Paper No.
106

CORROSION 95

The NACE International Annual Conference and Corrosion Show

THE EFFECTS OF OIL VISCOSITY ON SWEET CORROSION IN MULTIPHASE OIL, WATER/GAS HORIZONTAL PIPELINES

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ABSTRACT

Experiments were carried out in a 10 cm I.D., three phase oil/water/gas horizontal Plexiglass pipeline. Mixtures of salt water with oils of viscosities 2 cp and 96 cp ranging from 0% to 100% oil were used for the liquid phase with carbon dioxide as the gas phase. Results indicate that, for both full pipe flow and slug flow, at each water percentage up to approximately 60%, the corrosion rate increased with oil viscosity at each flow condition. Above 60% water, the corrosion rate decreased rapidly to negligible values. In slug flow, the corrosion rate increased with increase in Froude number. This may be attributed to presence of gas at the bottom of the pipe and the higher pressure drops across the slug front at each Froude number.

INTRODUCTION

Internal corrosion of carbon-steel pipelines is a common problem encountered in oil and gas production. Many oil wells are now located in remote areas (e.g. Alaska or subsea). Here the fluids are transported together in a large diameter multiphase pipeline to a platform or gathering station where the oil, water, and gas are separated. As the wells become depleted, enhanced oil recovery methods are used. These include the injection of seawater into the reservoir to help maintain the pressure within the reservoir. The water fraction can be as high as 80%.

This flow of the multiphase mixture creates a number of corrosion associated problems in the pipelines. The carbon dioxide-water mixture forms a weak but corrosive carbonic acid. This can result in high corrosion rates in the carbon steel pipelines. The oil and gas mixture may also contain waxes, hydrates, hydrogen sulfide and sand. If the pipelines carrying oil and gas are located in deep water or inaccessible places, maintenance, and/or replacement and clean up of spills is difficult and expensive. Consequently, it becomes important to understand the mechanisms of corrosion and the factors affecting it.

In horizontal pipelines, due to effect of gravity, there are sections of the pipe that are not contacted with liquid. This results in asymmetrical flow regimes which are very different from those seen in vertical pipelines. At low liquid and gas velocities, stratified or wavy regimes exist. As the gas velocity is increased, slug flow can occur. Kouba and Jepson[1] (1989) showed that this is an intermittent flow regime which has regions of high levels of wall shear stress and turbulence associated with it. An idealized slug is shown in Figure 1. Sun and Jepson[2] (1992) further showed that there are regions of high shearing forces which can destroy the liquid boundary close to the wall. This can hinder the formation of a stable corrosion inhibitor film. They showed that it is important to know the slug characteristics such as slug length, void fraction, pressure drop and shear stress in order to understand the relationship between slug flow and the corrosion processes. They also showed that the Froude number, Fr_f, before the jump is an important parameter that is calculated as follows:-

$$Fr_f = \frac{V_t - V_f}{\sqrt{g\, h_{EFF}}} \qquad ..(1)$$

where,

V_t	=	Translational velocity of the slug
V_f	=	Velocity of the film ahead of the slug
g	=	Acceleration due to gravity
h_{EFF}	=	Effective height of the film defined as the ratio of the wetted area to the width of the gas-liquid interface of the film.

Annular flow is seen at very high gas velocities.

It has been noted by several workers that flow does have an effect on the corrosion processes. Sydberger[3] (1987) introduced the term 'Flow related corrosion' to describe the three corrosion mechanisms present in flowing systems suggested by Ellison and Wen[4] (1981), i.e. convective-mass-transfer controlled corrosion, phase-transport-controlled corrosion and erosion corrosion. De Waard and Lotz[5] (1993), Ikeda et al.[6] (1985), Ogundele and White[7] (1986), and Videm and Dugstad[8] (1989) have investigated the mechanisms of carbon dioxide corrosion on carbon steel under different conditions of pH, temperature, pressure, and oil-water fractions. They have also proposed various models to predict carbon dioxide corrosion of carbon steel. The different types of products formed on the pipe wall depend on the experimental conditions. The corrosion products primarily found on the pipe wall are iron carbonate ($FeCO_3$), iron bicarbonate ($Fe(HCO_3)_2$), iron carbide (Fe_3C) and a wide variety of iron oxides.

Previously, the most common tests to study corrosion were measurements using stirred beakers, rotating cylinder electrode, jet impingement loop and recirculating flow loops. De Waard and Milliams[9] (1975) performed experiments in stirred beakers to obtain corrosion rate data in carbon dioxide systems.

Nesic and Lunde[10] (1993), performed similar experiments but in recirculating flow loops. The effect of temperature and carbon dioxide pressure on corrosion rates obtained by them were similar to De Waard, Lotz and Milliams[5]. However, they showed that the corrosion rate depended on the velocity of the flowing system, and increased with an increase in liquid velocity. Efird et al.[11] (1993) indicated the importance of using flow loops to simulate pipeline conditions. They used three types of test systems, namely flow loops, rotating cylinders and jet impingement systems. They showed that the corrosion rates obtained from rotating cylinders were much lower compared to those obtained by flow loops.

Later, Sun and Jepson[2] (1992), Zhou and Jepson[12] (1993), Kanwar and Jepson[13] (1994) and Vuppu and Jepson[14] (1994) further showed the importance of using flowloops to study corrosion in pipelines. The experiments were conducted in 10 cm internal diameter pipelines under several, full pipe and slug flow conditions for low (2 cp) and intermediate (15 cp) viscosity oils. They confirmed that velocity is a major factor to be considered in corrosion studies. The results indicated that corrosion rate increased with an increase in the velocity of the liquid phase. They also showed that the results obtained from small diameter (eg. 2.54 cm and 5 cm) flowloops cannot be easily extrapolated to large diameter pipelines as the flow mechanisms in both the systems can be entirely different.

They showed that as the Froude number increased the corrosion rate at the bottom of the pipe increased. There was a corresponding increase in the wall shear forces at the bottom of the pipe increased. the pressure drop across the slug increased with an increase in Froude number indicating a larger turbulent zone.

Vuppu and Jepson[14] (1994) showed the importance of a third phase, ie. producing an oil-water-gas system. They showed that the presence of oil up to 60% oil did not greatly affect the corrosion rates. However, at higher compositions, the corrosion rates decreased to negligible levels. This is different from data obtained from vertical flows where the oil can contact the pipe wall at much lower fractions.
This work investigates the effect of oil viscosity on the flow characteristics and corrosion rates.

EXPERIMENTAL SETUP AND PROCEDURE

The experiments were carried out in a facility similar to that developed and constructed by Jepson (1987).

The experimental setup is shown in Figure 2. The system consists of a 1.2 m^3 316 stainless steel tank which serves as a storage and separation unit for the multiphase oil/water/gas mixture. The temperature in the system is maintained by two 3.75 kw heaters present in the stainless steel tank. A 3.73 kW centrifugal pump, pumps the oil and water mixture into a 7.6 cm ID PVC pipeline. The flowrate is controlled by valves and a bypass. The flowrate is measured by an orifice meter in the PVC section.

