FLOW REGIME TRANSITIONS IN HIGH-PRESSURE INCLINED PIPELINES

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Abstract

An 18-m long, 9.72-cm i.d., inclinable 316 stainless steel pipeline has been commissioned for the study of multiphase flow and its subsequent effects on corrosion. The effect of inclination and pressure on flow regime transitions and slug flow characteristics is studied. The fluids used are carbon dioxide for the gas phase and ASTM substitute seawater with light oil in the liquid phase. The superficial gas and liquid velocities varied from 1.0-11 m/s and 0.1-1.5 m/s respectively. Additionally, the pressure varied from 0.27 to 1.48 MPa and the inclination varied from 0° to ±5°.

The results show that inclination has a dramatic effect on flow regime transitions. Even at an inclination of +2°, the stratified flow has completely disappeared within the range of velocities studied. Froude numbers are higher at the same velocities in upward inclined flow. Increasing pressure causes transitions to annular flow at lower gas velocities. Maps are presented for flow regime transitions at different pressures and inclinations.

Introduction

Previous work at the Corrosion Center (Lee, 1993) has explained multiphase flow regimes and the mechanisms governing their transitions. A great deal of work has been carried out for two phase flows in small diameter pipes. This is not scalable to larger pipes. Jepson and Taylor (1993) have shown that the pipe diameter should be at least 10 cm to mimic the mechanisms observed in large diameter pipelines.

Mandhane *et al.* (1974) created a two-phase flow map based on the superficial gas and superficial liquid velocities. Fluid properties, diameter, and inclination specify the flow map which applies. The Mandhane plots have become a standard format for publishing flow regime data in multiphase flow.

The first realistic two-phase mechanistic flow regime transition model was produced by Taitel and Dukler (1976). For the transition from stratified to intermittent or annular flow using the Taitel and Dukler model, the simultaneous solution of two relations is required, namely, the combined momentum balance equation for gas and liquid, and the instability criteria.This model has been verified (Barnea *et al.*, 1980, *etc.*) for small-diameter, low pressure, two phase systems at horizontal to near-horizontal pipe flow. The model has been shown to not work well if the diameter is large (Jepson and Taylor, 1993) or with the presence of a third phase (Lee, 1993).

Lin (1985) reported large and small diameter flow regime maps for horizontal air-water flow. Similarly, Jepson and Taylor (1993) and Wallis and Dobson (1973) reported large diameter flow regime maps, but they were also for horizontal air-water systems. Lee (1993) reported the flow regime transitions for a large diameter pipe with horizontal three phase flow. This data was for carbon dioxide gas, water, and a light-oil which is commercially available. Limited flow map data exists for inclined pipelines. Gould *et al.* (1974) introduced +45° and +90° flow pattern maps. Govier and Aziz (1972) presented a commonly used method of establishing flow patterns for inclined flow. Barnea *et al.* (1985) proposed a model predicting transitions in inclined pipelines. Stanislav *et al.* (1986) reported inclined flow pattern data. Kokal and Stanislav (1986) characterized, extensively, the upflow and downflow patterns. The models and data compared well, however all of these studies involved two-phase flow. Additionally, flow in large-diameter pipes and at high-pressure have not been reported in inclined pipelines. Further, little research has been done on three phase flow regimes and their transitions. This work will provide the data necessary in large diameter three phase flow to include the effects of inclination and pressure.

Experimental Setup

An 18-m long, 9.72-cm i.d., high-pressure (13 MPa), high temperature (90°C), inclinable 316 stainless steel flow loop has been commissioned for the study of multiphase flow and its subsequent effects upon corrosion. Figure 1 is a schematic of the system. A predetermined oil and water mixture is stored within a 1.4 m^3 mixing tank. The liquid is moved through the system by a centrifugal pump powered by a 3 - 15 kW variable speed Baldor motor and its flow rate maintained by the gate valves labeled A and B. The flow rate is determined with a TMTR 510 frequency analyzer which was calibrated to a GH Flow Automation (model 6531) in-line turbine flow meter.

A 2-MPa feed line supplies carbon dioxide gas from a 20,000 kg receiver. After passing through a pressure regulator, the gas flow rate is set by adjusting ball valve C. A Hedland variable area flow meter is used to determine the gas flow rate. The gas temperature and pressure are monitored between the flow meter and the pressure regulator. The gas then passes through a check valve, to avoid possible liquid backflow, and into the liquid flow. The multiphase mixtures then enters the test loop through a compression flange, allowing the inclination to be set at any angle. Upon entering the inclined portion of the test loop, the multiphase mixture travels 18 meters before reaching the test section.

