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Experimental Study of Slug Flow Characteristics in Horizontal, Multiphase Flows

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ABSTRACT

Many oil fields usually produce gas and oil - water mixtures with high carbon dioxide content and water cuts. Understanding the flow characteristics in multiphase pipelines is a subject of great importance. Experiments were conducted on a loop connected by plexiglass and PVC pipes with a operating pressure of 20psi and a temperature of 40C. A stationary slug was used to measure the shear stress, turbulent intensity and slug flow characteristics for mixtures of ASTM artificial sea water and Conoco LVT-200 oil. Typical results show that the higher the Froude number, the larger the shear stress, void fractions and pressure drops respectively. It is also concluded that flow conditions and fluid properties have significant effects on the slug flow characteristics.

Key words: multiphase flow, stationary slug, slug flow characteristics, shear stress, turbulent intensity, void fraction, pressure drop.

INTRODUCTION

Most oil and gas production has associated water and carbon dioxide which can give rise to flow related problems in multiphase pipelines. Understanding the flow characteristics for different pipeline flow regimes is a subject of great importance.

When transporting multiphase liquid and gas mixtures in horizontal pipelines, many flow regimes exist. These include stratified, intermittent and annular flow. The intermittent flow regime includes plug flow and slug flow, the slug flow being common in most flow lines when high liquid and gas flowrates are used for production. Understanding the mechanisms involved in this regime is essential.

A typical slug is shown in figure 1.1 and can be characterized by five sections: the liquid film ahead of the slug, the gas bubble zone above the liquid, the mixing zone, the slug body and the slug tail. Slugs are formed when a liquid wave grows on the stratified film and bridges the pipe to form a lump of liquid or slug. Since the gas velocity is much greater than the liquid velocity, this slug is accelerated to close the gas velocity. The slug front assimilates the slow moving liquid film ahead of it and the mixing zone is created and a high level turbulence is produced. This mixing zone entrains the fast moving gas which is above the slow moving liquid film and passes it back to the slug body. After the passage of the slug, liquid is shed from the slug tail and eventually combines with fresh incoming liquid to form a film on which the next slug will propagate. Jepson (1989) showed that high velocity slugs can cause high turbulence and shear forces. They can destroy or prevent adequate corrosion inhibitor performance. Based on the study of the

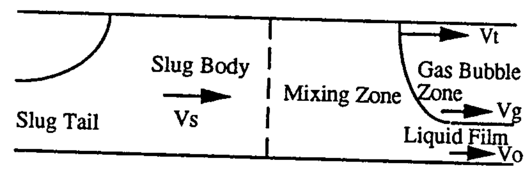


Figure 1.1 Slug Flow Unit

effect of slug flow characteristics on corrosion rates in oil and gas pipelines, Sun and Jepson(1992) demonstrated that when Froude numbers are increased, shear stress and turbulent intensity increase, and corrosion rates also increase. Therefore, slug characteristics such as slug length, velocity and frequency, void fraction and pressure drop have become very important parameters in investigating the flow characteristics in multiphase pipelines. This work uses stationary slugs to study the slug flow characteristics. The void fractions in the slug, the wall shear stress and flow turbulent intensity, and the pressure drop across the slug are all measured.

There has been much research examining slug flow. The first realistic model of slug flow was proposed by Dukler and Hubbard (1975), who found that liquid is entrained at the slug front, accelerated to the slug velocity and then passed back through the slug. Jepson (1989) developed a mechanistic model for the prediction of transition to slug flow. The model assumes that the slug forms as a result of a hydraulic jump which just touches the top wall of the conduit. This, together with a 'breaking dam' assumption at the rear of the slug, provides the necessary and sufficient conditions for the formation of a stable slug.

There are several different types of slug. Their 'strength' is proportional to the Froude number calculated in the liquid film ahead of the slug (Jepson ,1989). Jepson demonstrated that at low Froude numbers, there is some mixing at the front of the slug. When the gas and liquid flow rates are increased, the intensity of the mixing region increases and a strongly turbulent zone is formed at the slug front. At high Froude numbers, the film ahead of the slug is subjected to e---emely high shear stresses. These high shearing forces may ...oy an inhibitor layer close to the wall.