The liquid is then passed into the 10 m long, 10.1 cm ID plexiglass pipeline. Carbon dioxide from compressed cylinders is allowed to first pass through an expansion tank before it enters the system. The carbon dioxide enters at H. The carbon dioxide is also used to pressurize the system. The system pressure is monitored by gauge B.

Oil, salt-water and carbon dioxide are used as the working fluids. By measuring the wetted perimeter of the pipe that is contacted with liquid and the film depth, the area of flow and the mean velocity of the liquid film is calculated. The liquid film velocity is used to calculate the Froude number as described earlier. The liquid/gas mixture flows into the storage tank where the gas is released into the atmosphere while the oil-water mixture is recirculated.

The test section is illustrated in Figure 3. It consists of a 2 m long, 10.1 cm ID plexiglass pipe. At position A and B, flush mounted Electrical Resistance (E.R.) probes are inserted to measure the corrosion rate at the top and the bottom respectively. At position B a coupon holder is inserted. The coupons are flush mounted and are used for weight-loss measurements and for Scanning Electron Microscopy (SEM) studies. The coupons are made of 1 cm diameter, 0.4 cm thick 1018 carbon steel to simulate pipeline conditions. Four coupons are placed on a holder and, inserted flush with the pipe wall. Pressure tappings are located at points D and measure the pressure drop across and within the slug body using an U tube manometer.

Probe C consists of a 6 mm. diameter sampling probe which is used to withdraw fluid samples to measure the void fraction and oil-water fractions across the slug body. This tube is also used to test the pH as well as the concentration of oxygen, and iron ions present in the system.

The fluids used were a refined oil with a viscosity of 96 cp at 40 C and density 900 kg/m^3. ASTM D1141-52 Sea Salt was used for the water phase with carbon dioxide as the gas.

The experiments were carried at a pressure of 136 kPa and temperature of 40 C for full pipe flow and slug flows. The liquid velocities for full pipe flow were 1.0 and 1.8 m/s. For slug flows, Froude numbers of 6, 9, 12, and 14 were studied. These correspond to slug velocities of 3, 4.5, 6, and 7 m/s approximately.

RESULTS AND DISCUSSION

The corrosion rates for both full pipe liquid/liquid flow and three phase slug flow are now reported.

Full Pipe Flow

The effect of oil composition on corrosion rate is shown in Figure 4. It can be seen that, for full pipe flow for the two velocities considered, the corrosion rate increases as the velocity of the liquid phase is increased. The corrosion rate for a fluid composition of 20% oil and 80% water increases from 2.4 mm/yr at 1.0 m/s to 4.4 mm/yr at 1.8 m/s . At 1.0 m/s liquid velocity, as the oil fraction in the liquid phase increased from 20% to 60%, the corrosion rate increased from 2.4 mm/yr to 3.6 mm/yr respectively. However, at 1.8 m/s liquid velocity the amount of oil present in the liquid phase does not have much effect on corrosion rate. The corrosion rate drops from 4.5 mm/yr to negligible values when the oil fraction the liquid phase is changed from 60% to 80%. This is due to the oil contacting the probe and thus inhibiting corrosion.

Slug Flow

Figures 5 and 6 show corrosion rates at the bottom of the pipe for different Froude numbers. The Froude number is defined as given in Equation 1. Figure 5 indicates that, as the oil fraction in the liquid phase is increased the corrosion rate increases. This is seen at each Froude number. For Froude number 6, for water only, the corrosion rate is 2.0 mm/yr whereas the corrosion rate is 4.2 mm/yr when 60% oil is present in the liquid phase. For 60% oil, the corrosion rate has similar value of 4.2 mm/yr at each Froude number. At a Froude number of 14, the corrosion rate increased to 5 mm/yr. Beyond 60% oil fraction in the liquid phase corrosion rate decreases rapidly to negligible levels.

Figure 6 indicates that as Froude number increases the corrosion rate increases. The largest increase is seen above Froude numbers of 9. For 20% oil fraction, the corrosion rate increases from about 2.5 mm/yr to 3.8 mm/yr when the Froude number is increased from 6 to 14, respectively. At lower Froude numbers (eg. Froude number 6 & 9), there is less turbulence in the mixing zone of the slug. However, at the higher Froude numbers (eg. Froude numbers 12 & 14), the intensity of turbulence in the mixing zone of the slug is increased. This results in enhanced corrosion rates at higher Froude numbers.

The void fraction profiles at 30 cm and 60 cm in the slug for oil percentages of 20 and 40% are shown in Figure 7 (a),(b),(c), and (d). These indicate that, in each case, the void fraction at the bottom of the pipe is less than at the top. At the same liquid composition, as the Froude number increases the local and average void fraction increases. For 20% oil, the average void fraction is only 0.09 at Froude number 6, whereas it is 0.21 at Froude number 12. At higher Froude numbers, the mixing process in the slug is enhanced and allows more gas to be entrained in the slug. The degree of turbulence in the slug increases and due to the increased scouring effect the corrosion rate increases.

Also in Figure 7, at 60 cm in the slug, it is seen that the void fraction profiles in the lower half of the pipe are similar to those measured at 30 cm within the slug. However, in each case, at the top pipe the void fraction for Froude number 6 is greater than that at Froude number 12. This is to be expected because the mixing zone of the slug for Froude number 6 is small compared to that at Froude number 12, and all the gas has passed towards the top of the pipe.

The pressure drop at 30 cm and 60 cm across the slug front are shown in Figure 8 (a) and (b). These indicate that as the Froude number is increased the pressure drop across the slug front increases. For 20% oil at 60 cm into the slug, the pressure drop increases from 1.61 kPa to 4.27 kPa as the Froude number is increased from 6 to 12. At lower Froude numbers, there is little change in the pressure drop measured at 30 cm and 60 cm within the slug body. Whereas at Froude number 12 there is an appreciable change in the pressure drop at the two positions. This indicates that as the Froude number is increased the amount of turbulence in the slug increases and thus the length of the mixing zone increases.

The results obtained from these experiments are compared with other available data and models in Figures 9 and 10.

For full pipe flow, the equation developed by Kanwar[15] (1994) and de Waard[1] (1993) are shown in Figure 9. It is seen that both the models under-predict the corrosion rate obtained at higher velocities for the higher viscosity oil. At a velocity of 1.8 m/s the corrosion rate obtained by this study for a fluid composition of 20% oil and 80% salt water is approximately 4.8 mm/yr. The deWaard[1] (1993) model predicts a very low corrosion rate of 1.35 mm/yr. The Kanwar model is much better and predicts a corrosion rate of 3.2 mm/yr.

In Figure 10, a comparison is made with the data obtained by Zhou[12] (1993). Zhou[12] (1993) studied a low viscosity 2 cp oil at a pressure of 136 kPa and temperature of 40 C. It is seen that in both the studies, with an increase in Froude number corrosion rate increases. The corrosion rates at Froude Number 6 and 12 for a fluid composition of 20% of the 96 cp oil are 2.54 mm/yr, and 3.18 mm/yr and for 20% of the 2 cp oil are 1.4, and 1.9 mm/yr, respectively. In case of the higher viscosity oil, the corrosion increases with an increase in oil concentration which is similar to results obtained by Kanwar[15] (1994).

