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Study of Flow Regime Transitions of Oil-Water-Gas Mixtures in Horizontal Pipelines

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ABSTRACT

The flow regime transitions for flow of oil-water-carbon dioxide mixtures in horizontal pipelines are presented. The experiments were carried out in a 10cm diameter plexiglass pipe. The flow regime transitions differ greatly from those for gas-liquid and oil-water two phase flow systems. Flow regime maps for oil-water-carbon dioxide are presented for various oil-water ratios and compared with the flow regime maps for water-carbon dioxide and oil-carbon dioxide two phase flows and the Taitel and Dukler model. The results confirm that the liquid compositions have a large effect on flow regime transitions and these are not predicted by most commonly used models.

Key words: flow patterns, flow regime transitions, oil-water-gas three phase flow, horizontal pipe.

INTRODUCTION

The simultaneous flow of oil-water-gas mixtures flow in pipes is a common occurrence in the petroleum industry. This type of flow is frequently found in oil producing wells and associated pipelines. Most well fluids are composed of oil and gas but during the life of the well, the water content can increase greatly. In accessible places eg. subsea or Alaska, the fluids are often transported together in a single pipeline to a platform or central gathering station where the oil, water and gas are separated.

For oil-water two phase flows, Russell et al (1959) observed the flow patterns in a oil-water mixture in horizontal pipes. The input oil-water volume ratio was examined in their study. Three flow regimes were reported as shown in Figure 1: bubble flow, stratified and mixed flow. Bubble flow is characterized by oil droplets flowing in a continuous water phase. Stratified flow consists of the more dense fluid (water) flowing along the bottom of the pipe and the less dense fluid (oil) traveling above with a interface between the two phases. Mixed flow is defined as having no phase separation, where water and oil mixture flow flows as a emulsified liquid phase. Bubble flow occurs at very low oil velocities and low oil-water ratio. With an increase in oil velocity, the flow pattern changes to stratified flow. Mixed flow is observed at higher oil and water velocities.

Arirachakaran et. al (1989) conducted an experimental study to predict the flow patterns for an oil-water dispersions in a 3.75cm diameter horizontal pipe. Tap water and five oils with viscosity of 4, 7, 58, 84 and 115cp were used in their study. They found that with water being the continuous phase, the effect of oil viscosity on flow patterns was very small.

Charles et. al (1961) investigated the flow patterns in a equal density oil-water mixture flow in a 2.54cm pipe. They defined four flow patterns: water droplets in oil, oil in water concentric, oil slug in water and oil bubble in water. A flow regime map also was presented for an equal density oil-water flow system.

For horizontal gas-liquid flow, four distinct patterns exist; bubble flow, stratified (smooth, wavy and rolling wave), intermittent (plug, slug and pseudo slug) and annular flow. Stratified flow is identified as two separate phases with gas flow at the top and liquid flow along the bottom of the pipe. A smooth interface exists at low liquid and low gas velocities. When the gas velocity increases, two dimensional waves are formed at the interface. A further increase in gas velocity produces rolling waves. When liquid velocity is increased further, the waves grow and bridge the pipe resulting in slug flow. Slug flow consists of four zones; a stratified liquid film with gas pockets above it, the mixing zone, the slug body, and slug tail. Pseudo-slug flow has a similar structure to slug flow but the degree of aeration is greater in pseudo-slug flow. Annular flow is interpreted as a liquid film flowing along the entire pipe circumference with gas containing liquid drops in the core. When the gas velocity and the gas-liquid ratio are high, annular flow is obtained. The flow patterns are shown in Figure 2.

Slug flow is in general the most common gas-liquid flow pattern. The existence of slug flow in oil and gas pipelines can increase corrosion rates and may reduce the effectiveness of a corrosion inhibitor. Sun and Jepson (1992) have proposed that slug flow has regions with high shearing forces and flow turbulence that may strip off any existing corrosion inhibitor film and corroded material from the pipe surface. It is therefore essential to have a knowledge of when the slug regime exists.