Figure 2 illustrates the test section with the instrument port locations. Port A is a fluid sampling port used primarily when preparing for corrosion experiments. System temperature is measured through port B with a type-K thermocouple connected to an OMEGA DP3200-TC electronic analyzer with display. Any of the ports labeled C can be coupled and used to measure differential pressure. In these experiments, the differential pressures are measured between the two sets of taps placed 10 and 132-cm apart. The measurements are made with 0 to 35 kPa OMEGA PX-750 heavy duty differential pressure transducers. The entire pressure-signal based system has been patented in a non-visual technique to determine flow regime transition and is not described here. Port D is used to monitor the test section pressure. This pressure is measured with a 0 to 2.8 MPa Noshok pressure gauge. The ports marked E can be used to insert corrosion probes if necessary. Additional data can be taken using two upflow and two downflow acoustic sensors provided by BP Research.

Upon leaving the test section, the multiphase flow passes through a separator to prevent siphoning due to the declined angle of flow return and to destroy the flow pattern. The mixture passes back through another compression flange and then re-enters the mixing tank. The gas passes through a de-entrainment plate through a back-pressure regulating control valve, through a separator, and is vented to the atmosphere. The liquid from the separator is collected to be re-injected into the system.

Test Matrix

The matrix studied is listed in Table 1. ASTM D1141-52 substitute seawater with an oil of density 800 kg/m^3 and viscosity 2 cP were used in the liquid phase with carbon dioxide in the gas phase.

Table 1: Experimental test matrix for flow regime and flow property determination.

property	range
water cut	40, 80, 100%
pressure	0.27, 0.45, 0.79 MPa
inclination	horizontal, ± 2°, ± 5°
temperature	20 °C
diameter	0.0972 m
superficial gas velocity	0 - 13 m/s
superficial liquid velocity	0.1, 0.5, 1.0, 1.5 m/s

Results and Discussion

The flow regimes were determined from the criteria established by Wilkens and Jepson (1996). The flow regimes identified were plug flow, stratified flow, slug flow, pseudo-slug flow, and annular flow. Plug flow, slug flow, and pseudo-slug flow will often be collectively termed slug flow. Plug flow is actually of little interest and is not known to occur in downflow. Slug flow was found to dominate the flow regime map as the inclination was increased to as little as +2°. This is expected as it has been found by many researchers (Kokal and Stanislav, 1989, *etc.*). Figure 3 is a flow regime map for 100% saltwater, horizontal, 0.45 MPa flow. At superficial liquid velocities of up to 0.3 m/s, stratified flow is observed to occur while slug flow was observed to occur at a superficial liquid velocity of 0.4 m/s. Pseudo-slug and annular flow occurred at the higher gas flow rates while plug flow occurred at the lower gas flow rates. Figure 4 represents the flow regime map for 100% saltwater, +5° inclined, 0.27 MPa flow. No stratified flow was observed to occur. In its place at equal flow rates is slug flow. At a superficial liquid velocity as low as 0.1 m/s, slug flow is still observed to occur, allowing slug flow to dominate the flow regime map.

In downward flow, stratified flow dominates the flow regime map. The transition from stratified to slug flow also becomes much more dependent upon the superficial gas velocity. Figure 3 showed that the transition from stratified to slug flow on the axes given was relatively horizontal (*i.e.*, occurring at a similar superficial liquid velocity for all superficial gas velocities studied). Figure 5 shows that if the pipe inclination is set to -2°, the transition becomes much more dependent upon the gas flow rate. At a superficial gas velocity of about 1 m/s, only stratified flow is observed at superficial liquid velocities as high as 1.5 m/s. At a superficial gas velocity of about 3 m/s, slug flow occurs at a superficial liquid velocity as low as 1 m/s while stratified flow occurs at a superficial liquid velocity of 0.5 m/s. At a superficial gas velocity of around 9 m/s, slug flow is observed to occur at a superficial liquid velocity as low as 0.5 m/s while stratified flow occurs at a superficial liquid velocity of 0.1 m/s. This trend is observed at other water cuts and at other pressures.Figure 6 shows that with 80% water cut, the transition from stratified to slug flow does not changes greatly compared to 100% water cut in Figure 5.

These stratified-slug transition results are expected and have been seen by other researchers (Kokal and Stanislav, 1989, *etc.*). In downflow, the liquid film is thinner and faster. At lower superficial gas velocities, more liquid is required to bridge across the pipe. At higher gas velocities, the film thickness is not much different from that in horizontal flow at high gas velocities, and the transition occurs near where it is expected to occur in horizontal flow. Further downward inclination causes the transition from stratified to slug flow to occur at higher liquid flow rates.

The transition to annular flow was found to occur in roughly the same location for all conditions tested at a superficial gas velocity around 10 m/s. The transition occurred at lower gas flow rate with low liquid flow rates and at a higher gas flow rate for the higher liquid flow rates. This was also observed by Kokal and Stanislav (1989). Inclination was found to have little effect on the transition in the range of conditions tested here. It appears that the gas flow rate required to reach annular flow is slightly lower in upflow and slightly higher in downflow. But nothing is observed which exceeds the uncertainties associated with the superficial gas velocity. Kokal and Stanislav also observed a slight decrease in gas required to reach annular flow with an increase in inclination, but it was on the order of their uncertainty. They concluded that this transition was relatively insensitive to inclination (-9° to +9°). Water cut was also found to have little observable effect on the transition to annular flow for the conditions tested.

