

# Investigation of Flow Regime Transitions in Large-Diameter Inclined Pipes

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*Multiphase oil/water/gas flow regime transition studies are carried out in a 10-cm i.d., 18-m long pipe at inclinations of  $\pm 2$  deg at system pressures between 0 to 0.79 MPa. The results are compared to those of other researchers, and the effects of pressure, inclination, and liquid viscosity are shown. The water cut of the liquid has some effects on the transition from stratified to slug flow. Increasing the water cut results in the transition occurring at higher liquid velocity at the same gas velocity. Water cut has little effect on the slug/annular transition for low viscosity oil used. The system pressure has a moderate effect on the transition from stratified to slug and slug to annular. For the transition from stratified to slug, increasing the system pressure requires higher liquid velocity. The transition from slug to annular occurs at lower liquid velocity with increasing the system pressures. The inclination of the pipe has little effect on the transition from slug to annular flow. Increasing the inclination causes the transition to occur at approximately the same gas velocity at the same liquid velocity. The experimental results show a good agreement with Wilkens' model.*

## Introduction

Multiphase flow pattern prediction has many design applications. One of the most important is the oil and natural gas pipeline. Knowledge of the flow pattern is very important to understand the underlying fluid mechanics in multiphase flow. Given an exact set of conditions with fully developed flow and no terrain-induced flow effects, a particular flow pattern will occur. Many researchers have attempted to produce a way to report all of the necessary information to correlate the flow transitions.

To create a successful flow regime transition model, data is necessary for validation. The key parameters to observe are fluid properties, inclination, pipe diameter, and system pressure. In the literature, there are many flow regime data for horizontal and vertical flows, but limited flow map data exist for inclined pipelines, especially for flow in large-diameter pipes. This work reports more flow regime data, which include the effects of inclination, pressure, and diameter and liquid viscosity on oil/water/gas three-phase flow in large-diameter pipelines.

## Experimental Setup

Figure 1 shows the experimental setup of the flow loop. The entire system is made of 316 stainless steel and is designed to withstand a maximum pressure of 12 MPa. The volume of the tank is 1.44 m<sup>3</sup> and is filled with oil-water mixtures of specified water cuts. The fluid is pumped through a 7.62-cm i.d. stainless steel pipe and is metered using turbine flow meters; carbon dioxide gas from high-pressure storage tanks is introduced into the system and the gas velocity is measured using in-line flow meters. The multiphase mixture then flows through a 10-cm i.d. stainless steel test section where all the measurements are made. The gas-liquid mixture reenters the tank at the top through the pipeline. A de-entrainment plate is used to separate the gas and liquid. The gas is vented to the atmosphere and the liquid is

recycled. When the system is inclined, measurements in both upward and downward flows can be made at the same time. A back-pressure regulator is fitted on the top of the tank and is connected to the exhaust to control and maintain the required system pressure.

The flow patterns were determined with a technique using differential pressure fluctuations. The measurements were made with 0 ~ 35 KPa OMEGA PX-750 heavy-duty differential pressure transducers.

In this study, carbon dioxide was used for gas phase. Oil with a viscosity of 2 cp at 40°C and water were used for the liquid phases. The superficial gas velocity was varied from 0 ~ 17 m/s, while the superficial liquid velocity ranged from 0 ~ 2.5 m/s; The system temperature remained constant at 25°C, and the system pressure varied up to 0.79 MPa.

## Flow Pattern Transition Modeling

Wilkens (1997) developed a mechanistic model for predicting the transition from stratified to slug flow in three-phase large-diameter pipelines. The model includes the effect of inclination and pressure. The basis for the stratified to slug transition model is the coexistence of stratified flow and slug flow. This approach stems from the ideas expressed by Jepson (1989).

Wilkens (1997) also developed ideas for predicting the transition from slug to annular flow. Previous researchers have demonstrated the presence of secondary flows, wave spreading, droplet deposition, etc., in describing annular flow. The basis for this slug to annular transition model is the coexistence of annular and slug flows. The model also incorporated other criteria, such as a maximum film Froude number, maximum slug body void fraction, and the liquid holdup in the slug becoming equal to the liquid area in the film region. In addition to these, a criteria was developed based on the minimization of pressure drop.