Numerous researchers have conducted work in the area of gas-liquid flow in horizontal pipes. A number of flow regime maps have been developed. Baker(1954) obtained a flow regime map for small diameter pipes using several fluids. He used mass flow rates together with the fluid properties as coordinates. Wallis and Dobson (1973) produced a similar flow regime map for air-water flow in 2.54 and 30.5cm channels. Presently the most widely used type of flow regime map is a Mandhane plot (1974). The coordinates used are the superficial

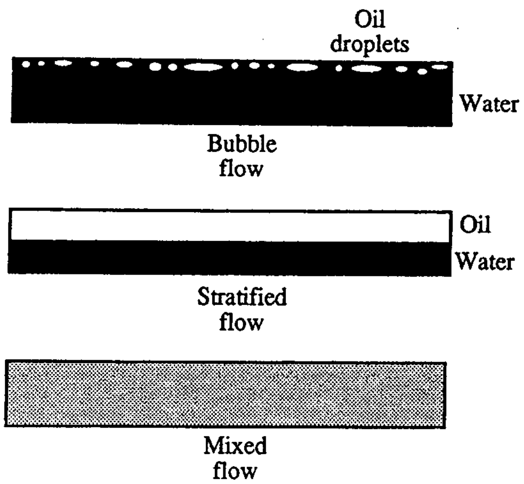


Figure 1. Flow patterns for oil-water two phase flow.

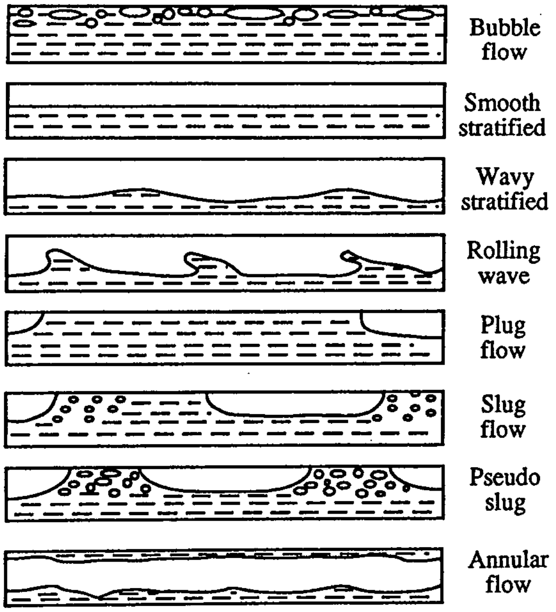


Figure 2. Flow patterns for liquid-gas two phase flow.

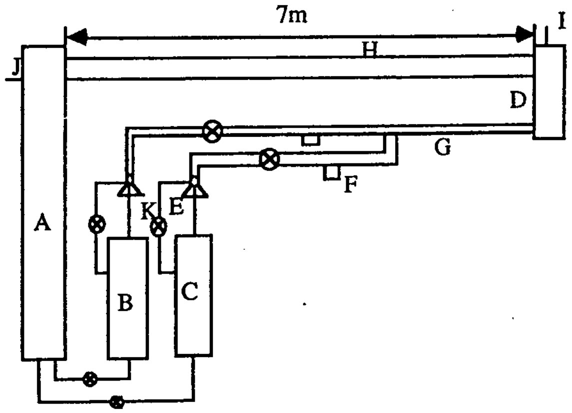
liquid velocity and superficial gas velocity. Barnea et. al (1980) proposed a flow regime map for a 2.54cm pipe for an air-water flow system. The results are in good agreement with Mandhane's map. Lin (1984) conducted an experimental study to investigate the mechanisms causing transitions for the stratified, slug and annular flow regimes. He concluded that the transition from wavy stratified to annular flow occurs because of atomization and redeposition of droplets. The effects of pipe diameter on the transition of stratified to slug flow is very strong at low gas velocities and is small at the high gas velocities. Jepson and Taylor (1989) observed the slug flow transition in a 30cm diameter horizontal pipe for an air-water system. They reported that pipe diameter had large effect on the transition to slug flow. When the pipe diameter is increased, the liquid velocity needed to get slug flow also increases. For large pipe diameters, annular flow occurs at lower gas velocities. This is due to the higher void fraction in slug flow which leads to coalescence of the gas bubbles and the subsequent earlier transition to annular flow. Andritsos et. al (1989) noted the effect of fluid viscosity on the flow transition from stratified to slug flow in horizontal pipe.