Pressure was found to have a marked effect on the transition. As the pressure was increased, the transition to annular flow was observed to occur at lower superficial gas velocities. This effect has been observed in the field (Green, 1997) and is reasonable. Since annular flow is largely a density driven effect, it follows that the ratio of densities of the process fluids should affect this transition. In oil-water flows, when annular flow conditions occur, the less-dense and more viscous fluid (oil) flows in the core. In gas-liquid annular flow, the less-dense and less viscous fluid (gas) flows in the core. Since liquid-liquid annular flow occurs at a less-dense fluid superficial velocity of around 1 m/s for an oil with a specific gravity of near unity and around 5 m/s for an oil with a specific gravity of around 0.8 (Brauner and Maron, 1992), and since for gas-liquid annular flow occurs at a less-dense fluid superficial velocity of around 10 m/s, the closer the densities are, the lower the velocity requirement. Brauner and Maron demonstrated that as the oil specific gravity approached unity, the effect increased rapidly. As listed earlier, the gas density increases from 5.02 to 14.9 kg/m^3 as the pressure is increased from 0.27 to 0.79 MPa. Although this is a slight change with respect to the liquid density, there is a large effect on the ratio of the two.

Figures 4 and 7 represent the same flow conditions at pressures of 0.27 and 0.79 MPa, respectively. At 0.27 MPa and a superficial liquid velocity of 0.1 m/s, slug flow was observed to occur at a superficial gas velocity of about 8 m/s. At 0.79 MPa and a superficial liquid velocity of 0.1 m/s, annular flow was found to occur at a superficial gas velocity as low as 7 m/s. This effect can also be seen at other water cuts and at other inclinations.

Conclusions

Inclination is found to have a dramatic effect on flow regime transitions. Stratified flow was eliminated in upflow while slug flow was found to dominate. In downflow stratified flow was dominant while slug flow was reduced. In downflow, water cut was found to have little measurable effect on the transition from stratified to slug flow. Water cut was found to have little effect on the transition from slug to annular flow. Increasing pressure caused the stratified to slug transition to occur at slightly higher liquid flow rates. The transition from slug to annular flow was found to not be largely dependent on the inclination. Increasing pressure caused the annular transition to occur at lower gas flow rates.