Slug flow characteristics have been experimentally studied for many years. Kordyban (1963) presented experimental techniques used to study the mechanism of two-phase slug flow in a horizontal tube. This results showed that the velocity of slug appeared to be a stronger function of air flow rate than of liquid flow rate, while the frequency of slugs was a strong function of liquid flow rate. The magnitude of pressure fluctuations varied considerably from slug to slug for a given value of air and water flow rate.

Crowley et al. (1984) studied the effects of liquid viscosities and gas densities on slug characteristics. Experiments were conducted on a horizontal, 17cm ID pipe for gas superficial velocities of 1.2, 2.4, 3.6 m/s and liquid superficial velocities of 0.6, 1.2, 1.8 m/s respectively. The fluids used were water (1cp in viscosity), Newtonian liquid (400 cp) and gas. The results showed that liquid viscosity has a significant effect on two phase slug flow characteristics while gas density has only little effect.

Kouba and Jepson (1989) examined the Froude number both in the film ahead of slug and in the slug body from the measurements of liquid fraction, translational velocity of slug, slug length and frequency. Experiments were carried out for gas and liquid superficial velocities ranging from 0.8 to 20 m/s and 0.3 to 3 m/s respectively. Typical results showed that the Froude number ahead of slug is always greater than unity, and the Froude number is basically less than unity after the front. This proves that a slug is a hydraulic jump that propagates along a pipe.

The necessary conditions for the existence of stable slugs ·e investigated by Lunda and Asheim (1989) and Ruder et al. ..89). Lunda and Asheim reported that slug growth/dissipation dependents on changes in superficial gas velocity and liquid holdup ahead of the slug. Lower gas velocities result in a shorter slug while higher gas velocities increase slug length. Ruder et al., however, predicted two necessary conditions. One defines a minimum gas velocity, the second defines a minimum height of the liquid layer for stable slug.

Due to the high velocity and transient nature of slug flow, it is very difficult to take accurate measurements on real moving slugs. Jepson (1987), (1989) showed that the mixing zones in moving slugs and stationary hydraulic jumps are identical in these regions at the same Froude number. Stationary slugs are much easier to study than the true moving slugs. The stationary slug is formed by forcing liquid and gas under a gate, and can be moved and made stationary at a given location by controlling the back pressure in the pipe. The stationary slug formed by a hydraulic jump can accurately show the flow mechanisms in certain regions of true slug flow, and the measurements in a stationary slug are much easier than in a fast moving real slug. The comparison of real moving slug and a stationary hydraulic jump is showed in Figure 1.2.

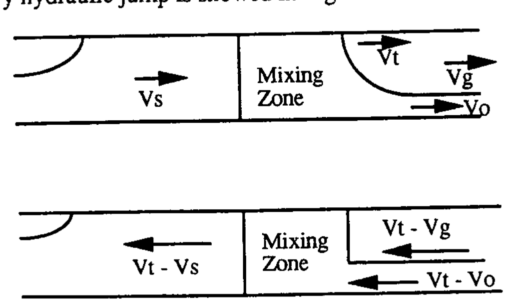
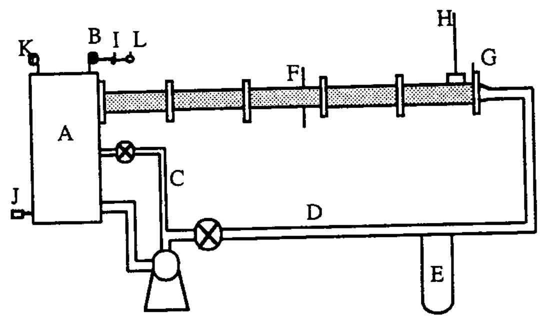


Figure 1.2 Comparison between real moving slug (top) and a stationary hydraulic jump (bottom).