Taitel and Dukler (1976) developed a theoretical model to predict the flow regimes for different fluid properties, pipe diameters and pipe inclinations for a gas-liquid system. They presented the first generalized flow regime map using a mechanistic approach. The flow regime transitions in their model are represented by using five dimensionless groups.

There is a conspicuous absence of work involving oil-water-gas mixture flow in pipes. The flow regime maps and correlations for two phase flow system have great limitations and cannot be used to predict the flow behavior in oil-water-gas three phase flows. The complexity increases when the third phase is present. This work determines the flow regime transitions in oil-water-carbon dioxide three phase flow in a horizontal pipeline.

EXPERIMENTAL SETUP

The flow system is shown in Figure 3. The oil and water are pumped from their respective tanks into a 7.5cm ID PVC pipe. The flow rate is controlled by using a by-pass system for each liquid. The oil and water flow rates are measured by individual orifice plates and manometers. The water and oil are combined at the 'T' junction and mixed with gas in a mixing tank. The mixture then passes into a 7m long, 10cm diameter plexiglass section where the flow patterns can be observed and recorded. The discharge from the pipe then flows into the separator. The gas is discharged to the atmosphere. The separated oil and water return to the oil tank and water tank respectively.



A. Water-oil separator
B. Oil tank
C. Water tank
D. Liquid-gas mixing tank
E. Pump
F. Orifice plate
G. 7.5 cm ID PVC pipe
H. 10 cm ID plexiglass pipe
I. Gas feed
J. Gas outlet
K. By-pass valve

Figure 3. Flow system.

Two types of oil are tested with three liquid compositions, 25% water-75% oil, 50% water-50% oil and 75% water-25% oil. The oil used are Conoco LVT200 oil and Arcopak90 oil where the viscosities are 2 and 15cp respectively. Carbon dioxide is used as the gas. Superficial velocities, have been used as coordinates in all flow regime maps. The flow patterns were observed over a range of liquid velocities from 0.05 to 2m/s and a range of gas velocities from 0.5 to 15m/s. The pressure in the system was maintained at 20psi and a temperature of 25C. The flow patterns in this study were determined visually and with pressure transducers. A VHS video camera was used to help define and classify the flow patterns.

RESULTS AND DISCUSSION

Characteristic flow patterns for oil-water-gas three phase flow

The flow patterns observed are obtained by combining the flow patterns in gas-liquid and oil-water two phase flow. The definitions of flow pattern used are similar to the definitions used for gas-liquid flow in previous work. All the observed flow patterns are shown in Figure 4. They comprise three types:

Stratified flow. Water flows at the bottom of the pipe, oil flows above the water and gas flows along the top of the pipe. Two interfaces exist, one at the gas-oil and the other at the oil-water interface. At low oil, water and gas velocities, both the interfaces are smooth. When the velocity of oil increases, some oil droplets appear in water phase while the water droplets flow in oil phase close to the interface. Waves are also formed at the oil-water interface. When gas velocity is increased, waves are produced at the gas-oil interface. With further increase in gas velocity, waves takes the shape of rolling waves at the gas-oil interface. At very high gas velocities, the oil-water interface tends to break up, and the oil and water stream becomes well mixed. The oil-water mixture flows as a homogeneous liquid phase, with wave or rolling wave flow at the gas-liquid interface. For Arcopak90 oil, the oil/water flow became well mixed at lower flow rates than the LVT200 oil.

Intermittent flow. This includes three types of flow patterns; plug, slug and pseudo slug flow. In plug flow, the oil flows over a water layer. The oil bridges the pipe and the gas pushes the blockage along the pipe. The oil plug flows at a faster velocity than the water layer. For slug flow, at low gas and low liquid flow rates, the oil flows above the water. When either liquid or gas flow rate is increased, the oil will break in to the water layer and produce an oil/water mixture. The distribution of oil in water never becomes homogeneous. More oil is found at the top of the pipe while water settles at the bottom of the pipe. At high gas velocities, the liquid phases become well mixed. The pseudo slug pattern resembles the pseudo slug regime for gas-liquid two phase flow.

Annular flow. Thus is similar to gas/liquid annular flow. The oil/water phase is very well mixed.