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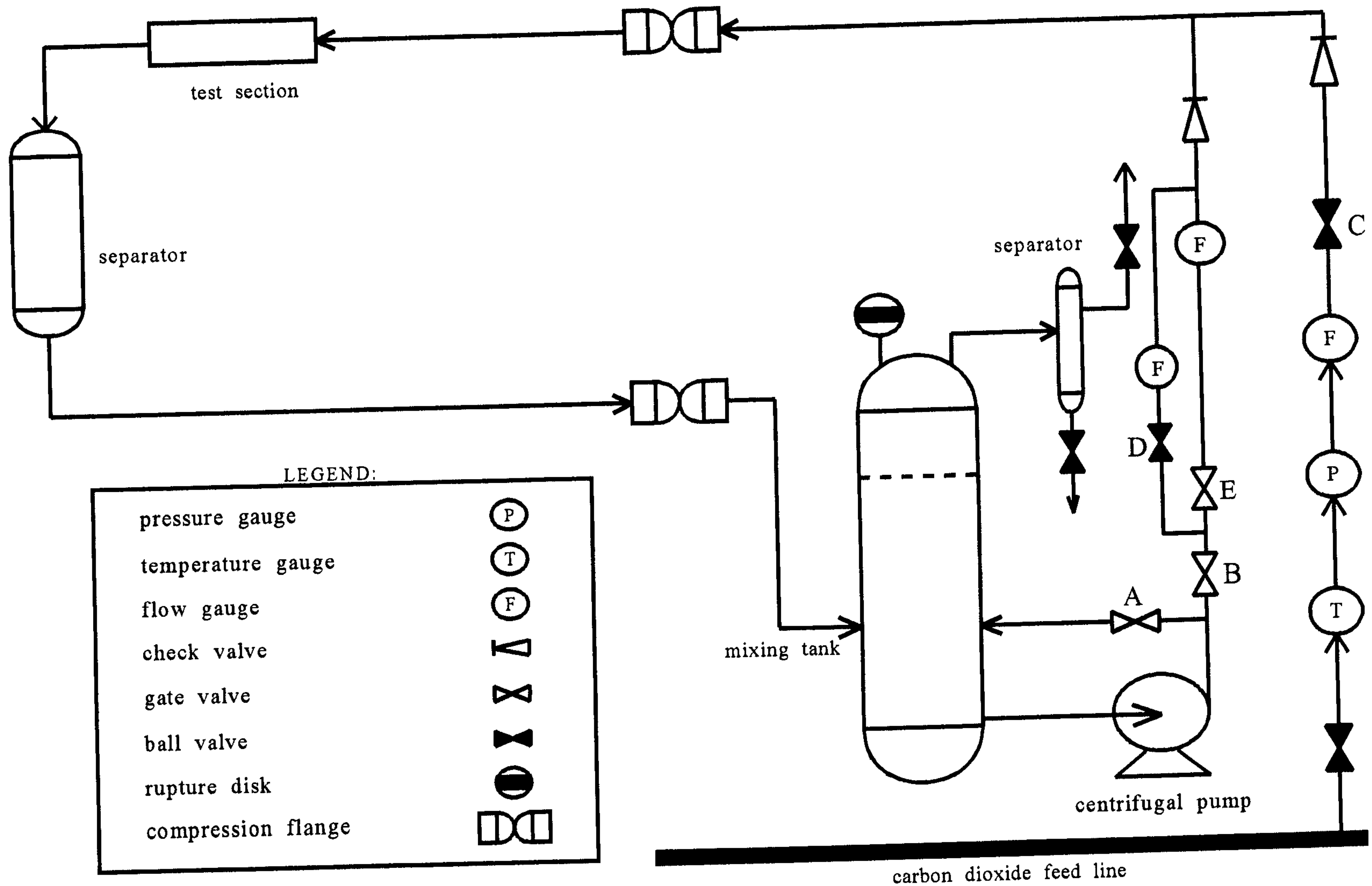
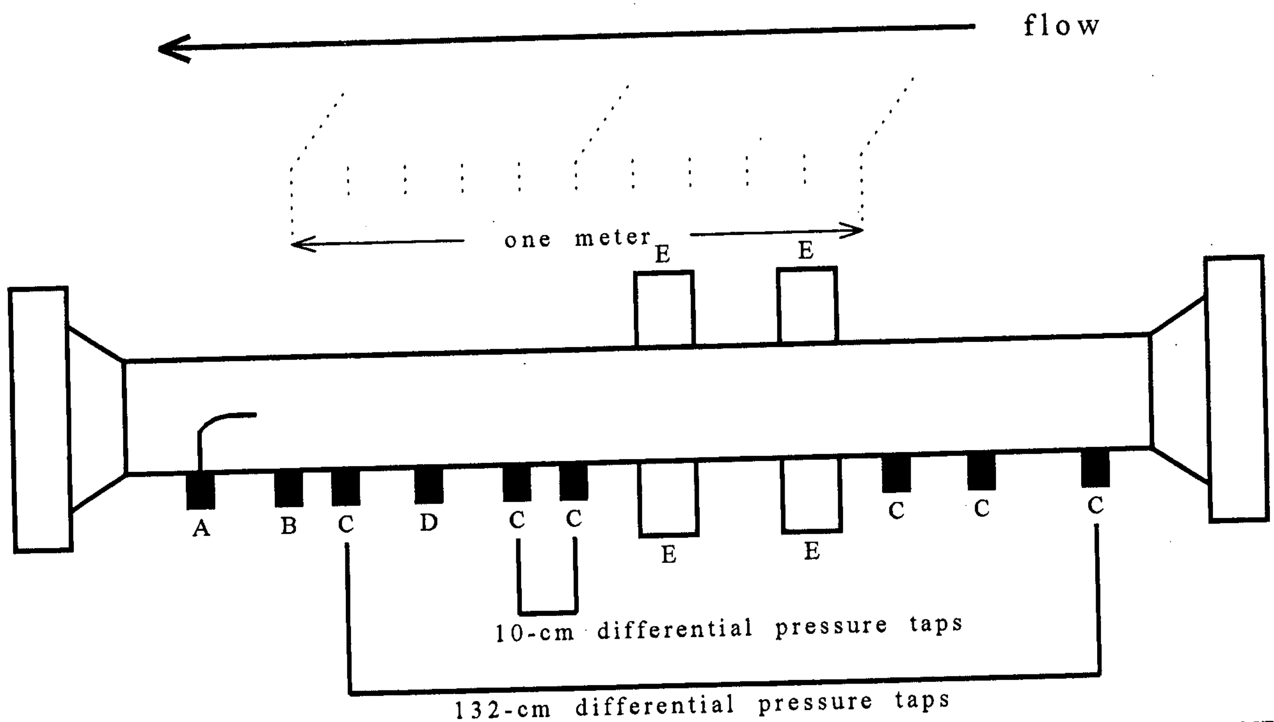


Figure 1: High-pressure, inclinable flow loop orientation.



LEGEND:

void fraction port	A
thermocouple port	B
differential pressure tap	C
system pressure/shear stress port	D
corrosion probe insertion port	E

Figure 2: Diagram of the test section.

