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FLOW REGIME TRANSITIONS IN LARGE DIAMETER INCLINED MULTIPHASE PIPELINES

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ABSTRACT

Experimental studies have been performed in a 10.16 cm diameter, 36 m long, multiphase flow loop to examine the flow regime maps in ±2°, ±15° and ±30° inclinations. Superficial oil velocities between 0.2 and 2.0 m/s and superficial gas velocities between 1 and 14 m/s were investigated. Oil with a viscosity of 2.5 cP was used for the study. Carbon dioxide was used for the gas phase. Temperature and pressure were maintained at 25 °C and 0.13 MPa.

It was observed that the dominant regime for upward inclinations was slug flow. No stratified flow was observed for these conditions. As the angle of upward inclination increases from 2° to 15°, the transition from plug to slug flow occurs at higher superficial gas velocities. However, the transition from slug to annular flow occurred at lower superficial gas velocities.

As the angle of downward inclination increases, the transition from stratified to slug flow occurs at higher liquid and gas flow rates. A considerable area of the flow regime map was found to be occupied by stratified flow with increasing downward inclination.

The transition from slug to annular flow occurred at slightly higher gas flow rates when inclination was changed from –2° to –15°. However, little difference was found during the transition from slug to annular flow when the inclination was changed from –15° to –30°.

INTRODUCTION

The flow of oil-gas mixtures in pipelines is a common occurrence in the petroleum industry. The multiphase mixture is transported through a single pipeline to a central gathering station since it is not practical and very expensive to separate the produced mixture of oil. During this transport, several flow regimes occur depending on the gas and liquid flow rates. The distances the multiphase mixture must be transported are often long and the deviations from horizontal flow are always present. These changes in inclination cause changes in the flow regime transitions and flow characteristics, which have a definite effect on the corrosion rate experienced by these pipelines.

The multiphase flow in horizontal multiphase pipelines results in several flow patterns such as stratified flow (smooth, wavy and rolling wave), intermittent flow (plug flow, slug flow and pseudo-slug flow) and annular flow. Here, the slug flow and annular flow are a common occurrence in the petroleum industry when multiphase mixture is transported through a single pipeline to a central gathering station.

Stratified flow exists at low gas and liquid velocities. A smooth interface exists between the liquid film flowing at the bottom of the pipe and gas above it.

An increase in the liquid velocity causes the waves to grow and fill the pipe cross section resulting in plugs of liquid with intermittent gas pockets.

At a higher gas velocity, the typical flow pattern observed in the flow lines is slug flow. This is similar to stratified flow except that there is an intermittent flow of the liquid slugs, which propagate between the stratified flow. Here, slug flow is a major concern since the front of the slug creates a highly turbulent mixing zone with a high void fraction, which leads to high corrosion rates. Also, there is a big pressure drop in this flow condition due to the deceleration. Here, accelerational pressure drop dominates rather than frictional pressure drop.

At higher gas velocities, pseudo-slug flow occurs. Pseudo-slugs have a similar structure to slugs. Pseudo-slugs are shorter and the frothiness is greater than in a slug flow.

Annular flow occurs at very high gas velocities. In annular flow, there is a liquid film flowing along the pipe wall with the gas in the central core.

The flow regime map depends on a lot of parameters such as pipe diameter, pipeline pressure, liquid velocity, gas velocity, oil viscosity, water cut, and pipeline inclination.

Many researchers have studied multiphase flow regime maps for the creation of a successful flow regime transition models.

Baker (1954) was one of the first, presenting flow regime maps in multiphase flow. Knowing the mass velocities of the liquid and gas phases, along with the fluid properties, the flow patterns would be predicted from the flow regime plot. This was two phase flow in small diameter pipes and did not include the effects of pressure, diameter or inclination.

Mandhane, et. al. (1974) created a two phase, air-water flow map for horizontal, small diameter, low pressure using superficial liquid and gas velocities as the axes. This procedure has since become a standard in the oil and gas industry.

Taitel and Dukler (1976) proposed a mechanistic model for predicting the flow regime transitions in horizontal two phase flow. Their model is based on a mechanistic approach and includes five dimensionless groups to account for fluid properties, pipe diameter, pipe inclination, and fluid velocities. This model is currently the most widely used. Their model has been verified (Barnea, et. al., 1980) for small diameter, low pressure, and two phase systems at horizontal to near horizontal pipe flow.