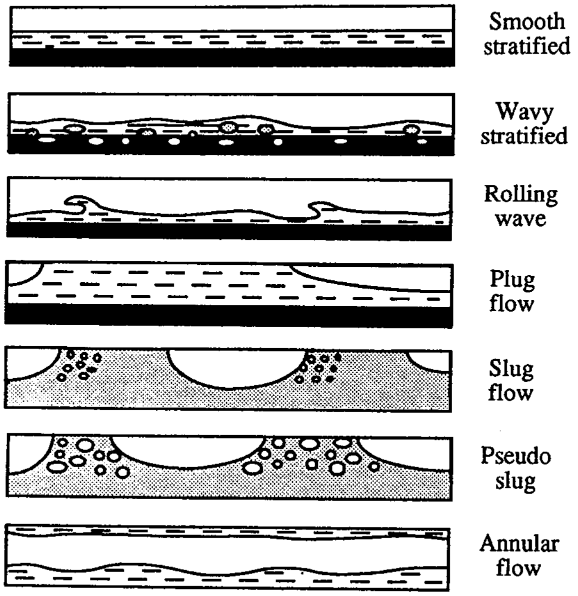


Figure 4. Flow patterns for water-oil-gas three phase flow.

Flow regime maps

Flow regime maps for gas-liquid two phase flow

Three flow regime maps for gas-liquid two phase flow were completed in order to compare with the previous work and the flow regime maps for three phase flow. The flow systems used are water-carbon dioxide, oil(LVT200)-carbon dioxide and oil(Arcopak90)-carbon dioxide. The flow maps are presented in Figure 5, 6 and 7 respectively. It can be seen that the flow regimes using both oils are similar to those for the water-carbon dioxide flow system. As the viscosity of the liquid increases, slug flow appears at lower liquid velocities. The rolling wave pattern is seen over a wider range of gas velocities as the liquid viscosity is increased. Annular flow occurs at lower gas velocities for the oil-carbon dioxide flow systems.

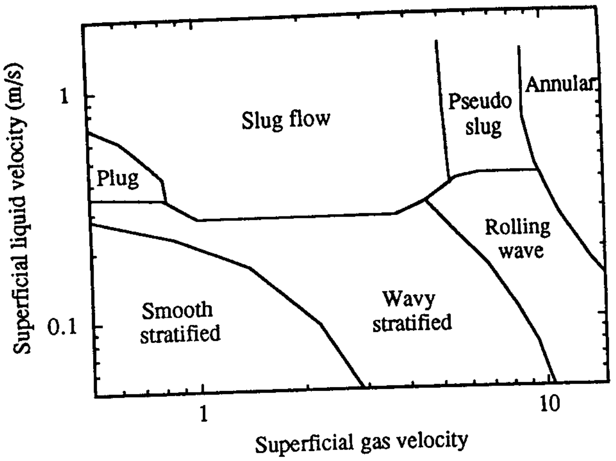


Figure 5. Flow regime map for water-CO2.

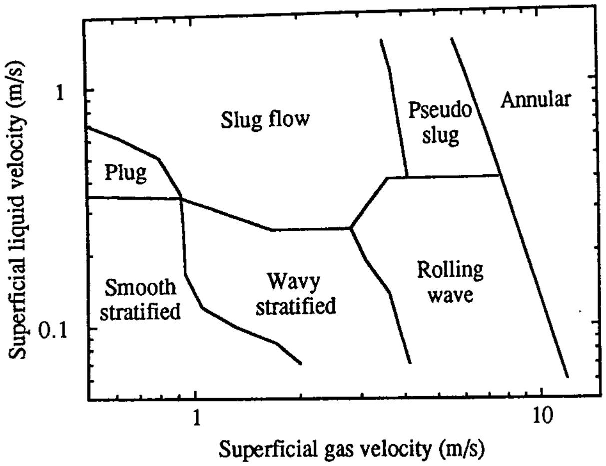


Figure 6. Flow regime map for oil(LVT200)-CO2.