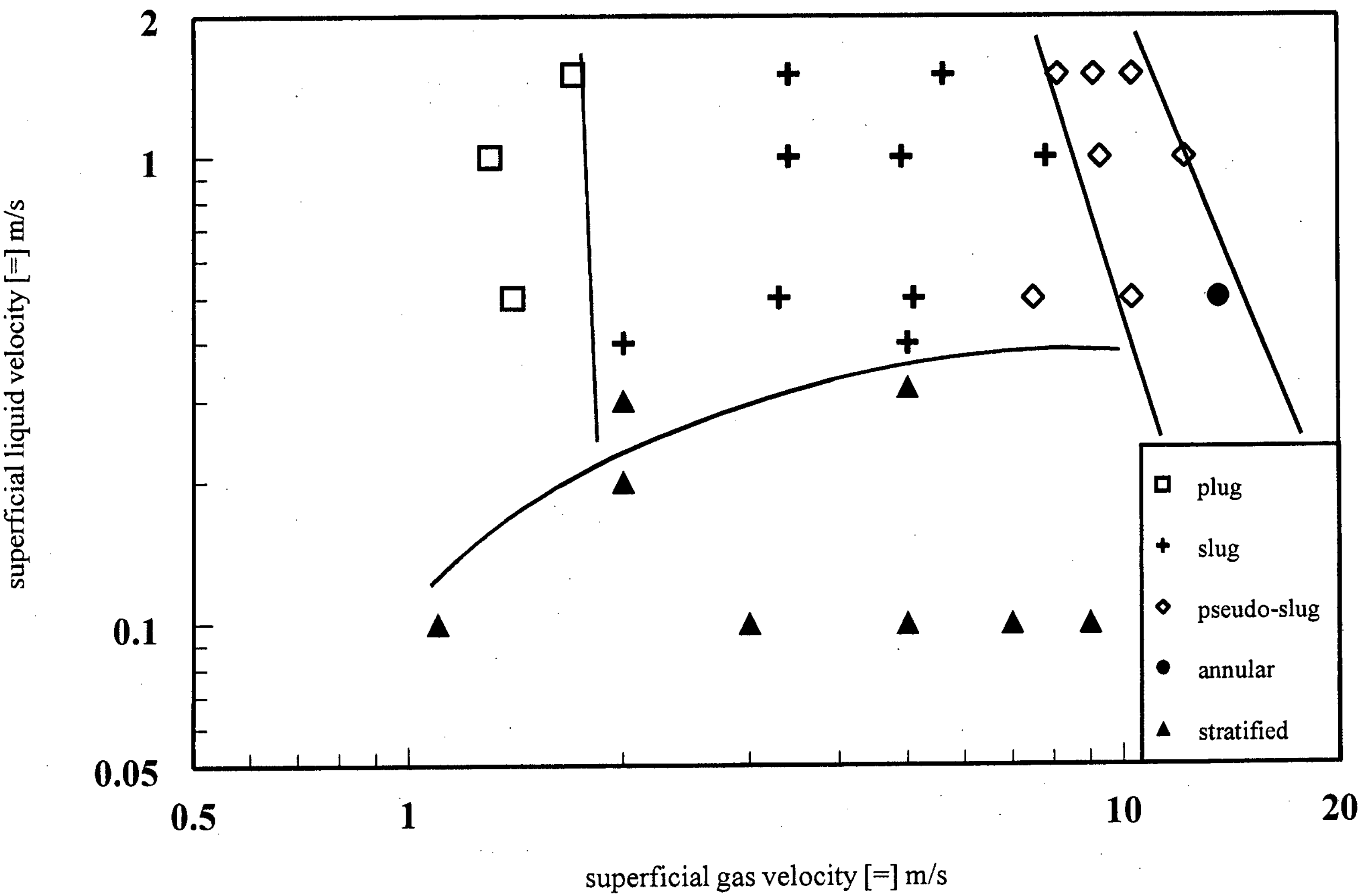


Figure 3: Flow regime map for 100% saltwater at 0.45 MPa and horizontal.