Limited flow regime data exists for inclined pipes. Gould, et. al. (1974) introduced $+45^o$ and $+90^o$ flow regime maps. Govier, et. al. (1972) presented a commonly used method of establishing flow regimes for inclined pipes. Barnea, et. al. (1982) presented flow regime maps for two phase flow in downward (0 ~90^o) small diameter pipes. He also proposed a model for predicting transitions in downward pipes. Stanislav, et. al. (1986) reported inclined flow pattern as compared with a modified Taitel and Dukler model in small diameter pipes. Kokal and Stanislav (1986) have characterized extensively the upward and downward flow patterns. However, all of these studies have been carried out in small diameter pipes

However, it has been demonstrated by Jepson and Taylor (1993) that the transitions did not hold for large diameter pipes.

EXPERIMENTAL SETUP

The experimental layout of the flow loop is shown in Figure 1. The specified amount of oil is placed in a 1.2 m^3 stainless steel storage tank (A). The tank is equipped with a 3.8-kW heater and 6-m long (2.5 cm ID) stainless steel cooling coils to maintain a constant temperature. The oil from the storage tank is then pumped into a 10-cm ID PVC pipeline by means of a 76 HP low shear progressing cavity pump (B). The liquid flow rate is controlled by varying the speed of the pump using a variable-speed controller.

Carbon dioxide gas from a 20,000-kg receiver (D) is introduced into the system. The gas flow rate is metered with a variable area flow meter. The gas is then mixed with the liquid at a tee junction (C). The multiphase mixture then flows through 3.1-m long flexible hose (10 cm ID), allowing the inclination to be set at any angle. The oil-gas mixture then flows into an 18-m long Plexiglas pipeline (10 cm ID) where the flow pattern is determined.

Table 1 shows the test matrix for the study.

RESULTS AND DISCUSSION

Experiments have been carried out to determine the flow regime maps in $\pm 2^o$, $\pm 15^o$ and $\pm 30^o$ pipelines.

Flow Regime Maps in Upward Inclinations

Figure 2 shows the flow regime map for 100% 2.5 cP oil/CO_2 for 2^o upward inclination. It was observed that the dominant regime was slug flow. No stratified flow was observed for these conditions. This has been found by many other researchers (Kokal and Stanislav, 1989; Kang et. al., 1996, etc.).

For superficial liquid and gas velocities of 0.8 and 1 m/s, transition from plug to slug flow occurred. As the liquid velocity was increased, the gas velocity required for the transition from plug to slug flow also increased. At a liquid velocity of 2.0 m/s, slug flow was obtained when the gas velocity reached 2.5 m/s.

The transition from slug to annular flow occurred at lower gas velocities with low liquid velocities and at higher gas velocities for the higher liquid velocities. It can be seen from Figure 1 that slug flow occurred at a superficial liquid velocity of 1.0 m/s and a superficial gas velocity of less than 10 m/s, while at a superficial liquid velocity of around 0.2 m/s, annular flow was observed to occur at a superficial gas velocity as low as 9 m/s. This phenomenon was also observed by Kokal and Stanislav (1989).

It was noticed that inclinations from 2^o to 15^o were found to have an effect on the transition. Figure 3 presents the flow regime map for 15^o upward inclination. It can be seen from Figures 2 and 3 that the transition from plug to slug flow occurred at higher superficial gas velocities. At a superficial liquid velocity of 1.2 m/s, the transition from plug to slug flow occurred at 1.5 m/s of gas velocity in 2^o upward flow and the same transition occurred at 2 m/s of gas velocity in 15^o upward flow. However, the transition from slug to annular flow moved to the left of the flow regime map with increase in upward inclination from 2 to 15 degrees. For example, at a superficial liquid velocity of 0.5 m/s, the transition from slug flow to annular flow occurred at 9.5 m/s of gas velocity in 2^o upward flow, while 8.5 m/s of gas velocity in 15^o upward flow. This is due to the fact that at 15^o upward flow, the height of the liquid film is higher, thus providing the gas to spread it around the pipe at higher gas velocities.

The transition from slug to annular flow did not change significantly when the pipeline was inclined from 15^o to 30^o as shown in Figures 3 and 4. However, the transition from plug flow to slug flow occurred at slightly higher superficial gas velocities.

The differences of the transitions can be clearly noticed from the comparison of flow regime plot as shown in Figure 5.

Flow Regime maps in Downward Inclinations

A flow regime map at -2^o downward inclination is shown in Figure 6. Here, the transition from stratified to slug flow becomes much more dependent upon the superficial gas velocity. At a superficial gas velocity of 1.0 m/s, only stratified flow was observed at all superficial liquid velocities studied. At a superficial gas velocity of 2 m/s, slug flow occurred at superficial liquid velocities of greater than 0.4 m/s, while stratified flow occurred at superficial liquid velocities of lower than 0.4 m/s. In 2^o downward flow, the height of the liquid film is thinned and faster. At lower velocities, more liquid is required to bridge across the pipe. At higher velocities, the height of the liquid film is not significantly different from that in horizontal flow, and the transition occurs near where it is expected to occur in horizontal pipes.