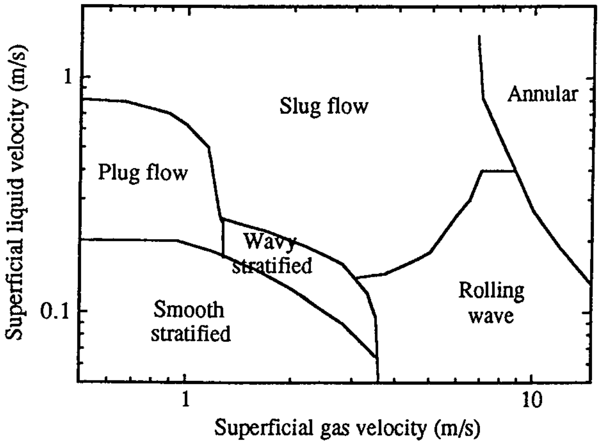


Figure 7. Flow regime map for oil(Arcopak90)-CO_2.

Figure 8 shows the comparison of experimental results with Jepson (1987) for 30cm diameter pipe. The transition from stratified to slug flow appears at a higher liquid velocity in Jepson's map. This indicates the effect of pipe diameter.

Figure 9 shows the comparison of the experimental results with Taitel and Dukler (1976) model. The results of present work on slug transition are close to Taitel's prediction. However, the transition to annular flow is not at all predicted. Jepson (1989) noted that the mechanisms for the transition from slug to annular flow in large diameter pipe are different and these are not present in the Taitel and Dukler model.

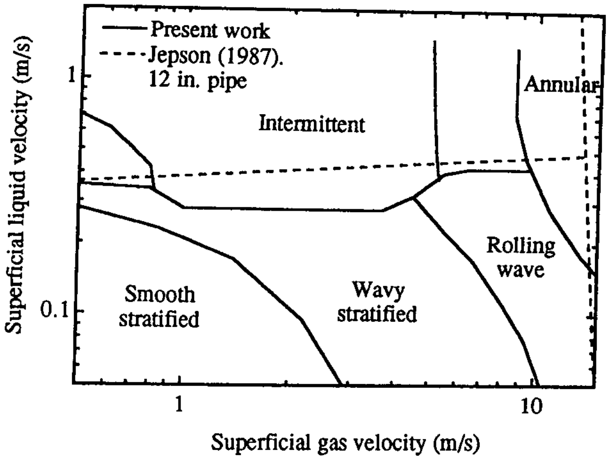


Figure 8. Comparison of experimental result with Jepson(1989).

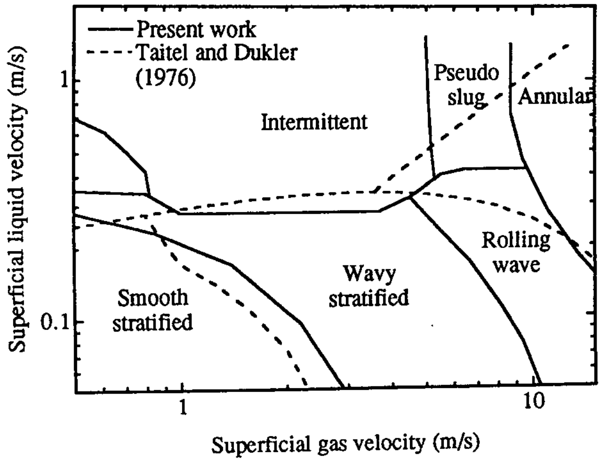


Figure 9. Comparison of experimental result with Taitel and Dukler's model.

Flow regime maps for water-oil-gas three phase flow

The flow regime map for oil-water-gas three phase flow were constructed for three liquid compositions which are 25%water-75%oil, 50%water-50%oil and 75%water-25%oil. Figure 10 shows the flow map for 50% water-50% oil-gas for LVT200 oil. The Superficial velocities of each liquid phase can be obtained by multiplying the total superficial velocity by the liquid composition. It can be seen that the configuration of the flow map is similar to the flow map for gas-liquid two phase flow but with the transitions in different locations. The comparison of oil-water-CO2 mixture with liquid-gas two phase flow is summarized in Figure 11. It can be seen that the transition to slug flow occurs at a lower liquid velocity than either the water-gas or the oil-gas case. This is due to the presence of the oil/water interface and this changes the flow characteristics of both the oil and water phases. These mechanisms are not in the Taitel and Dukler model. At the high gas velocities, the liquid phases are well mixed and behave as a pseudo fluid. The other transitions are similar to that of the oil alone.