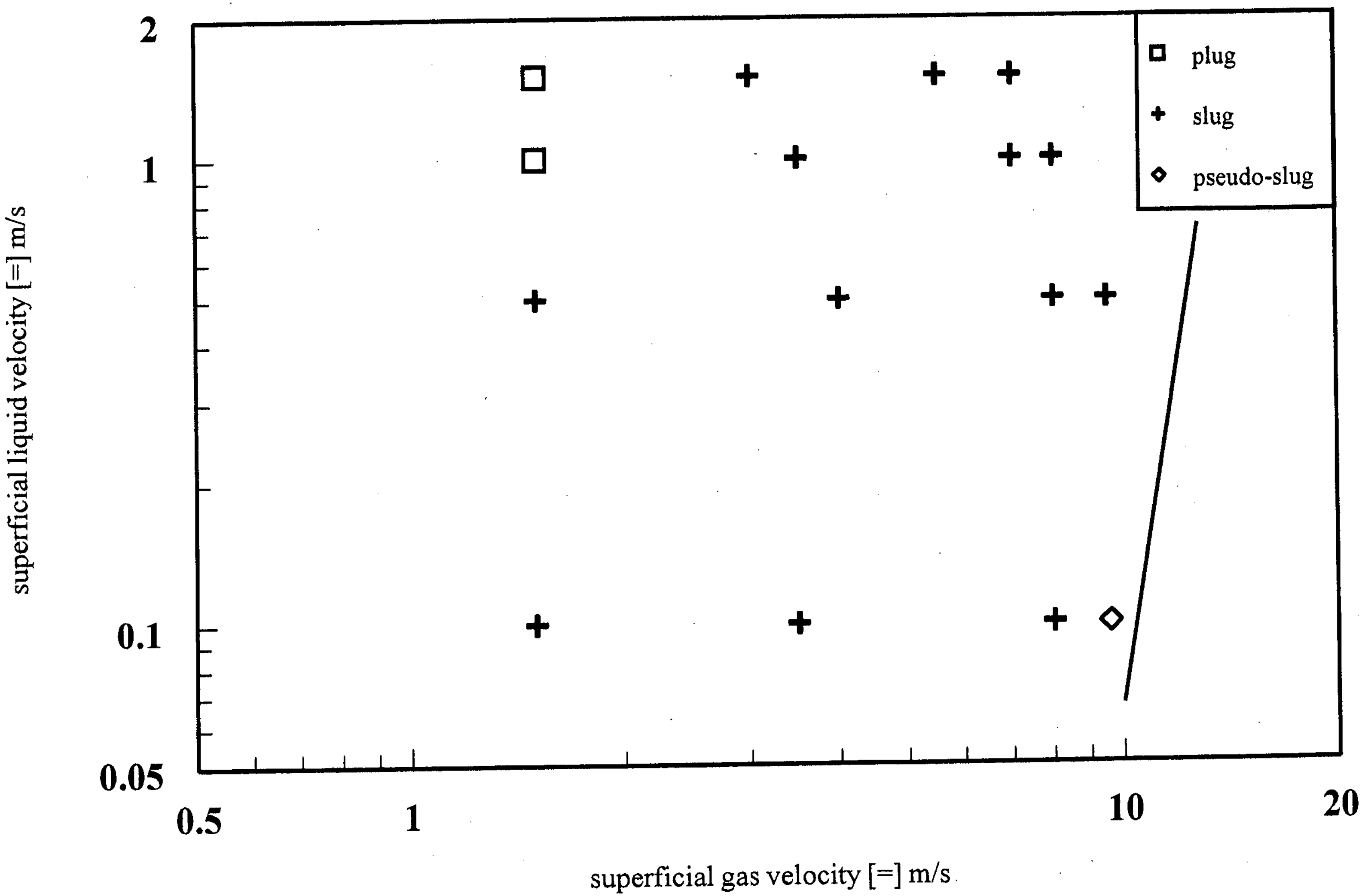


Figure 4: Flow regime map for 100% saltwater at 0.27 MPa and +5° inclination.