It was noticed from Figures 2 and 6 that the transition from slug to annular flow occurred at higher superficial gas velocities in -2^{o} inclination than in $+2^{o}$ inclination. For example, at superficial liquid velocity of 0.5 m/s, the transition annular flow in -2^{o} inclination occurred at a superficial gas velocity of 10.5 m/s, while 9.5 m/s in $+2^{o}$ inclination. Similar trends have been observed in $\pm 15^{o}$ and $\pm 30^{o}$.

Further downward inclination caused the transition from stratified to slug flow to occur at higher liquid and gas flow rates. Figure 7 shows the flow regime map in -15^{o} downward flow. A considerable area of the flow regime map was found to be occupied by slug flow in -2^{o} inclination, but only a small region at high gas and liquid velocities in -15^{o} inclinations was occupied by slug flow. For example, at superficial liquid and gas velocities of 0.5 and 2 m/s for -2^{o} inclination, slug flow was noticed. However, at the same liquid flow rate and gas velocities of less than 4 m/s, stratified flow in -15^{o} inclination was found.

The transition from slug to annular flow occurs at slightly higher gas flow rates when inclination is changed from -2^{o} to -15^{o}. For example, at a superficial liquid velocity of 0.5 m/s for -2^{o} inclination, the transition from slug to annular flow occurred at a superficial gas velocity of 10.5 m/s, while 11.5 m/s for -15^{o} inclination at the same liquid flow rate. A similar trend has been noticed in small diameter pipes by Barnea et. al. (1982). They found that the transition from slug to annular flow up to about 70^{o} downward inclination occurs at high gas flow rates.

In -30^{o} inclination, the transition from stratified to slug flow shifted to the right with increasing downward inclination as shown in Figure 8. However, not much difference was found during the transition from slug to annular flow when inclination was changed from -15^{o} to -30^{o}.

The differences of the transitions can be clearly noticed from the comparison of flow regime plot as shown in Figure 9.

CONCLUSIONS

Flow regime maps have been determined in $\pm 2^{o}$, $\pm 15^{o}$ and $\pm 30^{o}$ inclinations in large diameter pipes.

Flow Regime Maps in Upward Inclinations

- For upward inclinations, it was observed that the dominant regime was slug flow. No stratified flow was observed for these conditions.
- As the liquid velocity was increased, the gas velocity required for the transition from plug to slug flow also increased.
- The transition from slug to annular flow occurred at lower gas velocities with low liquid velocities and at higher gas velocities for the higher liquid velocities.
- The transition from plug to slug flow occurred at higher superficial gas velocities with increase in upward inclination. However, the transition from slug to annular flow occurred at lower superficial gas velocities. This is due to the fact that more liquid is stored at the bottom of the pipe, thus providing the gas to spread it around the pipe at higher gas velocities.
- The transition from slug to annular flow did not change significantly when the pipeline was inclined from 15^{o} to 30^{o}. However, the transition from plug to slug flow occurred at slightly higher superficial gas velocities.

Flow Regime maps in Downward Inclinations

- The transition from stratified to slug flow becomes much more dependent upon the superficial gas velocity.
- As the angle of downward inclination increased, the transition from stratified to slug flow occurred at higher liquid and gas flow rates.
- The transition from slug to annular flow occurred at slightly higher gas flow rates when inclination was changed from -2^{o} to -15^{o}. However, not much difference was found during the transition from slug to annular flow when inclination was changed from -15^{o} to -30^{o}.
- A considerable area of the flow regime map was found to be occupied by stratified flow with increasing downward inclination.

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TABLE 1
TEST MATRIX FOR THE STUDY

Property	Range
Water cut (%)	0
Pressure (MPa)	0.13
Inclination (degrees)	±2, ±15, ±30
Temperature (°C)	25
Superficial gas velocity	1 - 14 m/s
Superficial liquid velocity	0.2 ~ 2.0 m/s
Gas	Carbon dioxide
Oil	Light oil, 2.5 cP