A similar map for Arcopak90 oil is shown in Figure 12. Here, the slug transition takes place between that for water-gas and oil-gas systems. The wavy stratified flow pattern occurs at the smaller range of gas velocities, the rolling wave flow pattern appears at a wider range of liquid and gas velocities. The annular flow transition approach as that for water-CO_2 system. For Arcopak90 oil, the oil and water become emulsified at low liquid velocities and a homogeneous liquid mixture is formed. The properties of this mixture are between those of the water and oil.

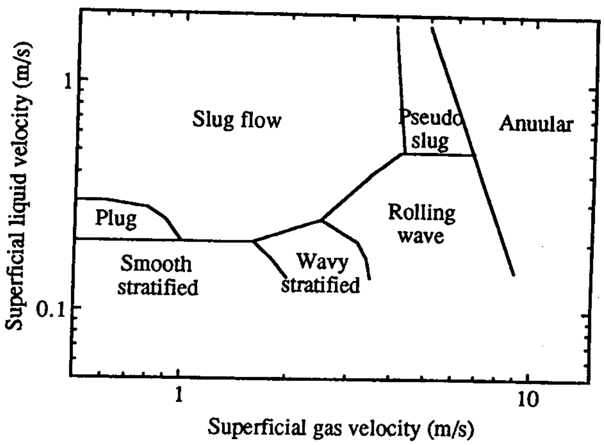


Figure 10. Flow regime map for 50% water-50% oil(LVT200)-CO2.

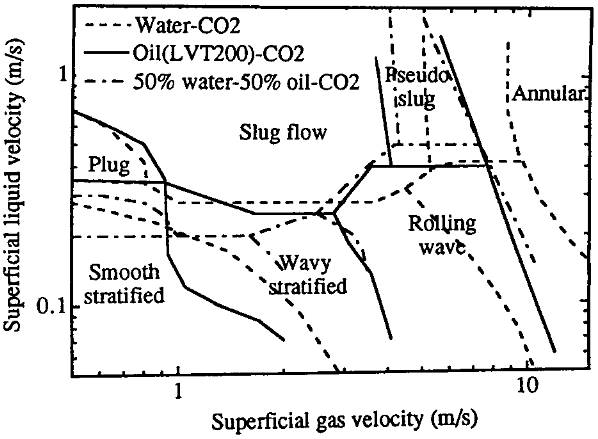


Figure 11. Comparison of flow regime for water-oil-gas mixture with those for liquid-gas two phase flow.

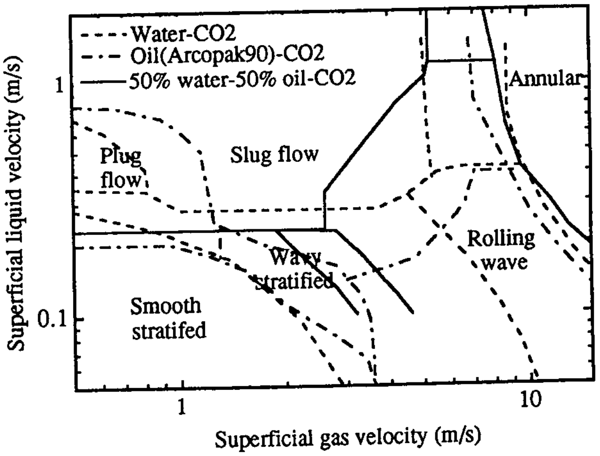


Figure 12. Comparison of flow regime for water-oil-gas mixture with those for liquid-gas two phase flow.