The increase in corrosion rate with increase in Froude number may be attributed to the local increases in void fraction and pressure drop within the slug front. The presence of gas bubbles at the bottom of the pipe, which may impact on the pipe wall there, and/or the increase in wall shear stress in the mixing zone of the slug has an effect on the corrosion rate. The effect of viscosity on void fraction is shown in Figure 11. The low viscosity oil entrains more gas in the slug than the higher viscosity oil. At a Froude number of 12, 30 cm within the slug, the 20% oil mixture of the 96 cp oil, entrains approximately 20% gas in the mixing zone, whilst the 2 cp oil entrains nearly 50% gas in its mixing zone. However, there is gas still present at the bottom of the pipe. Further, the pressure drop across the slug is larger for the higher viscosity oil. Zhou[12] (1993) also showed that the length of the mixing zone increases with an increase in Froude number. This is also seen here.

CONCLUSIONS

Corrosion experiments have been carried out for full pipe flow and slug flow conditions in three phase oil/water/gas mixtures in large diameter 10 cm I.D. pipes at 0.137 MPa and 40C. ASTM D1141-52 Sea Salt solution, oil with a viscosity of 96 cp, and carbon dioxide were used in the study.

Full Pipe Flow

For the range of velocities studied, increasing velocity, increased corrosion rate. At each velocity, high levels of corrosion were noted at oil compositions up to 60%. An increase in the oil percentage from 60% to 80% reduced the corrosion rate to negligible values. This is probably due to oil contacting the pipe wall.

Existing models of both Kanwar[15] (1994) and De Waard[1] (1993) under-predicted the corrosion rate at high velocities. The Kanwar model seemed to be much better in its predictions than the De Waard model.

Slug Flow

The Froude number is an important non-dimensional group that describes the "strength" of the mixing zone at the front of a slug. An increase in Froude number results in increased levels of wall shear stress and turbulence resulted in increased corrosion rates.

Increasing the oil concentration up to 60% gave an increase in the corrosion rate. Above 60% oil, the corrosion rates were negligible.

As the Froude number was increased, the void fraction in the slug also increased. There was always more gas at the top of the pipe. However, at high Froude numbers, the void fraction at the bottom of the pipe was also increased due to higher levels of turbulence. Comparison with oil of viscosity 2 cp shows that less gas is entrained by the more viscous oil.

Higher Froude numbers result in a higher a pressure drop across the slug front. The length of the mixing zone also increases. The pressure drop is higher for the higher viscosity oil at the same Froude number.

Increased corrosion rates in slug flow may be attributed to two causes, increased void fraction where gas bubbles can impact on the bottom of the pipe, and/or increased wall shear stresses due to the high turbulence levels encountered at the slug front.

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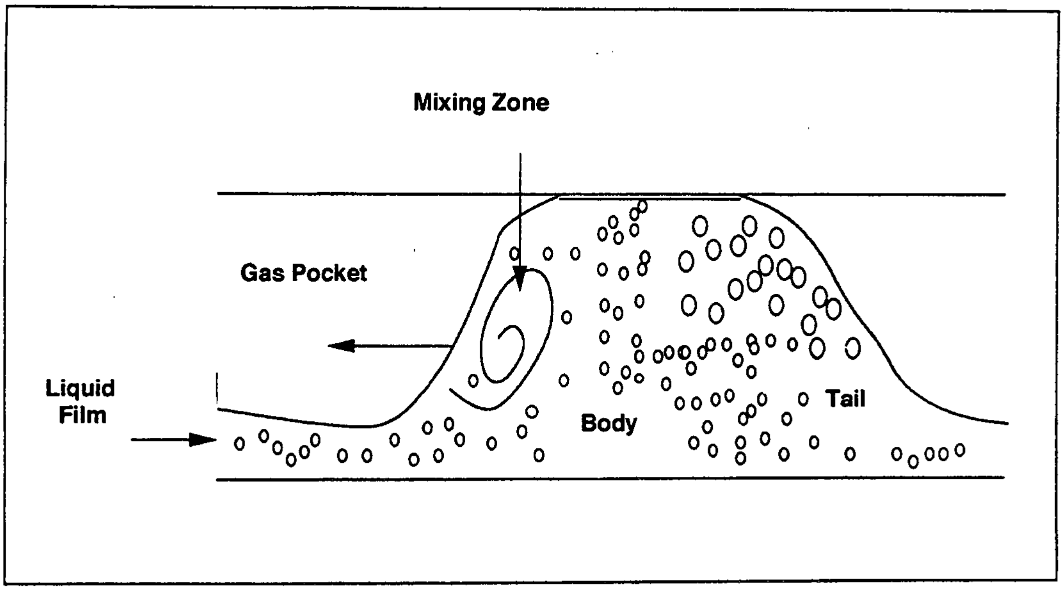
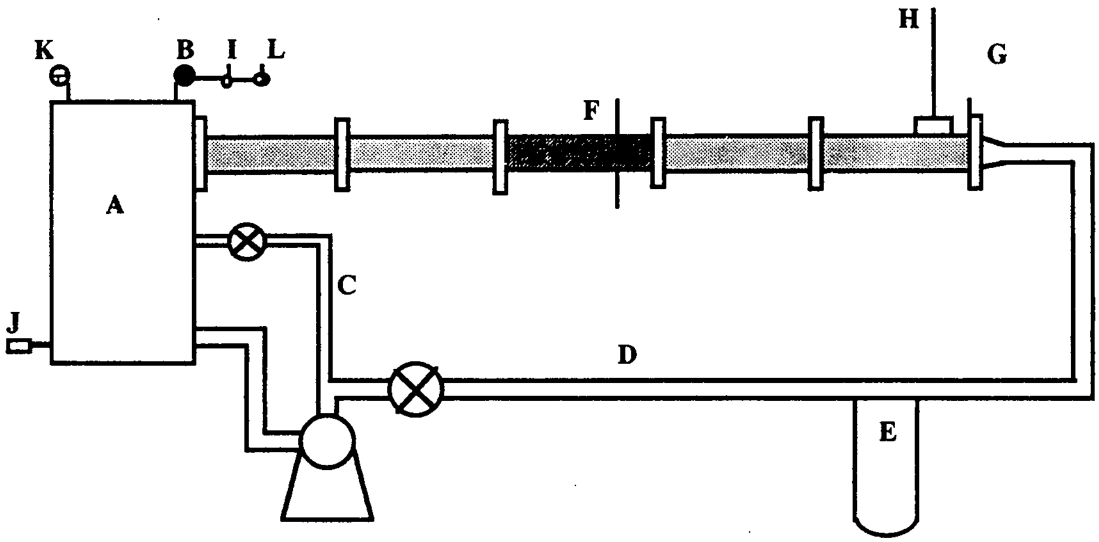


Figure 1: Profile of different regions of slug



A. Liquid Tank
B. Pressure Gauges
C. Liquid Recycle
D. Liquid Feed - 7.5 cm PVC
E. Orifice Plate Manometer
F. Test Section - 10 cm Plexiglass
G. Flow Height Control Gate
H. CO2 Feed Line
I. VENT w/valve
J. Heater
K. Safety Valve
L. Back Pressure Regulator