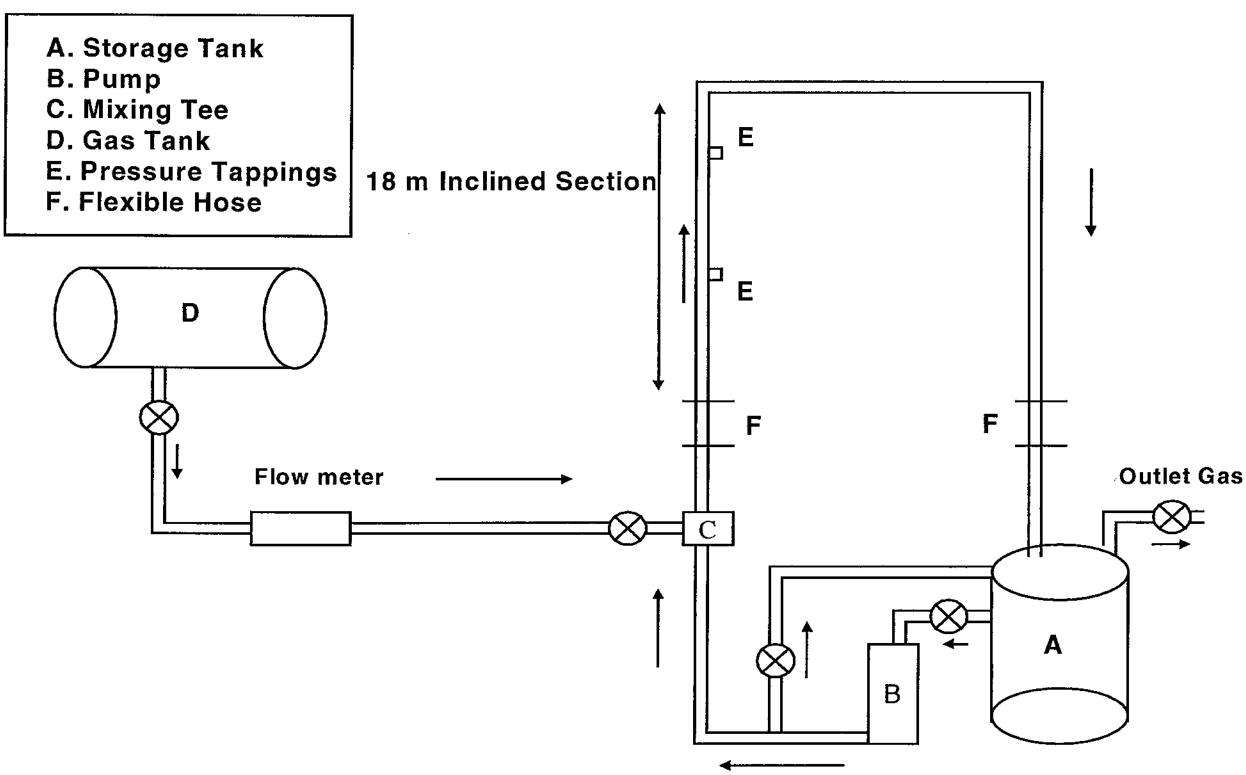

Figure 1. Experimental Layout of the Flow Loop

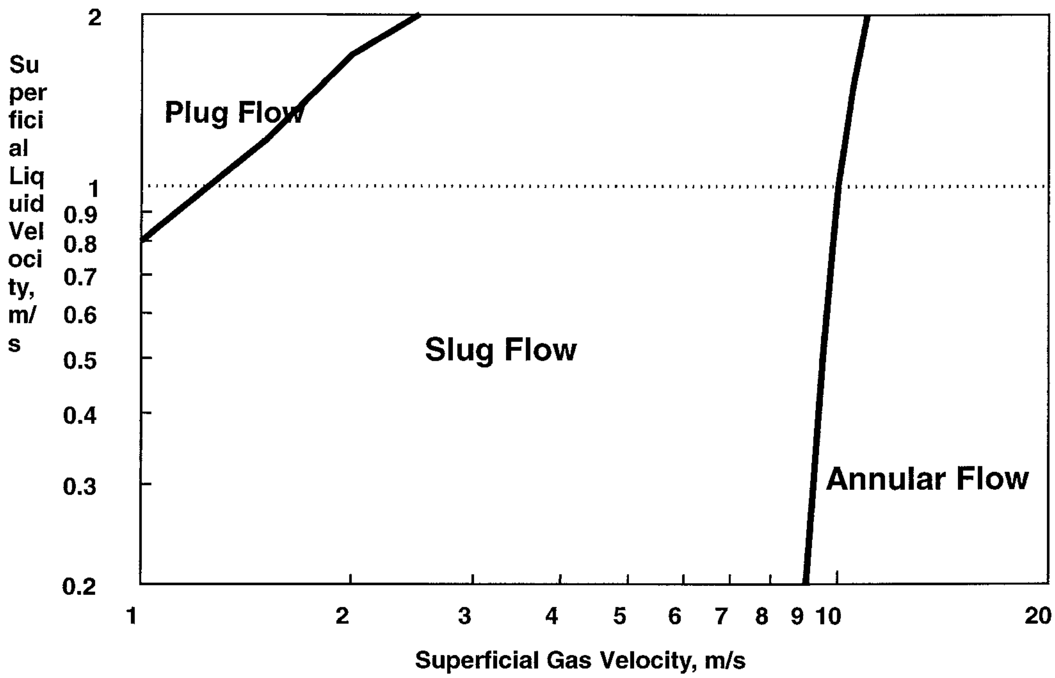

FIGURE 2. Flow Regime Map in +2 Degrees
100% 2.5 cP Oil/Gas, P = 0.13 MPa