The comparison of experimental results for oil-water-gas three phase flow with Taitel et al (1976) for water-CO_2 and LVT200 oil-CO_2 is presented in Figure 13. The Taitel and Dukler model which can only

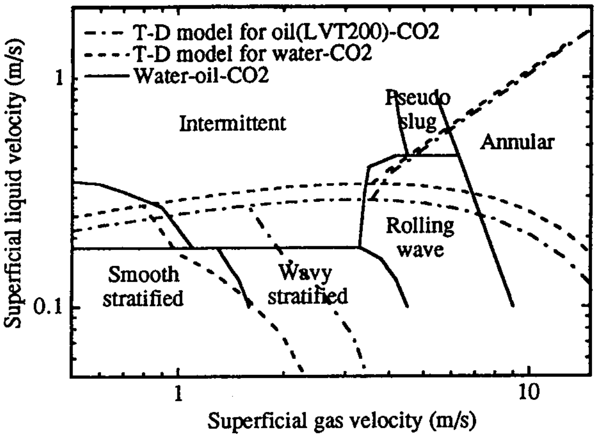


Figure 13. Comparison of flow regime transitions for water-oil-gas mixture with Taitel and Dukler model for liquid-gas two phase flow.

use individual liquid phase properties, does not accurately predict any of the transitions. This shows that the Taitel and Dukler model should only be used with caution for oil-water-gas three phase flows.

Effect of fluid composition on flow regime transitions.

Flow regime maps for 25% water-75% oil-gas, 75% water-25% oil-gas were completed for both oils. The comparison of different fluid compositions are summarized in Figure 14 and 15.

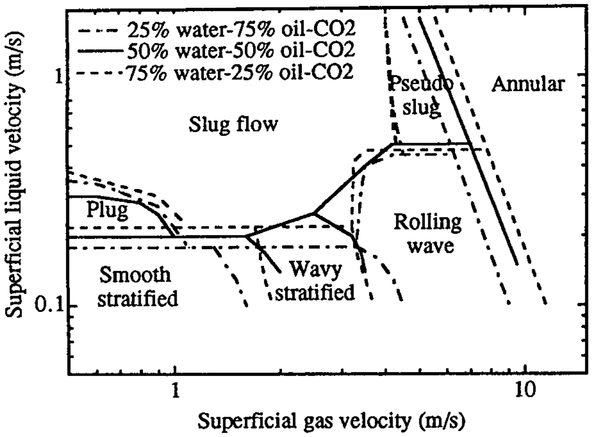


Figure 14. Effect of water fraction in oil(LVT200) on flow regime transitions.

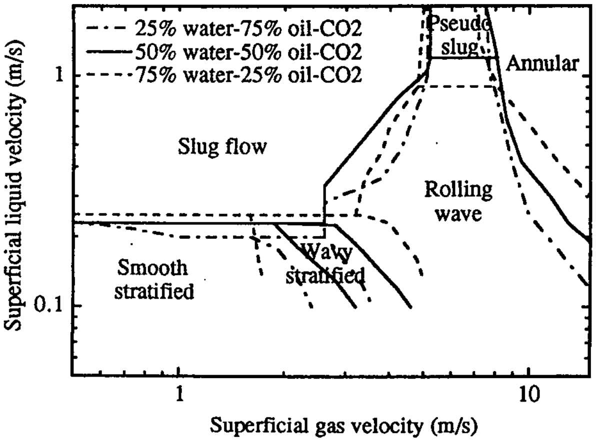


Figure 15. Effect of water fraction in oil(Arcopak90) on flow regime transitions.

For LVT200 oil, as the oil concentration increased the transition to slug flow occurs at the lower liquid velocity. For 25% water, slug flow occurs at 0.18m/s. As the water fraction is increased to 50 and 75%, slug flow is reached at liquid velocities of 0.2 and 0.22m/s respectively. The gas velocity to obtain annular flow increases with an increase in water fraction. The transition from slug to pseudo slug flow is not affected much by fluid compositions.

For Arcopak90 oil, similar observations are obtained.

CONCLUSIONS

There is a large effect of fluid compositions on flow patterns and flow regime transitions. The flow patterns and the flow regime transitions in oil-water-gas three phase flow are found to differ from those obtained in both gas-liquid and oil-water flow systems.

For LVT200 oil, the slug flow occurs at lower liquid velocities in water-oil-gas three phase flow than for both water-gas and oil-gas system. At higher oil concentrations, annular flow appears at lower gas velocities than two phase flow. For Arcopak90 oil, the slug transition takes place between that for water-gas and oil-gas flows. The annular flow appears at the lower gas velocity than in water-gas system.

In three phase flow, as the oil fraction is increased, slug flow occurs at lower liquid velocities and annular flow appears at lower gas velocities.

The Taitel and Dukler model does not predict the effect of a second liquid phase.

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