Figure 2: Layout of the experimental system

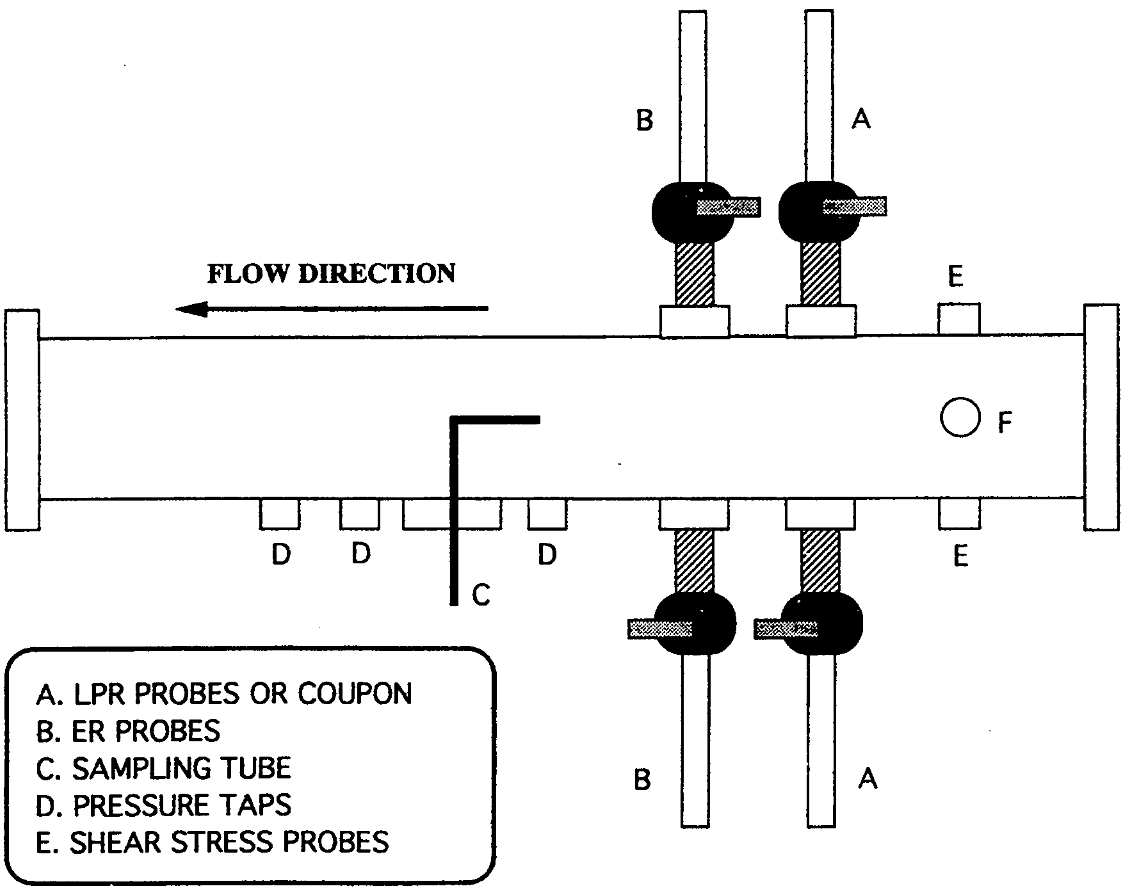


Figure 3: Test Section

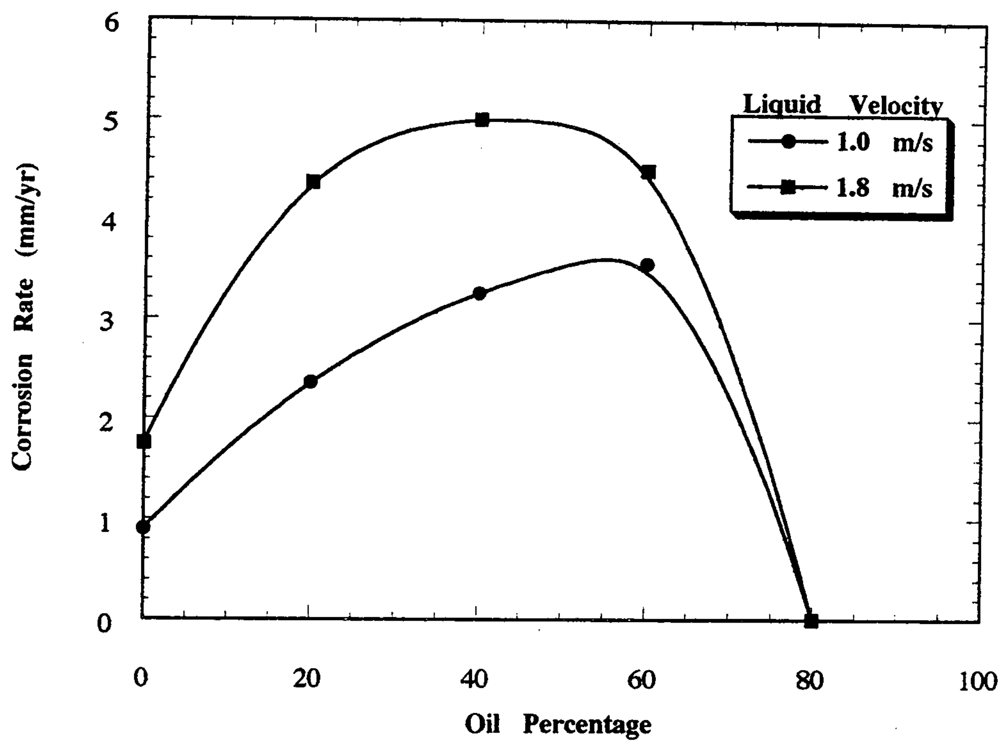


Figure 4: Effect of oil percentage on corrosion rate for full pipe flow

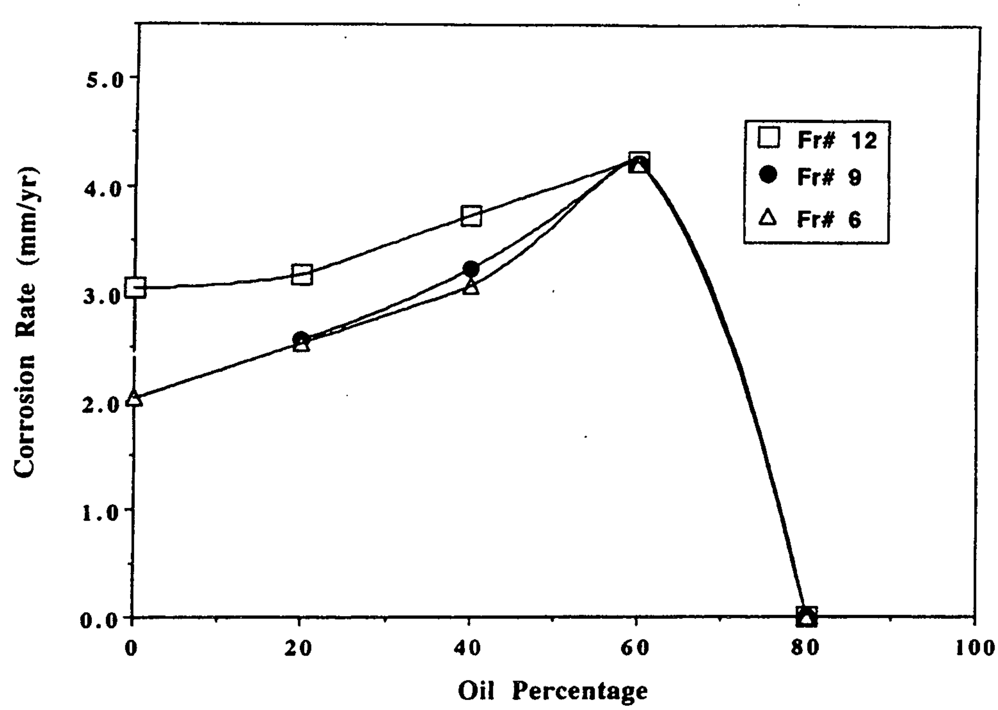


Figure 5: Corrosion rate vs oil percentage