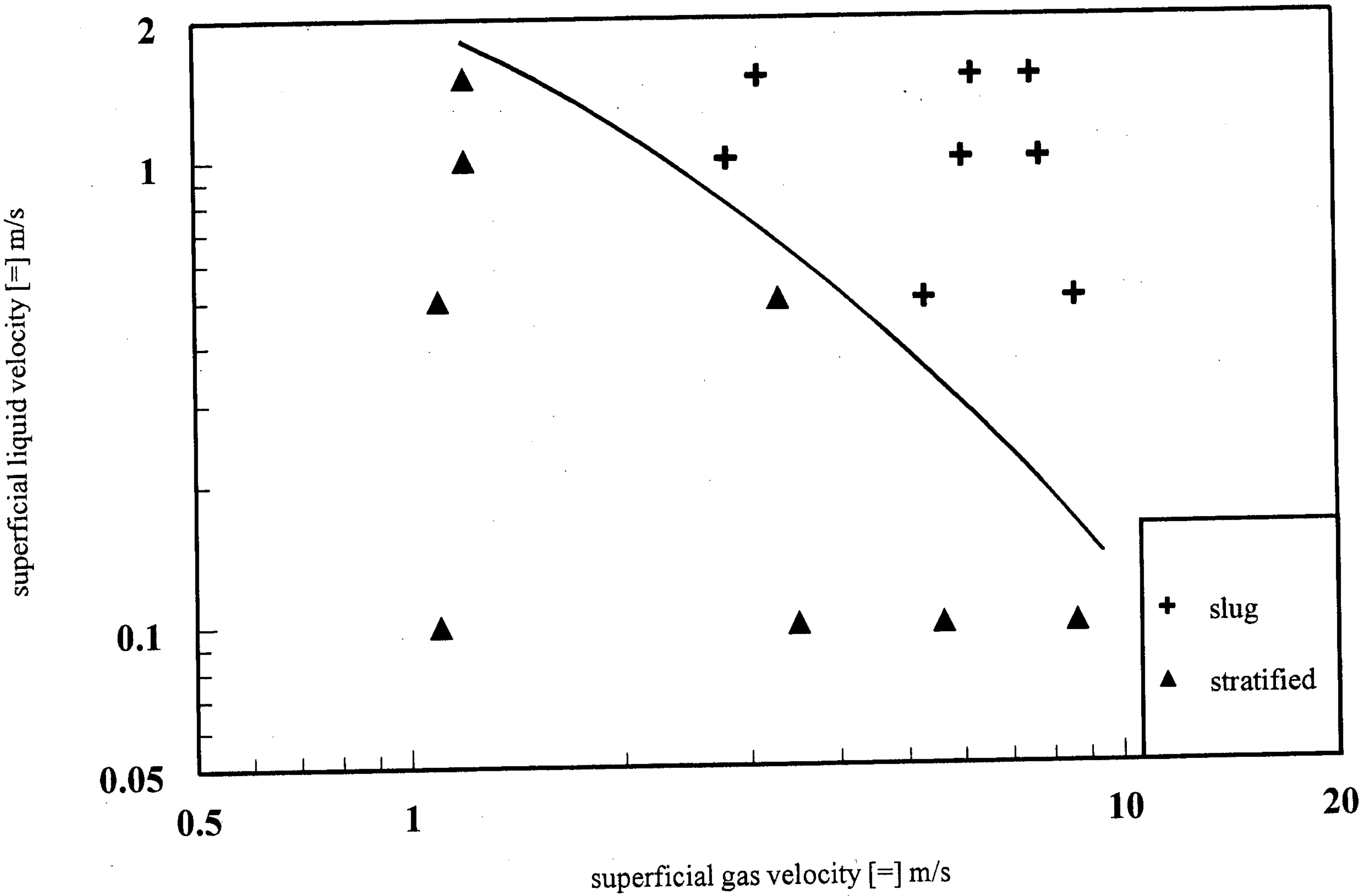


Figure 5: Flow regime map for 100% saltwater at 0.45 MPa and -2° inclination.