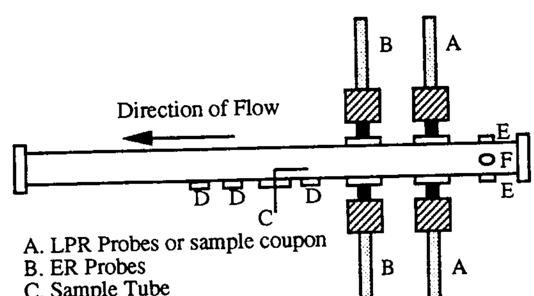
EXPERIMENTAL FACILITY AND PROCEDURE

The experimental facility used for this research was developed by Jepson (1987), It consists of a closed loop system in which oil and water are prepared and mixed in a tank. The mixture is pumped through 7.5cm inside diameter PVC pipe where the flowrate is measured using an orifice plate. The flow is then forced under a gate of height 4cm into a 10m long and 10cm diameter plexiglass pipeline. In addition, the system is equipped with a heating unit to maintain the temperature at 40C required for the measurements. A 400# compressed gas cylinder is used to store and supply the carbon dioxide. A back pressure regulator installed on top of the tank is used to maintain the system pressure at 20psi. The schematic layout of the system is showed in Figure 2.1.



A. Liquid Tank	F. Test Section - 4" Plexiglass
B. Pressure Gauge	G. Flow Height Control Gate
C. Liquid Recycle	H. CO2 Feed Line
D. Liquid Feed - 3"PVC	I. VENT w/valve
E. Orifice Plate Manometer	J. Heater
	K. Safety Valve
	L. Back Pressure Regulator

Figure 2.1 Layout of The 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 2.2 Test Section

The test section is illustrated in Figure 2.2 . At position E, a TSI flush mounted, hot film sensor was used to measure the mean wall shear stress and turbulent intensity at the bottom of the pipe. In order to prevent the probe from burning out, great care was taken to ensure that the probe was immersed in the liquid during the test. The voltage signal from the probe was passed to an IFA 100 anemometer system which converted the signals through a MetraByte's Model DAS20 AD converter in order to store the data in digital form. The data was then processed using the TSI Anemometry Software Package, Model DAP, and 386 personnel computer. By moving the slug to different axial locations, it was possible to measure the wall shear stress and turbulent intensity at several points, before, at the front of, and within the slug. The probe was calibrated with each working fluid using full pipe flow. Three pressure tappings (D) to allow the pressure drops before, within and across the slug to be measured using differential U tube manometers. A sampling tube (C) was used to take fluid samples for chemical composition and void fraction analysis.

Void fraction measurements were obtained at five positions across a vertical diameter and two distances of 30 and 60cm into the slug body with Froude numbers of 6, 10 and 12 respectively. A 62.5 ml and 1m long glass pipe with valves at both ends was connected to the sampling tube. The sampling fluids were taken by opening both valves and closing them simultaneously when the flow was isokinetic. A graduated glass cylinder was used for storing the sample fluids and for allowing oil-water separate. By taking readings of total liquid volume V_L, the void fraction can be easily calculated. The oil - water fraction was also monitored.

RESULTS AND DISCUSSION

Shear Stress / Turbulent Intensity

The shear stress and turbulent intensity were measured for the various fluids under the different slug flows.

Figure 3.1.1 and 3.1.2 illustrate the shear stress and turbulent intensity of pure salt water and pure LVT-200 oil. The results show that in the mixing zone at the slug front, there are regions of high shear forces and high levels of turbulence. The magnitude of the shear stress and turbulence increased with an increase in Froude number. In addition, the shear stress of the oil was much larger than the water at each Froude number. This is expected because the shear stress is affected by the physical