Slug flow
Bottom of the pipe

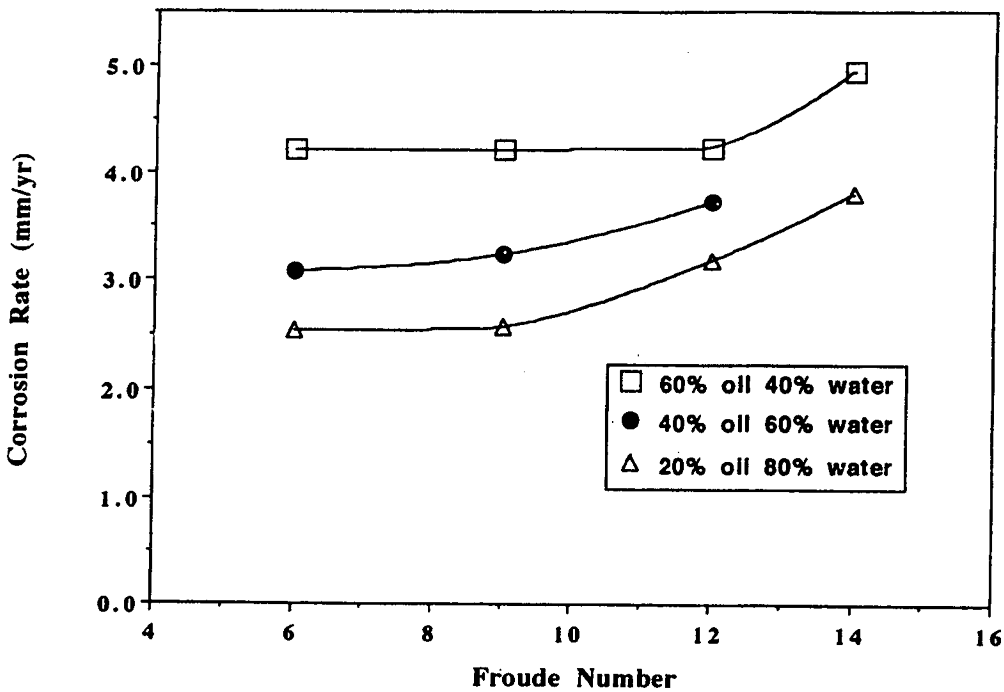


Figure 6: Corrosion rate vs Froude number
Slug flow
Bottom of the pipe

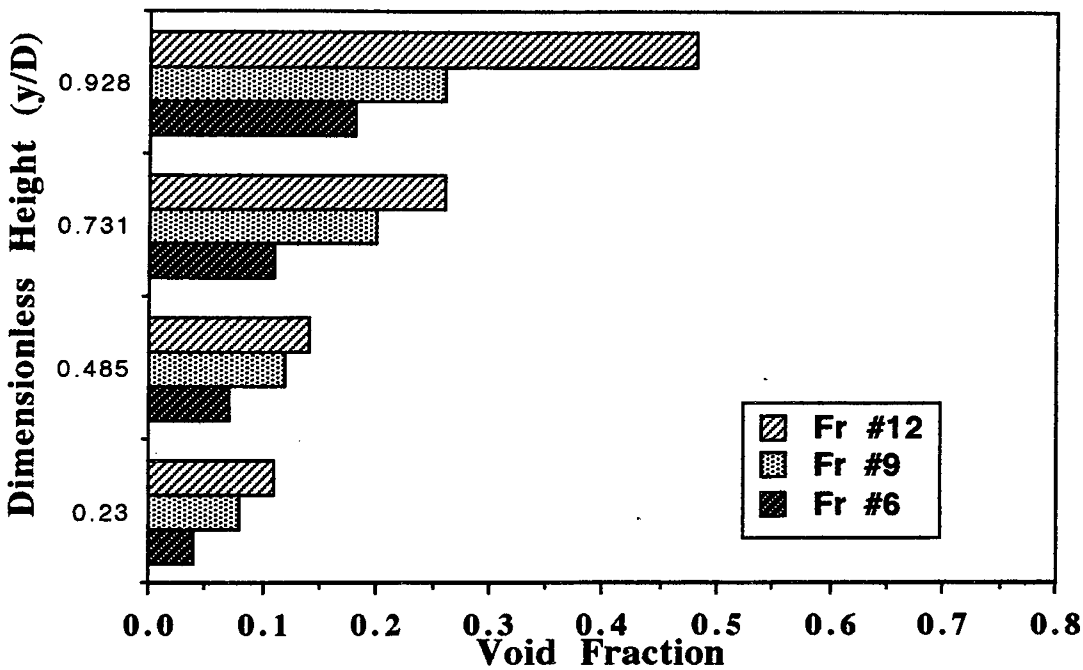


Figure 7a: Void fraction across the pipe Diameter
96 cp Oil 20%, Salt water 80%
30cm within the slug