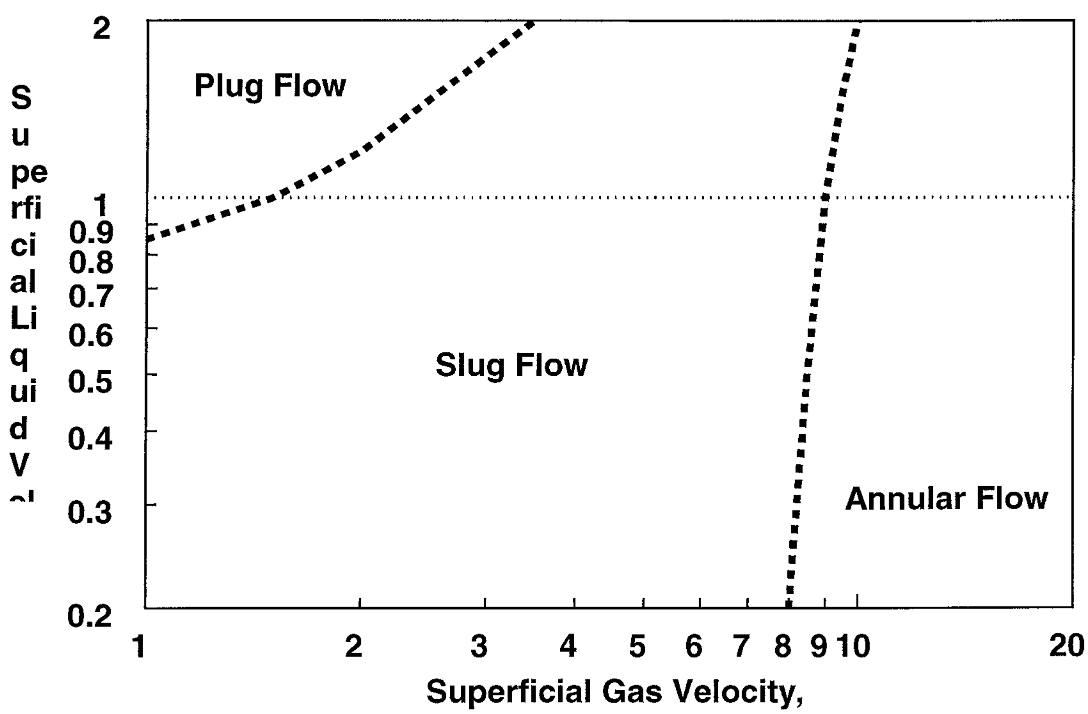

FIGURE 3. Flow Regime Map in +15 Degrees
100% 2.5 cP Oil/Gas, P = 0.13 MPa

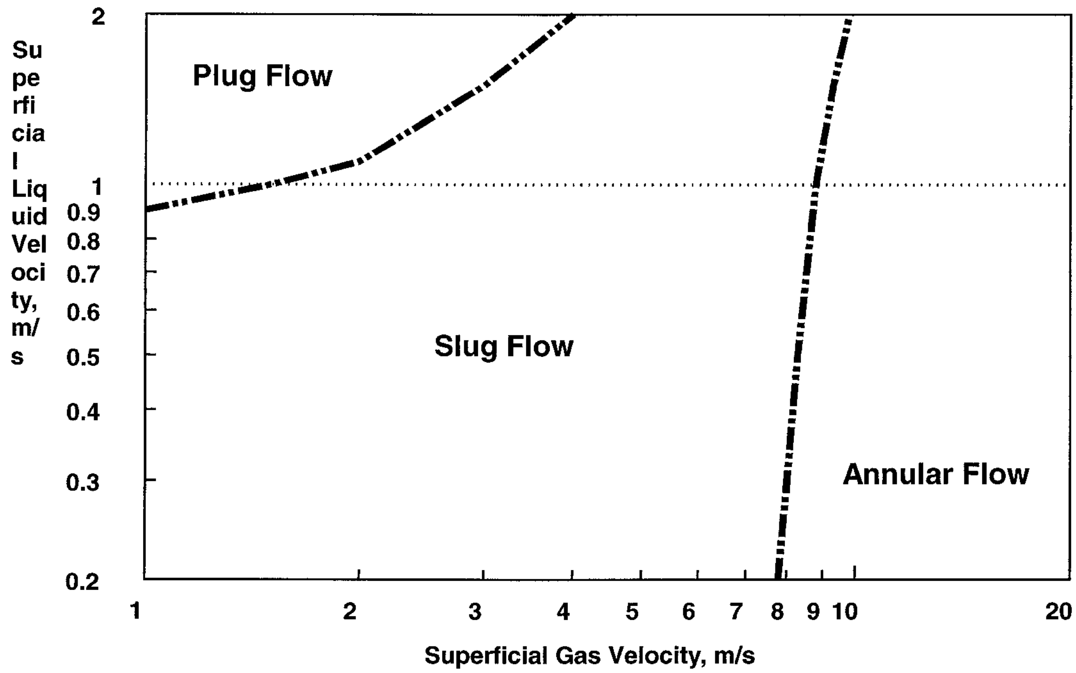

FIGURE 4. Flow Regime Map in +30 Degrees