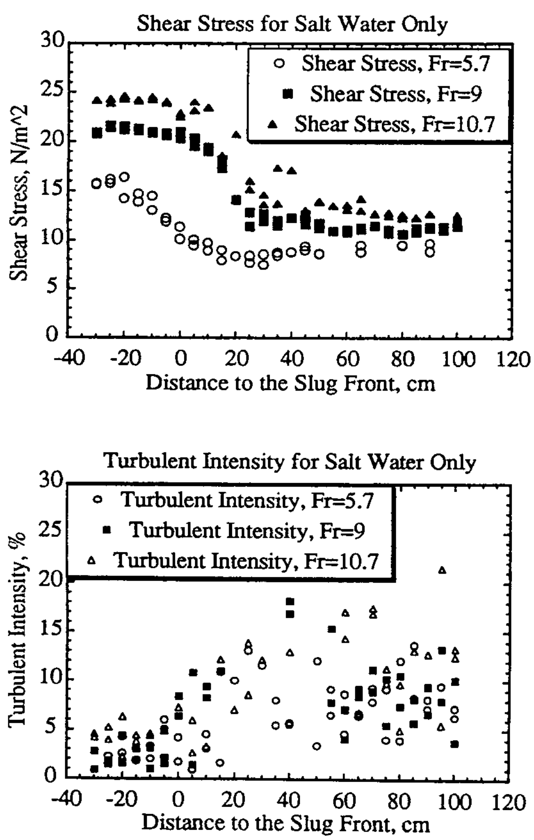


Figure 3.1.1

properties of the fluids. The mean values of shear stress were 16 N/m^2, 24 N/m^2 for salt water and 25 N/m^2, 82 N/m^2 for oil at both Froude numbers of 5.7 and 10.6. However, the turbulent intensity of the oil was lower than the salt water. This decreases the ability of the slug front to entrain gas. The turbulent intensity was 27% for salt water and 18% for oil at a Froude number of 10.7 (Turbulent Intensity = Standard Deviation / Mean Shear Stress).

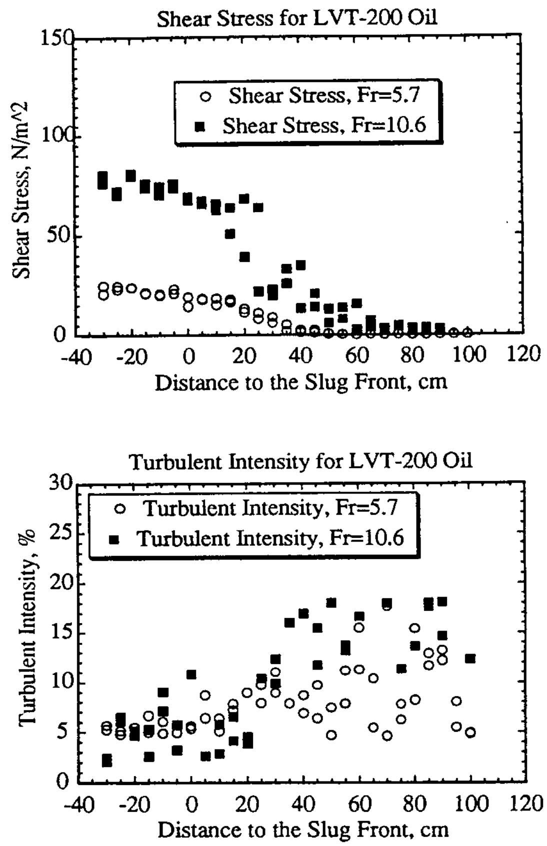


Figure 3.1.2

The shear stress and turbulent intensity of the mixtures containing 20%, 40%, 60% and 80% oil are presented separately in Figures 3.1.3, 3.1.4, 3.1.5 and 3.1.6. By comparing these data, a large difference in the shear stress for the 20% oil mixture compared to the other three mixtures is noticed. At a Froude number of 12, the mean values were 30 N/m^2, 105 N/m^2 and 140 N/m^2 for the oil concentrations of 20%, 40% and 60% respectively. There seems to be a phase inversion between the mixture containing 20% oil and 40% oil. The shear stress and turbulent intensity for these mixtures continue to increase with an increase in Froude number. However, for the mixtures with the high oil content, there was no apparent difference of the turbulent intensity under the different Froude numbers.

In each of the above cases, the shear stress changed substantially across the slug front, the greatest change occurring at high Froude numbers. These changes existed within 20cm - 30cm from the slug front. This is within the area normally defined as the mixing zone of the slug flow. The turbulent intensity was also shown to change rapidly at some distance from the slug front into the slug body with the steepest change areas being 30cm - 60cm from the slug front. Further, instantaneous values of the shear stress can be much greater than the mean values. Instantaneous shear stresses in excess of 500 N/m^2 were noted at the high Froude number.