Neogi et al. (1994) noted that in both annular flow and slug flow, the oil and water are completely mixed. For this reason, the equation for two-phase flow can be used here as well. Lin (1985) suggested that annular flow can be reached when the film was spread completely around the pipe. In this case, the gas-liquid interface is quite rough and liquid has spread completely around the pipe, although the thickness may be only 1

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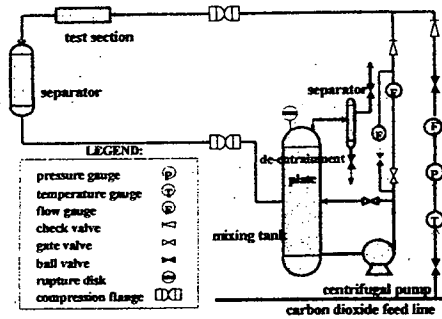


Fig. 1 High-pressure, inclinable flow system process flowsheet

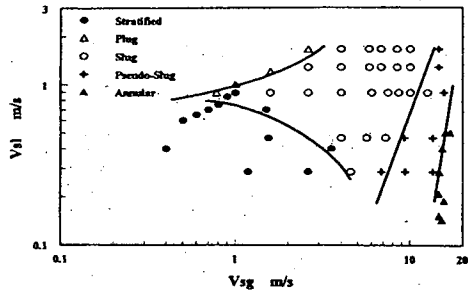


Fig. 2 Flow regime at 100 percent water cut, -2 deg and 0.13 MPa

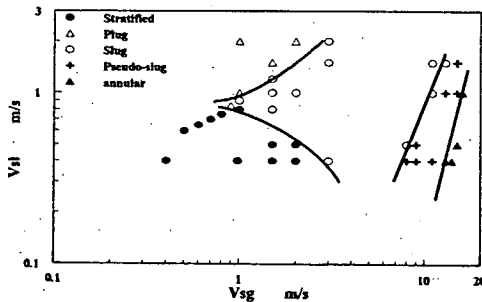


Fig. 3 Flow regime at 50 percent water cut, -2 deg and 0.13 MPa

Figure 6 illustrates the transitions from slug to annular flow at different water cuts at 0.13 MPa, at an inclination of  $-2$  deg. It is seen that there is little effect of water cut in the slug-annular transition. The results are similar to those observed by Maley (1997).

**Upward Flow.** Figures 7, 8, and 9 are flow regime maps for water cuts of 100, 50, and 0 percent, in  $+2$  deg upflow at 0.13 MPa. Slug flow is the main flow pattern, and no stratified flow occurs at the conditions tested. The results are similar to those of other researchers. At low liquid and gas superficial velocities, plug flow occurs. Upon increasing the gas velocity,

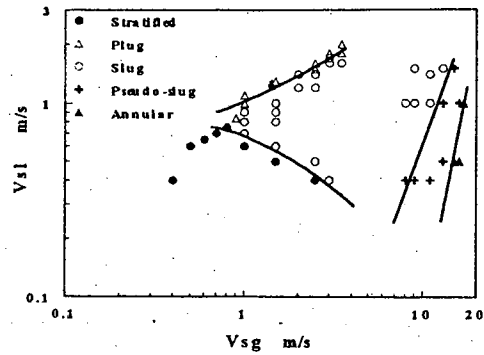


Fig. 4 Flow regime at 0 percent water cut, -2 deg and 0.13 MPa

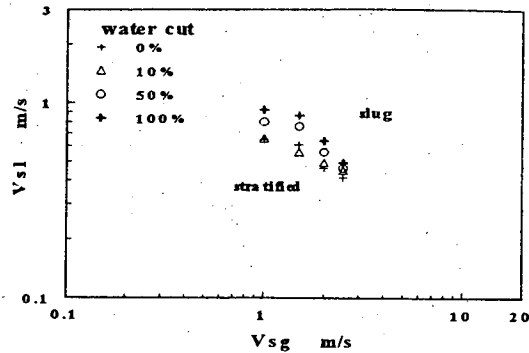


Fig. 5 Transition from stratified to slug at different water cuts, -2 deg and 0.13 MPa

to 2 mm at the top. For Wilken's model, the annular film is considered to spread just enough that it meets at the top of the pipe.

## Results and Discussion

**Downward Flow.** Figure 2, 3, and 4 are flow regime maps for water cuts of 100, 50, and 0 percent, in  $-2$  deg downflow at 0.13 MPa, respectively. It is noted that the transitions are similar at each water cut. The results are also similar to those of Mantripragada (1998). Comparing the flow regime maps, it is seen that water cut has an effect on the stratified to slug transition. Figure 5 is a plot of the stratified-slug transition at different water cuts. It shows that as the water cut is increased, the transition occurs at higher superficial liquid velocities at the same superficial gas velocity. This is due to the decrease in liquid viscosity and these results are similar to those of Hanratty (1987).