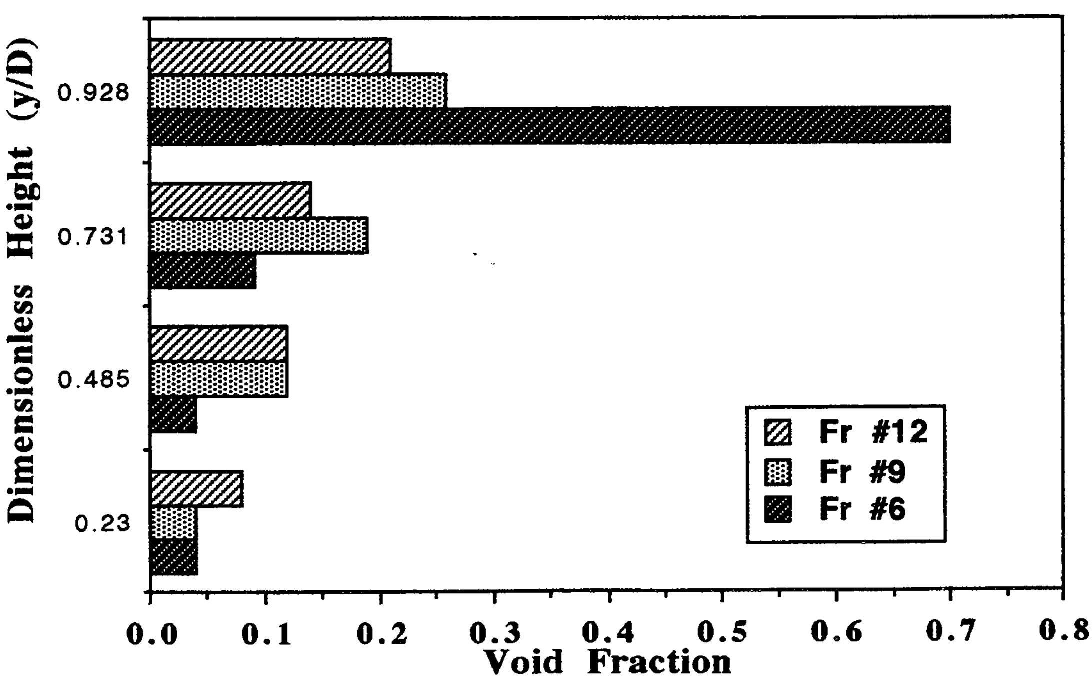


Figure 7b: Void fraction across the pipe diameter
96 cp Oil 20%, Salt water 80%
60cm within the slug

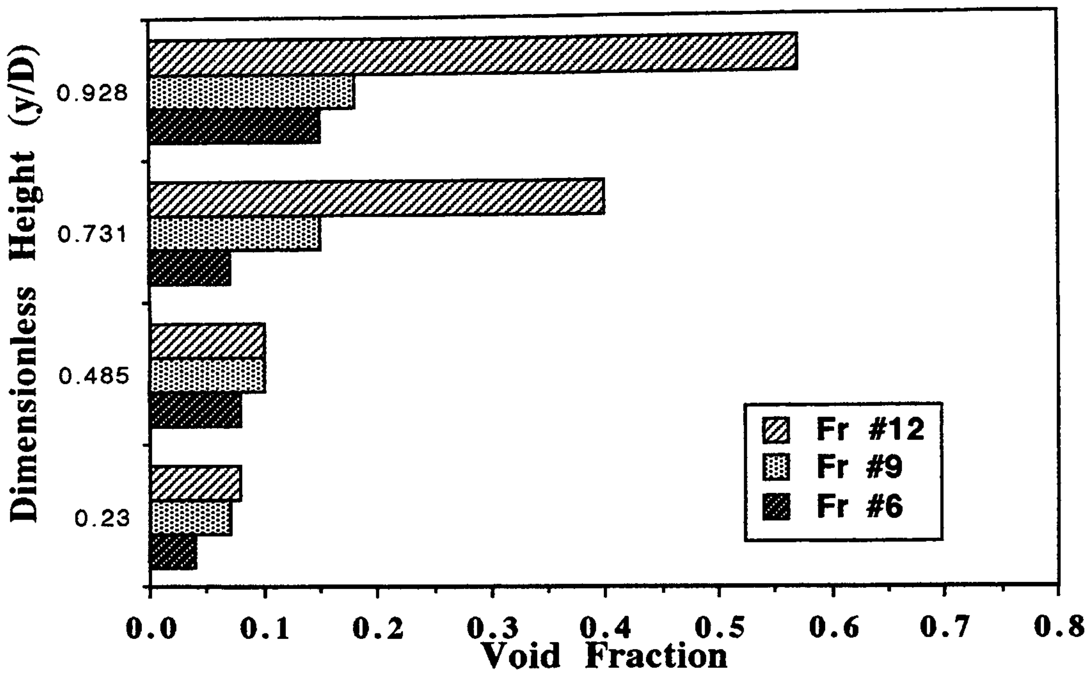


Figure 7c: Void fraction across the pipe diameter
96 cp Oil 40%, Salt water 60%
30cm within the slug

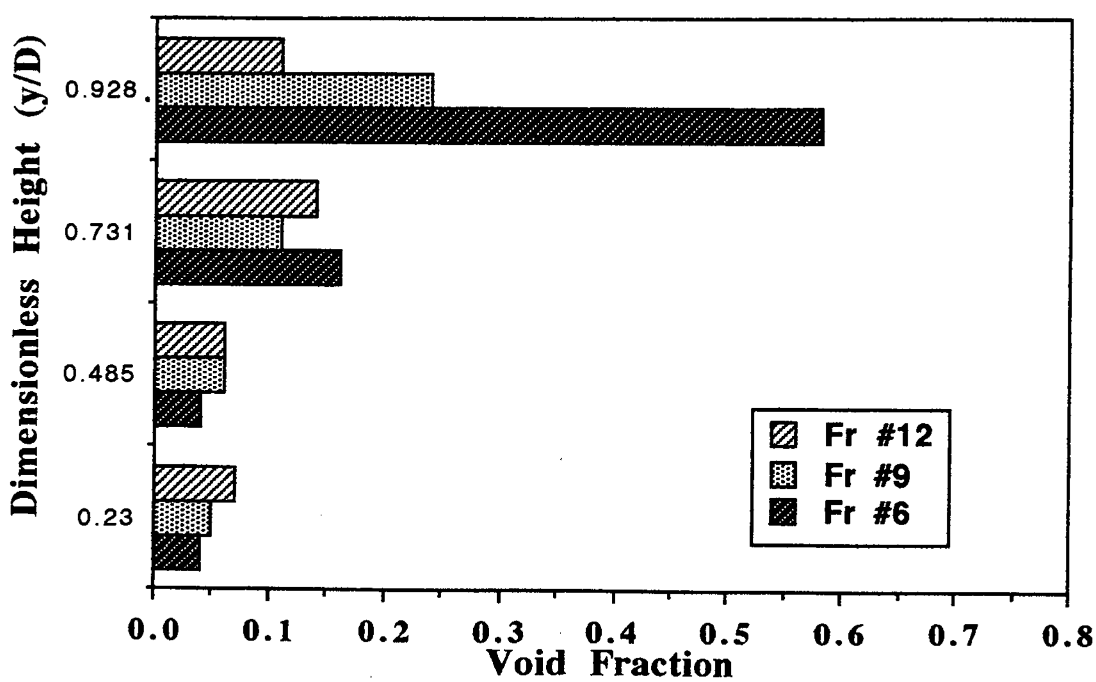


Figure 7d: Void fraction across the pipe diameter
96 cp Oil 40%, Salt water 60%
60cm within the slug