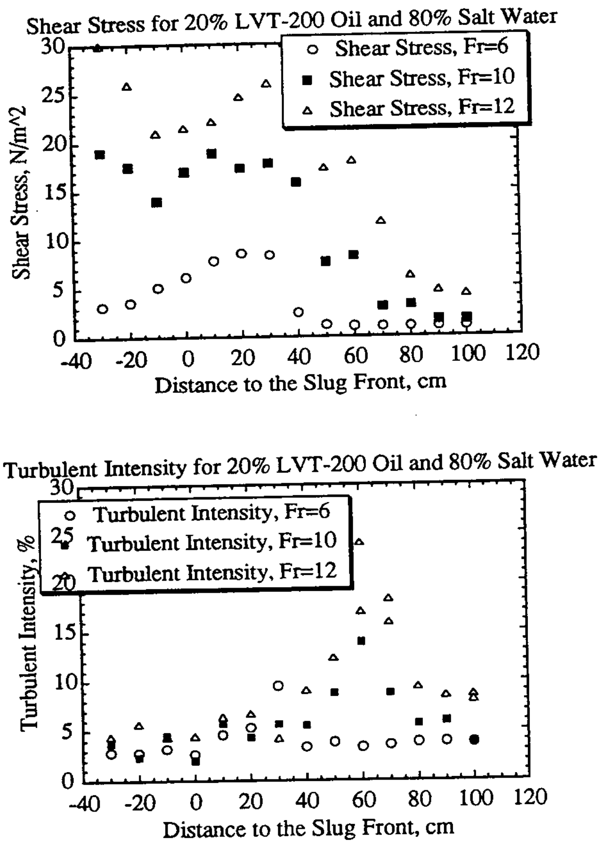


Figure 3.1.3

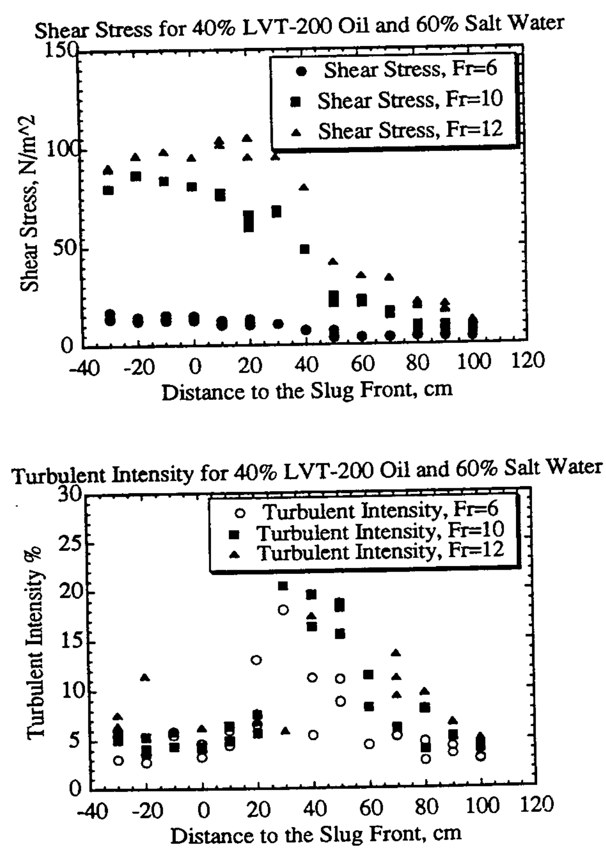


Figure 3.1.4

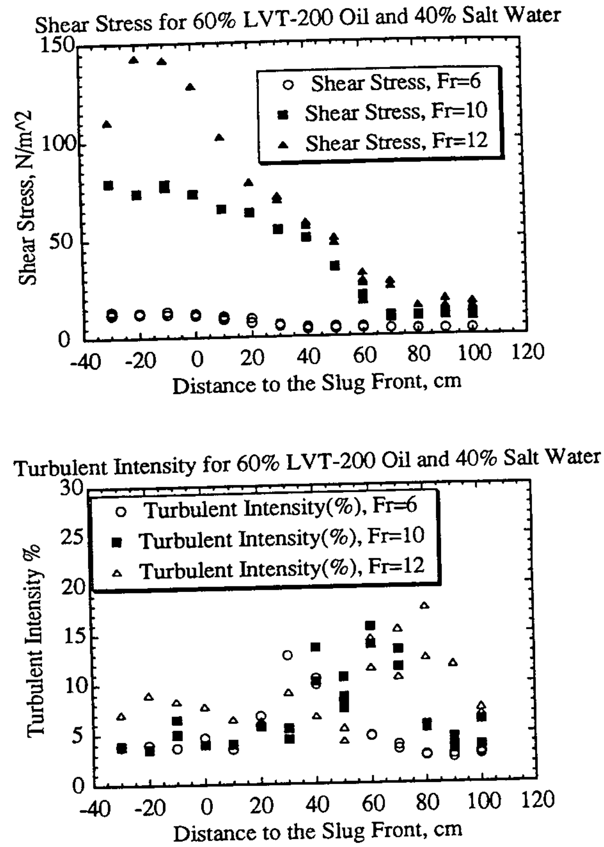


Figure 3.1.5

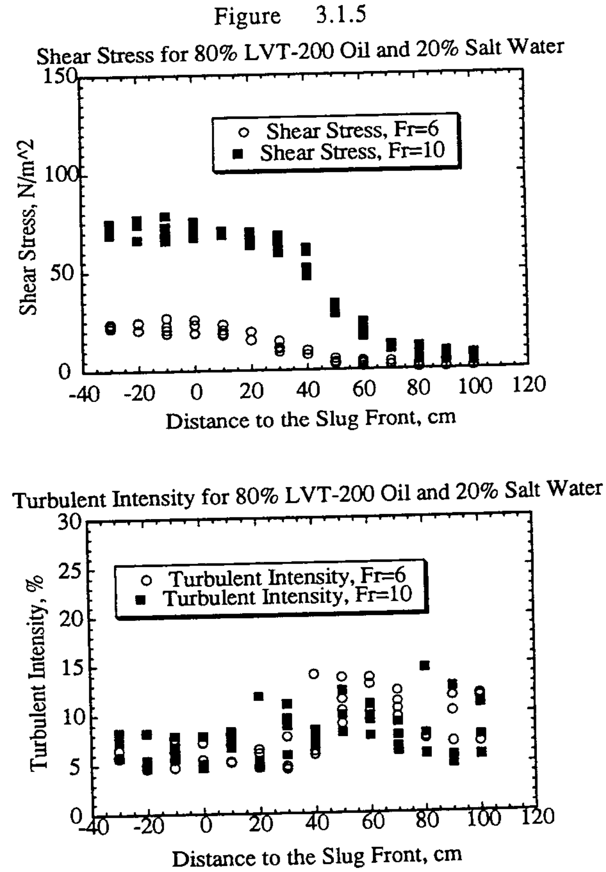


Figure 3.1.6

Void Fraction

The void fraction for various fluids are listed in Tables 3.2.1, 3.2.2 and 3.2.3.

In each case, the void fraction is always smaller at the bottom of the pipe than at the top. At a Froude number of 10 and a position of 30cm to the slug front, the void fraction varied from top to bottom with the values of 0.392 to 0.043 for 20% oil, 0.568 to 0.176 for 40% oil, 0.680 to 0.259 for 60% oil and 0.614 to 0.165 for 80% oil respectively. An increase in the Froude number causes an increase in the amount of gas entrained. For 80% oil & 20% water at 30cm into the slug, the average void fraction increased from approximately 23% at a Froude number of 6 to 55% at a Froude number of 12. In addition, as the Froude number increases, the length of the mixing zone increases. This enhances the mixing process and allows more gas to be passed back into the slug body. A more homogeneous flow was also observed at higher Froude numbers. Hence, at the medium to high Froude numbers, the void fraction at the distance of 60cm to the slug front was similar but smaller than the void fraction at the 30cm to the slug front. It is noted that not all the gas is passed through the slug. Some of the gas is returned to the gas pocket ahead of the slug.

