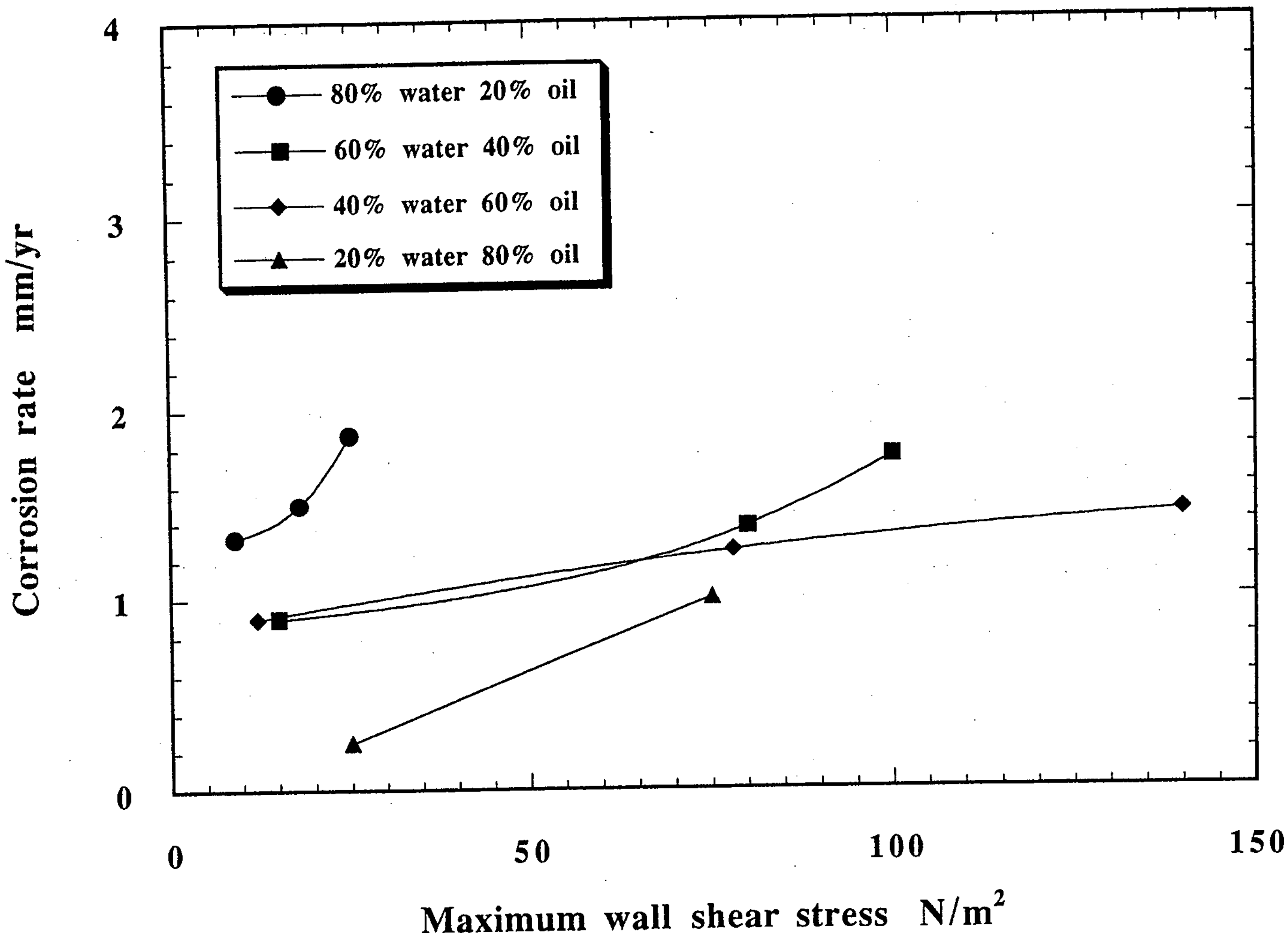


Figure 11. Variation of corrosion rate with maximum wall shear stress.