100% 2.5 cP Oil/Gas, P = 0.13 MPa

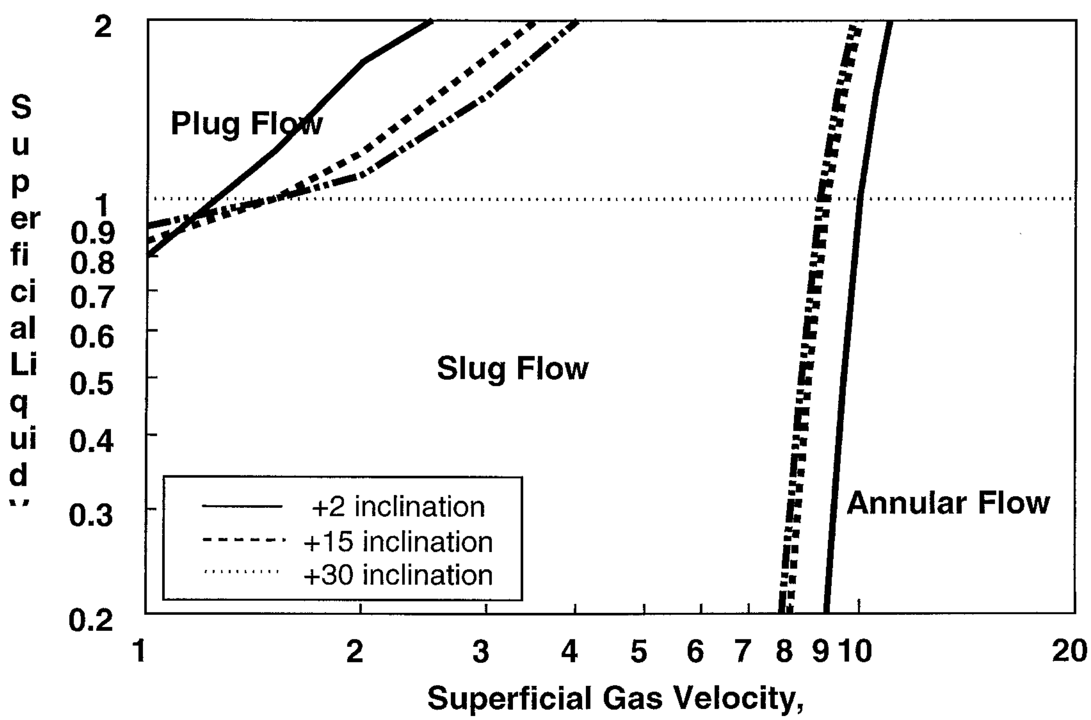

FIGURE 5. Comparison of Flow Regime Map
100% 2.5 cP Oil/Gas, P = 0.13 MPa

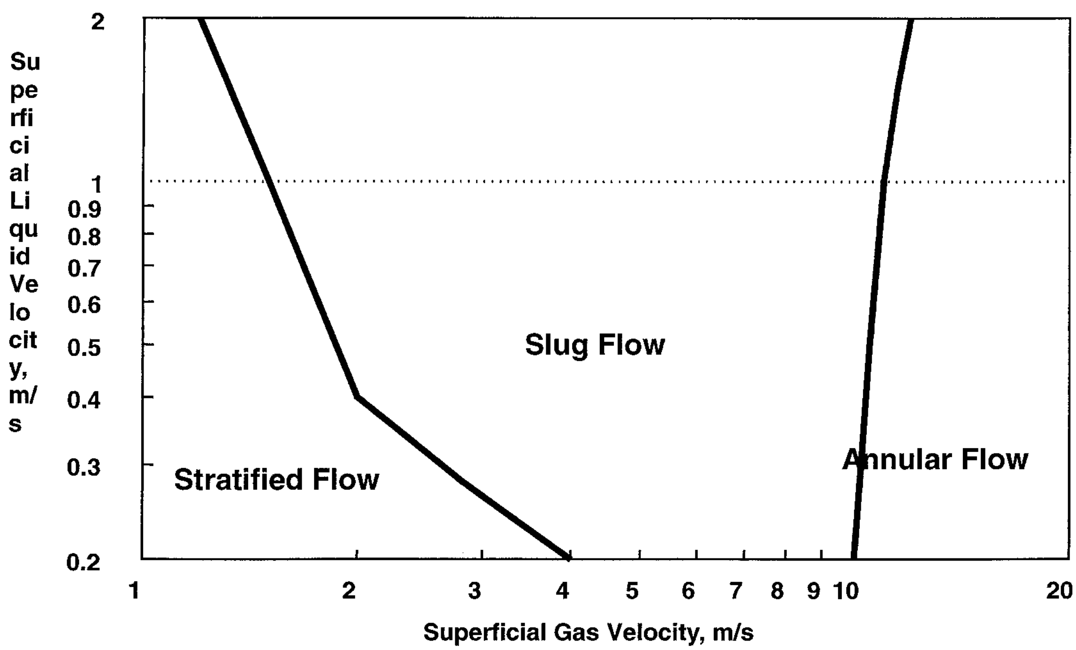