Table 3.2.2 Void Fraction

Froude Number	Location *	20% oil & 80% water		40% oil & 60% water	
		30cm	60cm	30cm	60cm
Fr = 6	1	0.251	0.285	0.264	0.24
	2	0.171	0.192	0.208	0.152
	3	0.125	0.04	0.144	0.12
	4	0.016	0.04	0.128	0.136
	5	0.061	0.029	0.088	0.08
Fr = 10	1	0.392	0.2	0.568	0.344
	2	0.312	0.144	0.376	0.304
	3	0.197	0.205	0.336	0.304
	4	0.205	0.117	0.232	0.24
	5	0.043	0.107	0.176	0.216
Fr = 12	1	0.664	0.451	0.616	0.4
	2	0.6	0.52	0.552	0.336
	3	0.648	0.427	0.464	0.312
	4	0.381	0.28	0.248	0.28
	5	0.235	0.224	0.184	0.248

* Distance to the top of the pipe (mm)
1 = 5, 2 = 20, 3 = 45, 4 = 65, 5 = 85 (for 20% oil & 80% water)
1 = 5, 2 = 26, 3 = 48, 4 = 64, 5 = 82 (for 40% oil & 60% water)

Table 3.2.3 Void Fraction

Froude Number	Location *	60% oil & 40% water		80% oil & 20% water	
		30cm	60cm	30cm	60cm
Fr = 6	1	0.386	0.448	0.383	0.269
	2	0.514	0.284	0.308	0.158
	3	0.341	0.170	0.249	0.112
	4	0.249	0.101	0.099	0.04
	5	0.173	0.176	0.099	0.04
Fr = 10	1	0.680	0.485	0.614	0.394
	2	0.700	0.569	0.607	0.387
	3	0.672	0.523	0.552	0.314
	4	0.560	0.346	0.267	0.229
	5	0.259	0.395	0.165	0.235
Fr = 12	1	N/A	N/A	0.633	0.443
	2			0.712	0.439
	3			0.655	0.429
	4			0.477	0.331
	5			0.221	0.320

* Distance to the top of the pipe (mm)
1 = 5, 2 = 17, 3 = 41, 4 = 64, 5 = 83

Table 3.2.1 Void Fraction

Froude Number	Location *	salt water only		Location *	LVT-200 oil only	
		30cm	60cm		30cm	60cm
Fr = 5.7	1	0.272	0.456	1	0.44	0.38
	2	0.22	0.36	2	0.41	0.34
	3	0.18	0.168	3	0.38	0.32
	4	0.12	0.1	4	0.32	0.24
	5	0.07	0.05	5	0.26	0.18
	6	0.05	0.02	6	0.21	0.175
				7	0.15	0.18
				8	0.08	0.16
Fr = 10.7	1	0.64	0.296	1	0.65	0.45
	2	0.61	0.272	2	0.62	0.38
	3	0.58	0.232	3	0.6	0.37
	4	0.47	0.224	4	0.58	0.35
	5	0.14	0.2	5	0.52	0.3
	6	0.056	0.12	6	0.38	0.3
				7	0.22	0.26
				8	0.12	0.22

* Distance to the top of the pipe (mm)
1 = 0.1, 2 = 9.94, 3 = 20.15, 4 = 39.9, 5 = 58, 6=84.5
(for salt water only)
1 = 0.1, 2 =8.29, 3 = 17.34, 4 = 29.38, 5 = 45.09, 6 = 62.28, 7 = 75.44, 8 = 93.45 (for LVT-200 oil only)

The void fraction increased with an increase in oil concentration, but there was only small difference for those mixtures at higher oil concentrations.

Pressure Drop

The results of pressure drop are presented in Table 3.3.1. Three test positions indicate separately the pressure drop within the film, across the slug front and within the slug body.