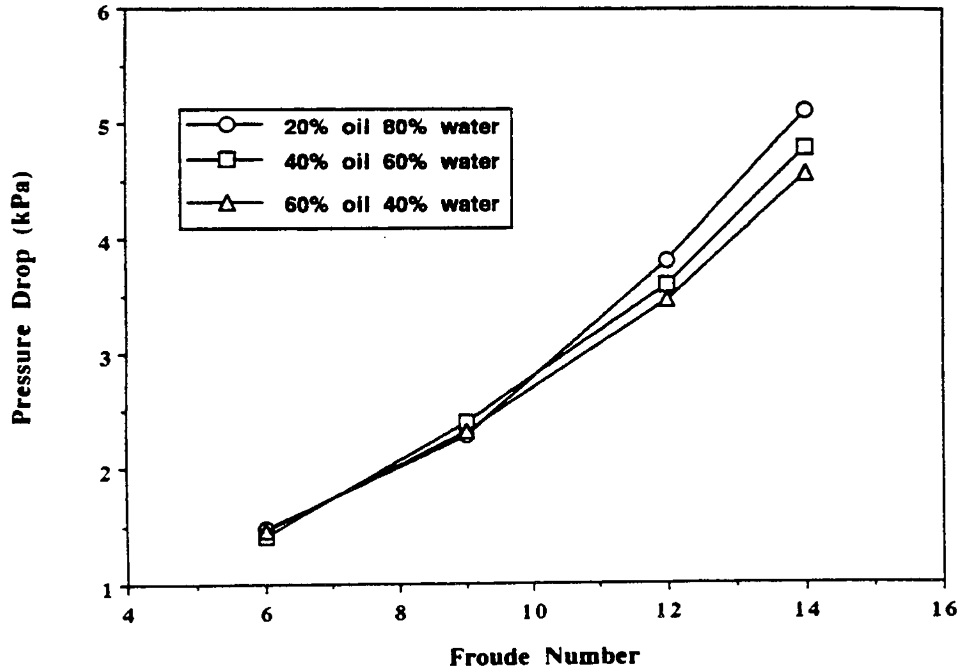


Figure 8a: Pressure drop vs Froude number
Slug flow
30 cm to the slug front

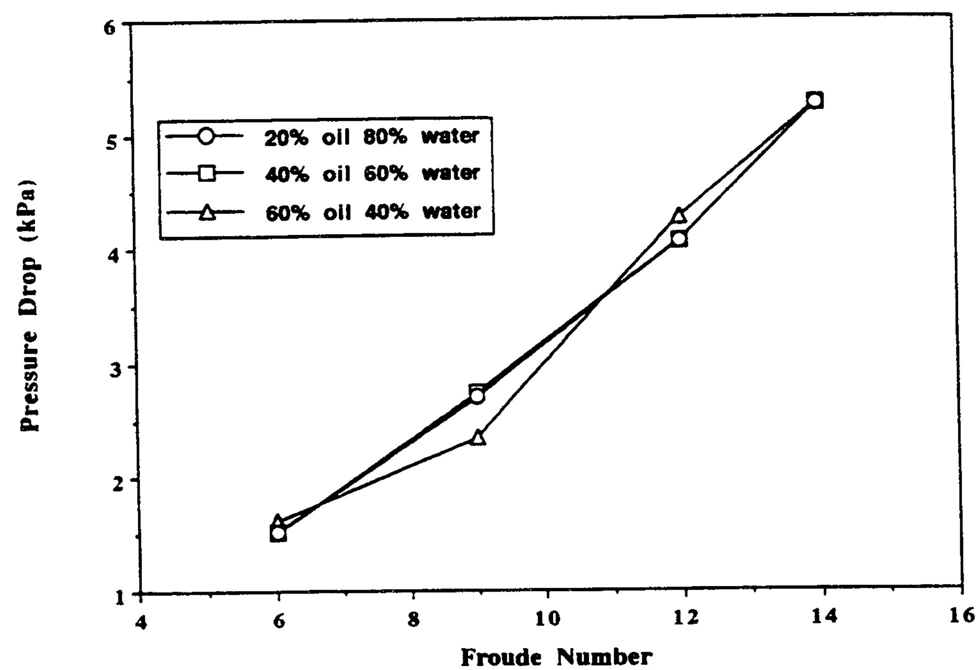


Figure 8b: Pressure drop vs Froude number
Slug flow
60 cm to the slug front

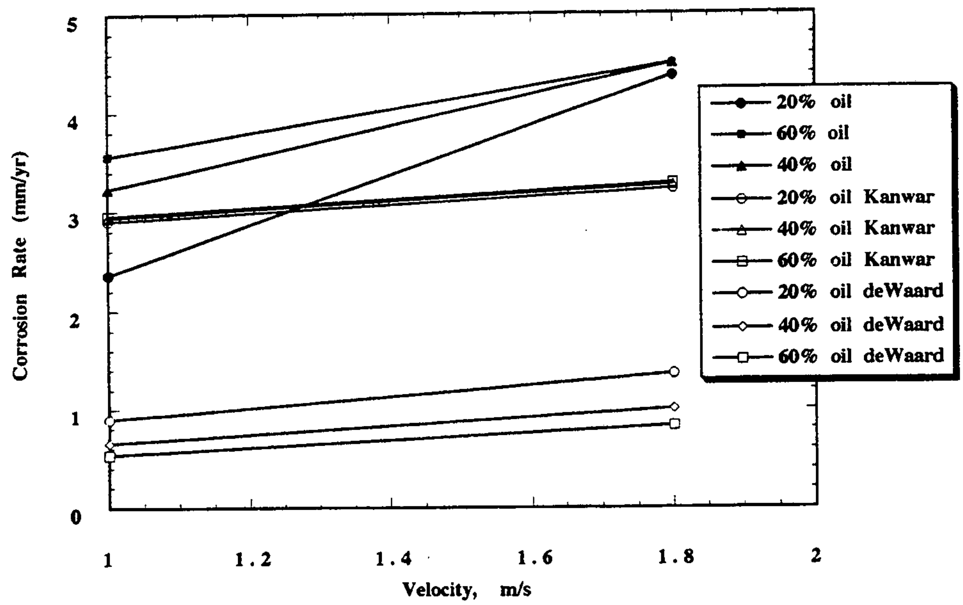


Figure 9 : Corrosion rate vs velocity using 96 cp oil
Comparsion between this study, deWaard (1993), and Kanwar (1994)
Pressure = 136 kpa, Temperature = 40 C