FIGURE 6. Flow Regime Map in -2 Degrees 100% 2.5 cP Oil/Gas, P = 0.13 MPa

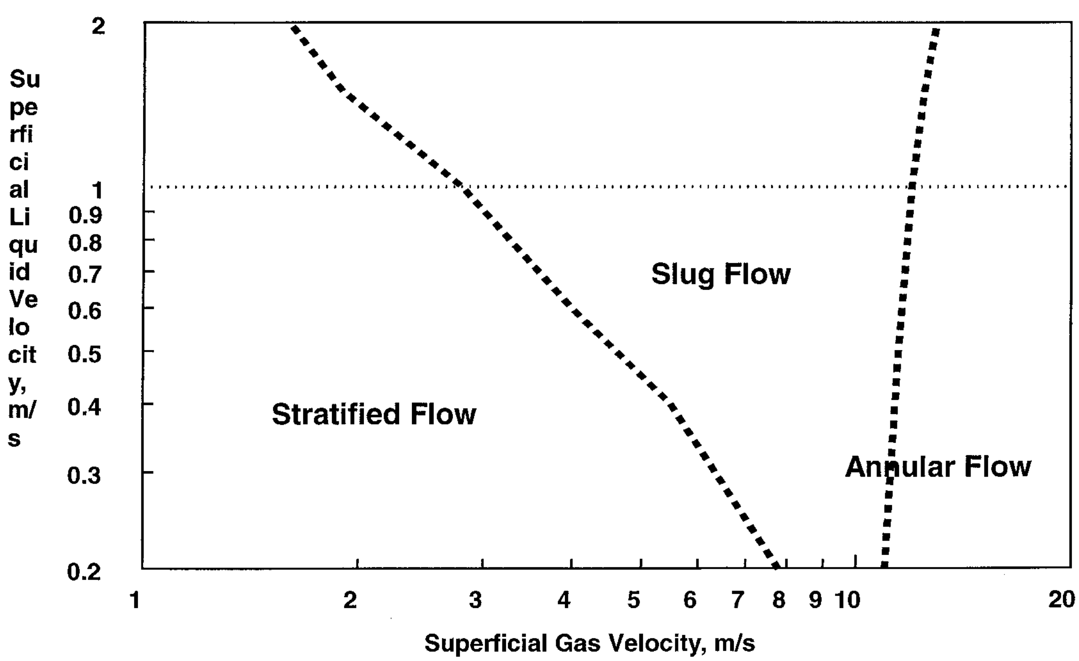

FIGURE 7. Flow Regime Map in -15 Degrees 100% 2.5 cP Oil/Gas, P = 0.13 MPa

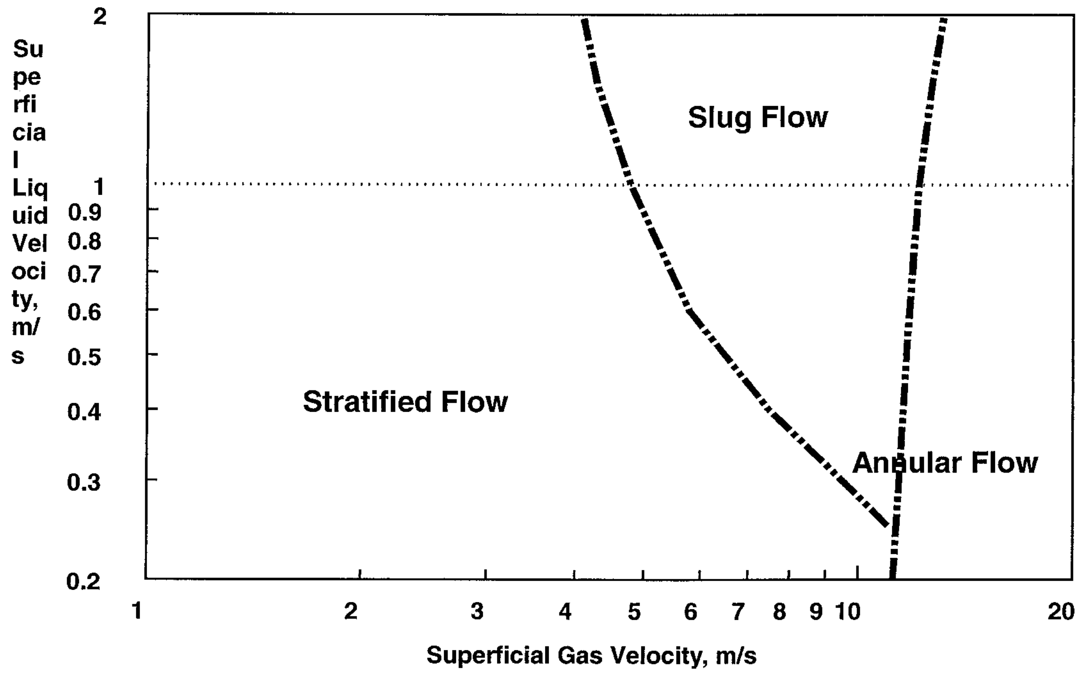