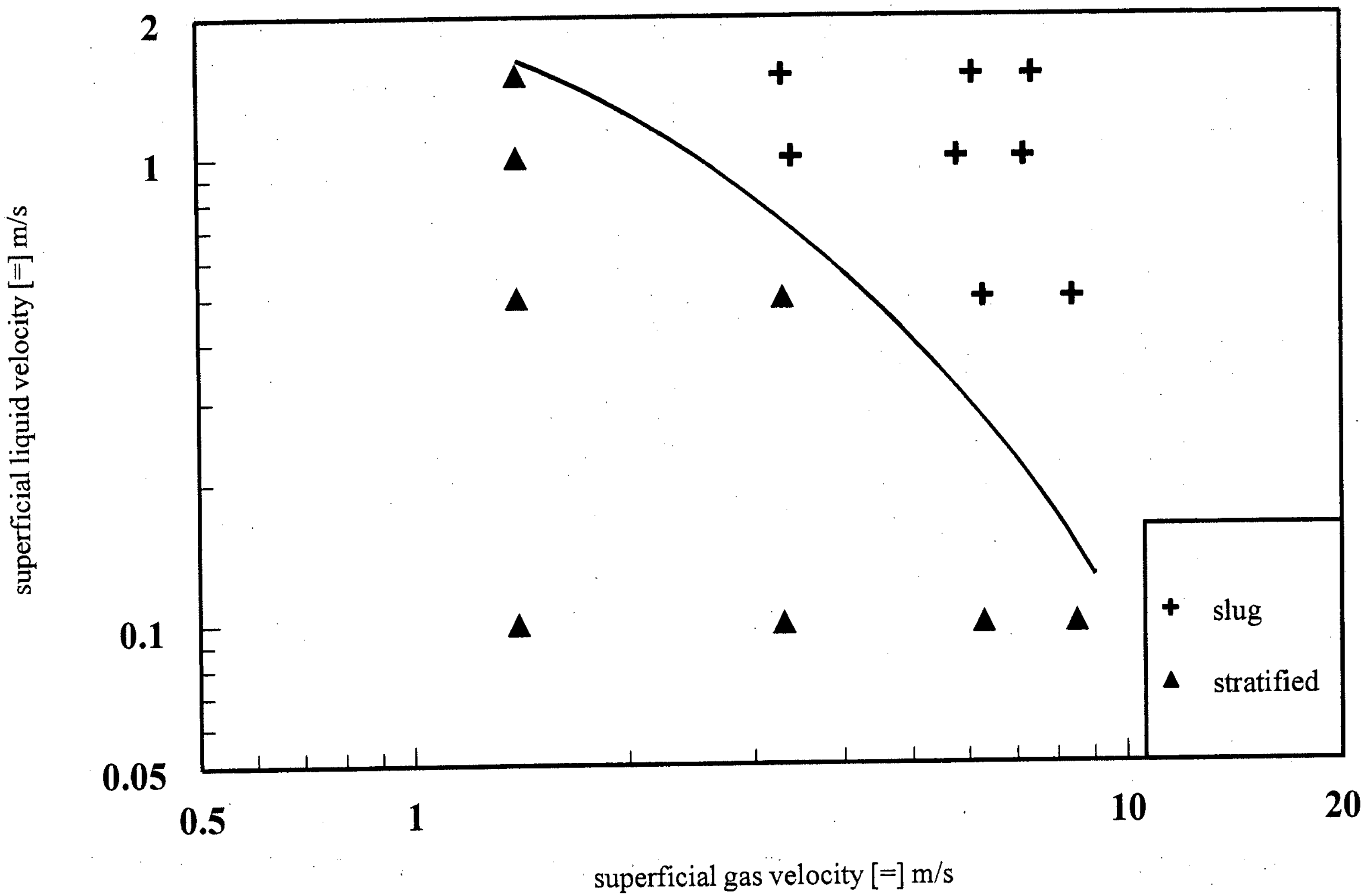


Figure 6: Flow regime map for 80% saltwater/20% light oil at 0.27 MPa and -2° inclination.

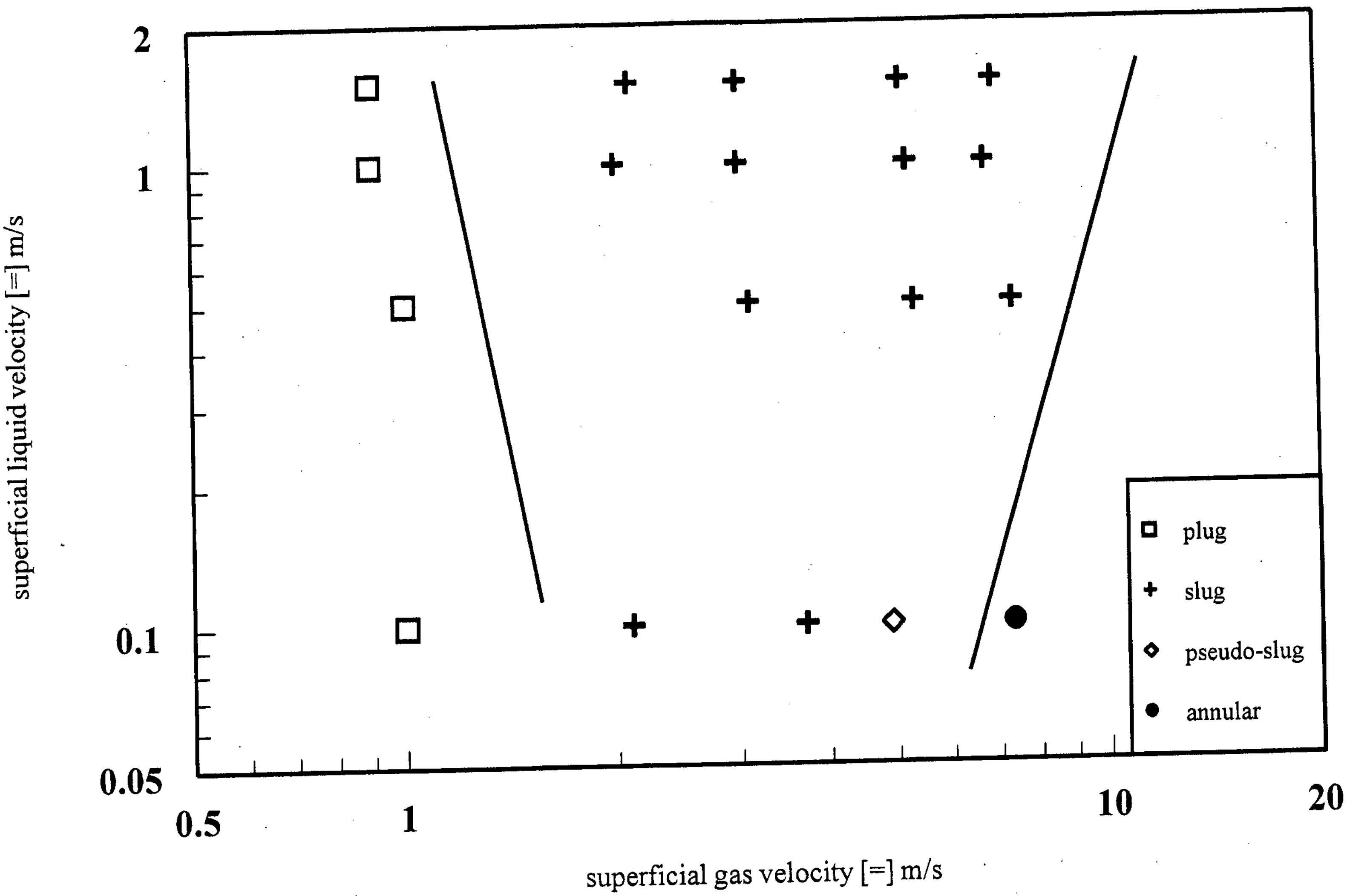


Figure 7: Flow regime map for 100% saltwater at 0.79 MPa and +5° inclination.