Table 3.3.1 Pressure Drop

LVT-200 Oil/ Salt Water	Froude number	Pressure Drop (psi)		
		0 *	30 cm	60 cm
Salt Water Only	6	0.024	0.367	0.432
	9	0.041	0.774	0.876
	12	0.106	1.003	1.455
20%/80%	6	0.037	0.349	0.411
	10	0.050	0.647	1.038
	12	0.126	0.767	1.320
40%/60%	6	0.053	0.308	0.408
	10	0.147	0.461	0.925
	12	0.230	0.506	1.214
60%/40%	6	0.052	0.301	0.349
	10	0.128	0.530	0.749
	12	0.151	0.647	1.008
80%/20%	6	0.062	0.232	0.354
	10	0.165	0.472	0.697
	12	0.231	0.632	0.875

* Distance to the slug front:
0* = Pressure drop at position of slug front
30cm=Pressure drop at position of 30cm within the slug
60cm=Pressure drop at position of 60cm within the slug

It was seen in each case that the pressure drop increased with an increase in Froude number. As the Froude number increased from 6, 10, to 12, the length of mixing zone increased. By comparing the pressure drop at the positions of 30cm and 60cm within the slug, at the low Froude number, there is little change between these two positions, while at the high Froude number, a substantial difference still exists. The pressure drop at a position of 30cm within the slug increased from 0.349, 0.647, to 0.767psi for 20% oil; 0.308, 0.461, to 0.506psi for 40% oil; 0.301, 0.530, to 0.647psi for 60% oil and 0.232, 0.472, to 0.632psi for 80% oil. As stated before, the turbulence decreased with an increase in oil concentration, so the pressure drop across the slug front and within the slug body decreased with an increase in oil fraction. At a Froude number of 12 and a position of 60cm within the slug, the pressure drop decreased from 1.455, 1.320, 1.214, 1.008 to 0.875psi with an increase in oil concentration from 0, 20%, 40%, 60% to 80%.

CONCLUSIONS

Several conclusions can be drawn from the experimental results.

Shear stress increases with an increase in Froude number. Shear stress also increases with an increase in oil fraction, while turbulent intensity decreases. Shear stress and turbulent intensity change rapidly within mixing zone of the slug.

Within the body of a slug, the mixing zone length increases with an increase in Froude number. The void fraction at the bottom of the pipe is always smaller than at the top of the pipe, and void fraction increases with an increase in the Froude number and the oil concentration. The pressure drops across the slug front and within the slug body increase with an increase in the Froude number and a decrease in the oil fraction.

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LIST OF REFERENCE

1. Crowley, C. J., R. G. Sam, G. B. Wallis, and D. C. Mehta, "Slug Flow in a Large Diameter Pipe: I. Effect of Fluid Properties," paper presented at AICHE Annual Meeting, San Francisco, California, November, 1984.

2. Dukler, A. E. and M. G. Hubbard, "A Model for Gas-Liquid Slug Flow in Horizontal and Near Horizontal Tubes," Industry Engineering Chem., Fundam.,14(4), 1975.

3. Jepson, W. P., "Modeling the Transition to Slug Flow in Horizontal Conduit ," The Canadian Journal of Chemical Engineering, 67, October, 1989.

4. Jepson, W. P., "The Flow Characteristics in Horizontal Slug Flow," paper presented at 3rd International Conference on Multi-Phase Flow, The Hague, Netherlands, May, 1987.

5. Kouba, G. E. and W. P. Jepson, "The Flow of Slug in Horizontal, Two Phase Pipelines," paper presented at the Twelfth Annual Energy-Sources Technology Conference and Exhibition, Houston, Texas, January, 1989.

6. Kordyban, E. S., "Experimental Study of the Mechanism of Two-Phase Slug Flow in Horizontal Tubes," paper presented at Winter Annual Meeting of the ASME Philadelphia, Pennsylvania, November, 1963.

7. Lunda, O. and H. Asheim, "An Experimental Study of Slug Stability in Horizontal Flow," paper presented at 4th International Conference on Multiphase Flow, Nice, France, June, 1989.

8. Ruder, Z., P. J. Hanratty and T. J. Hanratty. " Necessary Conditions for the Existence of Stable Slugs," International Journal of Multiphase Flow, 15(2), 1989.

9. Sun, J. , "An Investigation into Problems of Pipeline Corrosion Caused by the Ineffective of Corrosion Inhibitor," PH.D dissertation, University of Illinois, 1990.

10. Sun, J. and W. P. Jepson, "Slug Flow Characteristics and Their Effect on Corrosion Rates in Horizontal Oil and Gas Pipelines," paper presented at the 67th Annual Technical Conference and Exhibition of the SPE, Washington, DC, October 6-7, 1992.