FIGURE 8. Flow Regime Map in -30 Degrees
100% 2.5 cP Oil/Gas, P = 0.13 MPa

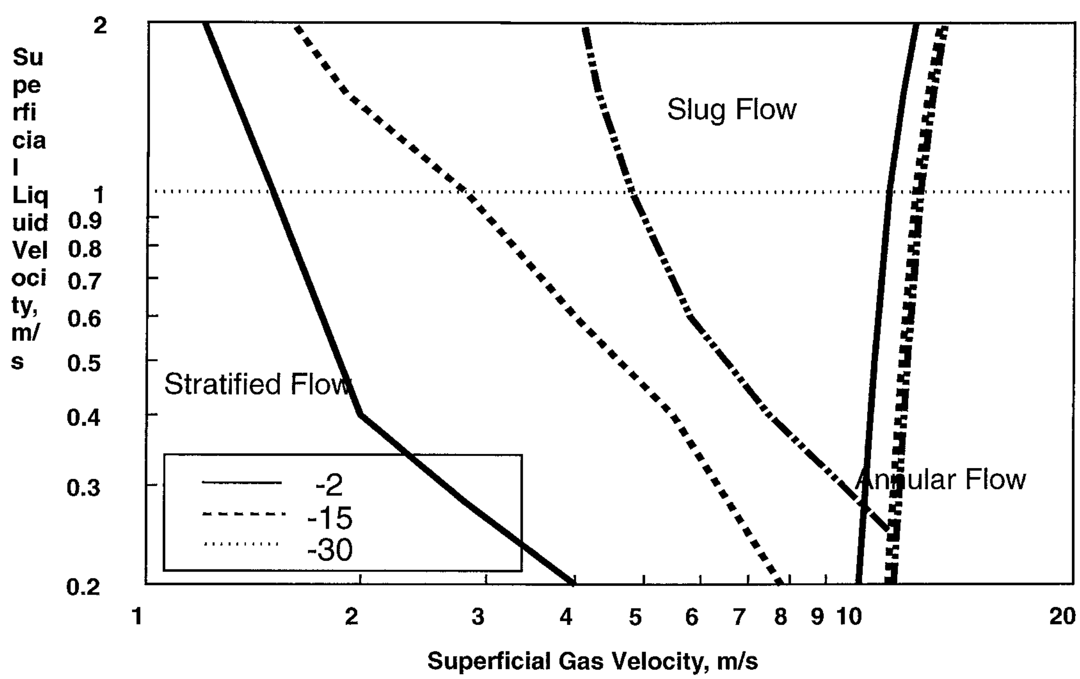

FIGURE 9. Comparison of Flow Regime Map
100% 2.5 cP Oil/Gas, P = 0.13 MPa