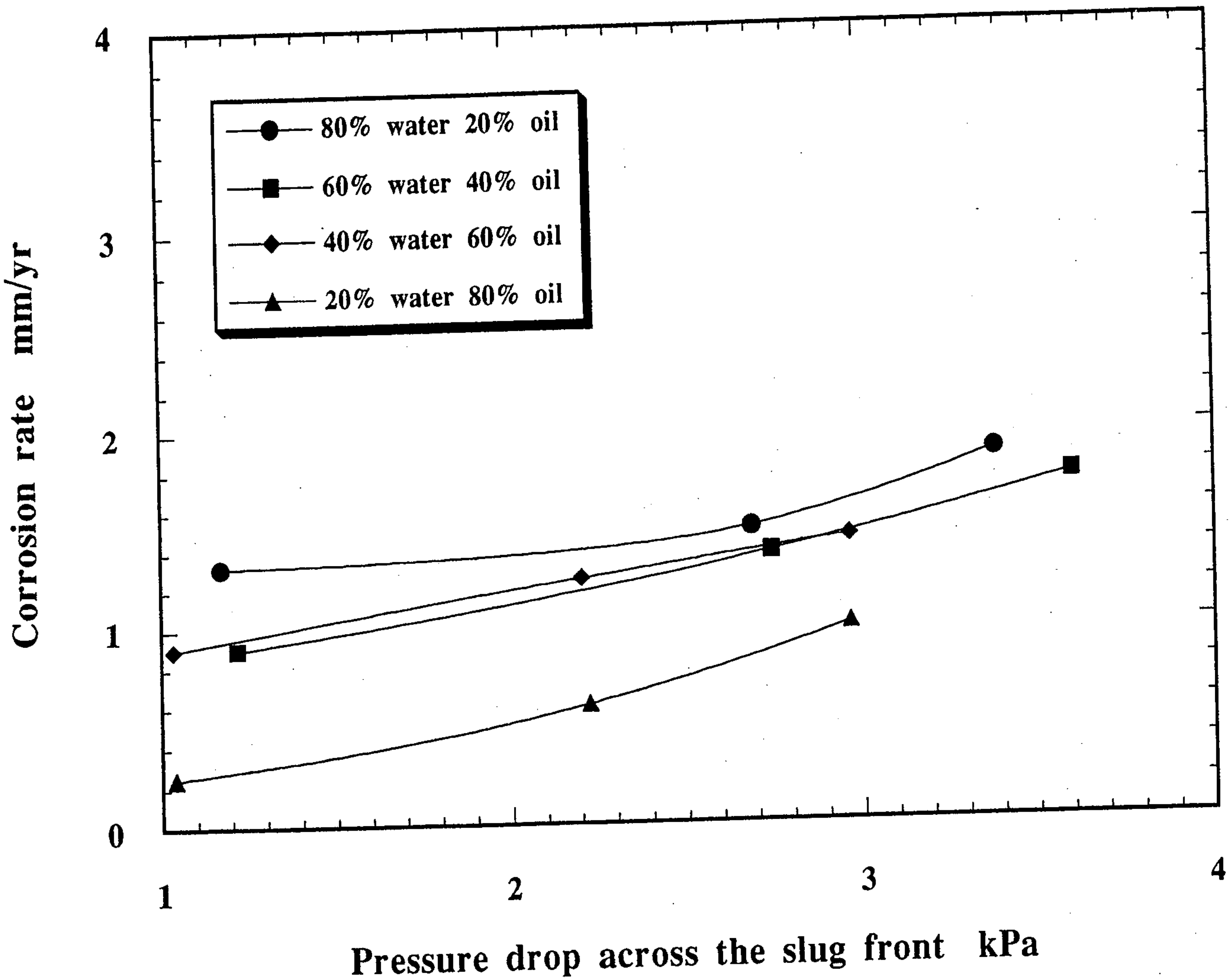


Figure 12. Plot of corrosion rate against pressure drop across the slug front.

Table 1. Void Fraction data.

	Oil Composition.											
	20%			40%			60%			80%		
Froude number	6	10	12	6	10	12	6	10	12	6	10	12
average void fraction	.12	.17	.36	.17	.28	.33	.17	.40	-	.23	.30	.39
void at bottom of pipe	.06	.11	.22	.09	.22	.25	.10	.25	-	.10	.24	.32