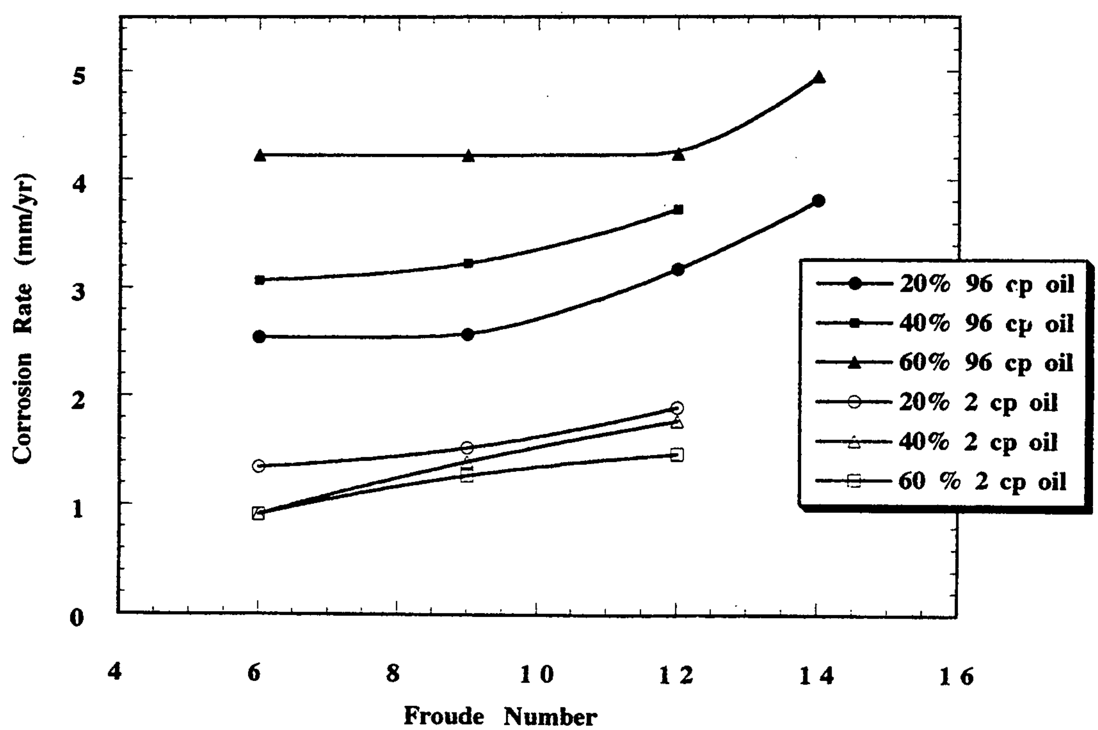


Figure 10: Corrosion rate vs Froude number
Pressure = 136 kpa, Temperature = 40 C

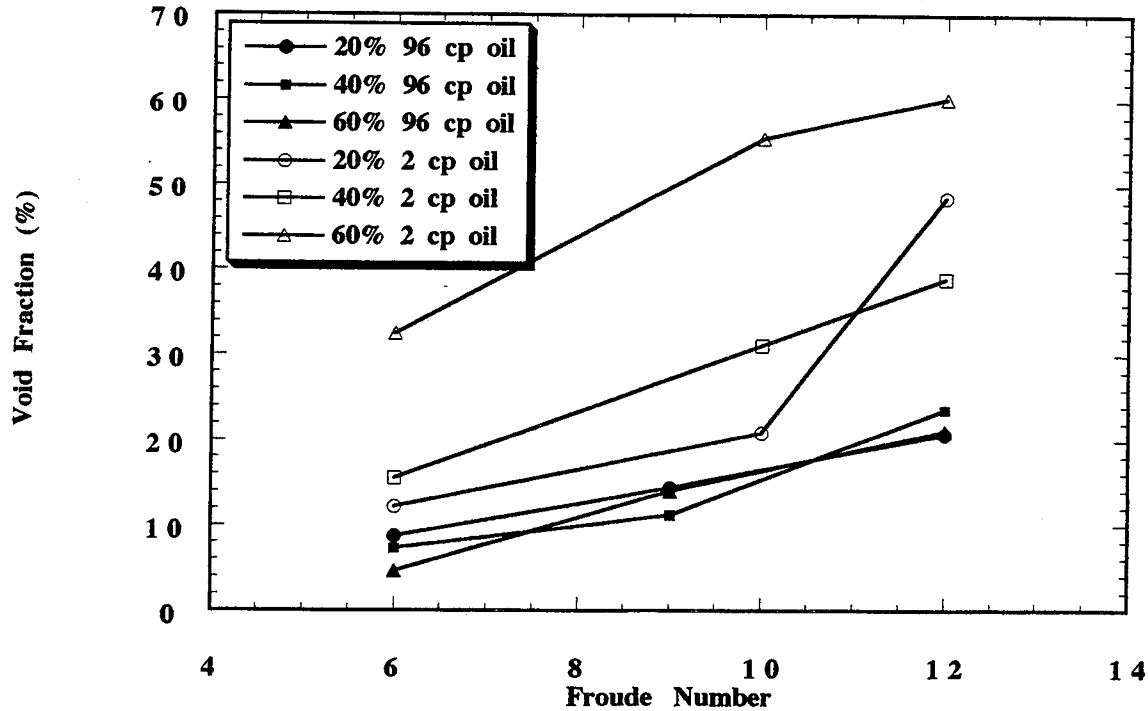


Figure 11a: Void fraction vs Froude number
slug flow
30 cm to the slug front

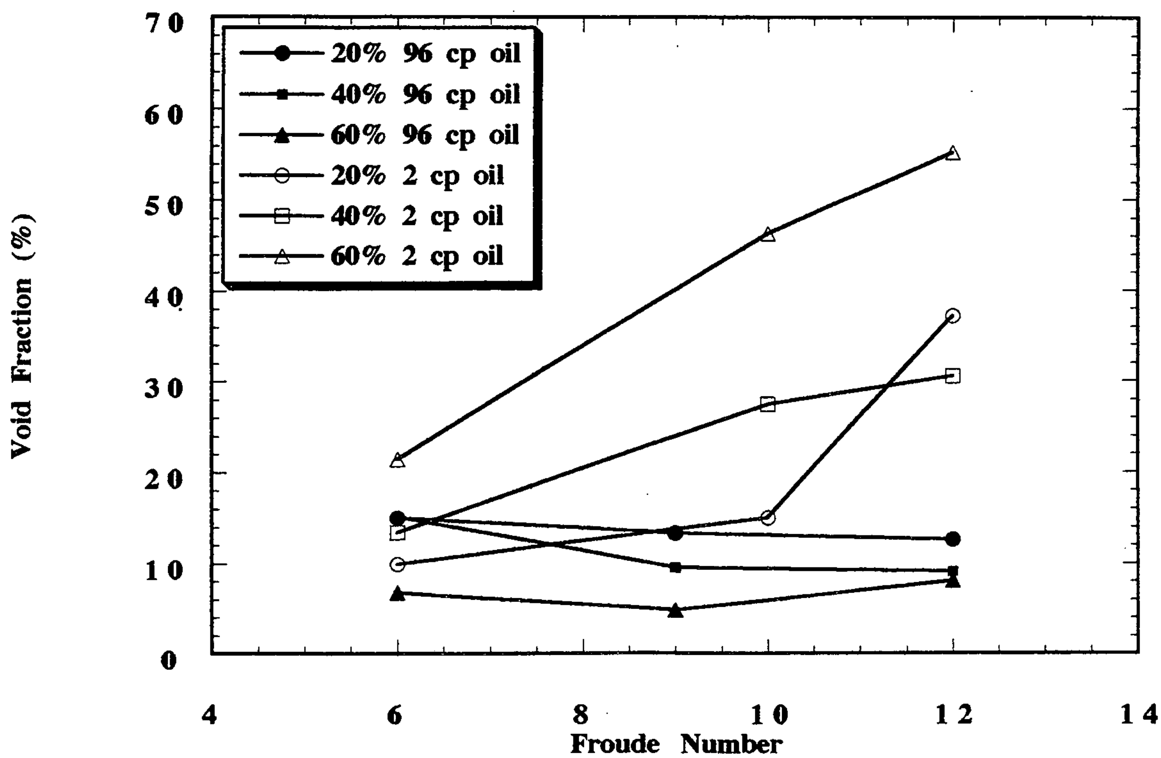


Figure 11b: Void fraction vs Froude number
Slug flow
60 cm to the slug front