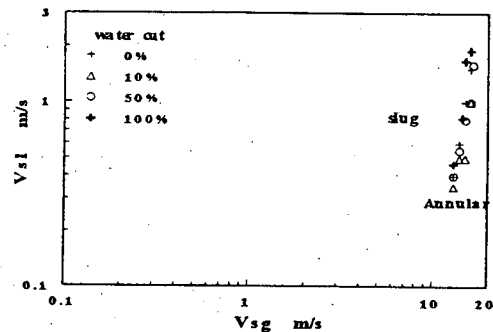


Fig. 6 Transition from slug to annular at different water cuts, -2 deg and 0.13 MPa

## Nomenclature

$T$  = temperature,  $^{\circ}\text{C}$   
 $V_{sg}$  = superficial gas velocity, m/s

$V_{sl}$  = superficial liquid velocity, m/s

$P$  = system pressure, MPa

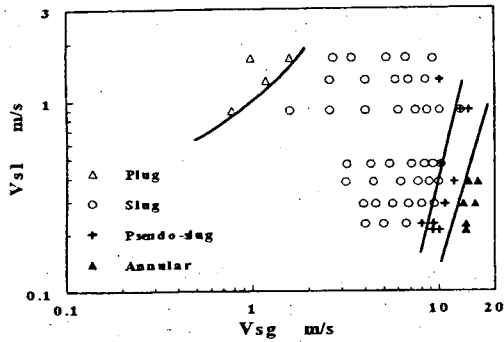


Fig. 7 Flow regime at 100 percent water cut, +2 deg and 0.13 MPa

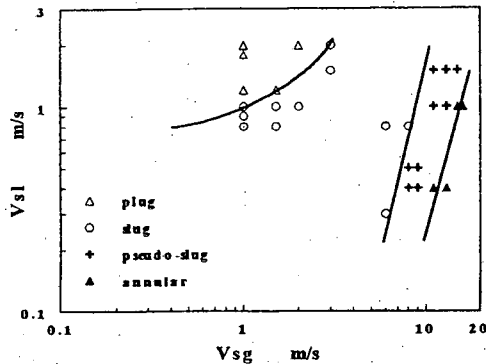


Fig. 8 Flow regime at 50 percent water cut, +2 deg and 0.13 MPa

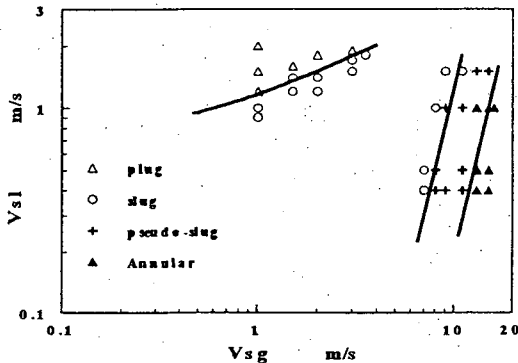


Fig. 9 Flow regime at 0 percent water cut, +2 deg and 0.13 MPa

the slug flow regime is reached. At even higher gas flow rates, pseudo-slug flow will occur. Annular flow occurs at the highest gas velocities with the denser fluid flowing as an annular ring around the pipe wall.

Figure 10 shows the transition from slug to annular at different water cuts at the conditions of system pressure 0.13 MPa, an inclination of +2 deg. Water cuts have little effect on the transition.

**Effect of System Pressure.** Now consider the effect of system pressure on the transition from stratified to slug flow. Figure 11 shows the transition for different system pressures, at a water cut of 100 percent, at an inclination of -2 deg. Increasing the system pressure causes the transition to occur at higher liquid superficial velocity at the same superficial gas velocity. This is because at a higher pressure, the gas wall friction factor is increased. This causes more momentum to be lost to the wall and a higher liquid velocity is sustained. Also, the liquid level will decrease with increasing system pressure

at the same gas and liquid velocities. In this case, it is difficult to make the liquid level high enough to touch the top of the pipe and finally block the pipe section. So, at the same gas velocity, increasing the system pressure, the transition from stratified to slug will occur at higher liquid velocity.

Figure 12 shows that the transition from slug to annular flow at the conditions of different system pressures, water cut 100 percent, at an inclination of -2 deg. Increasing the system pressure causes the transition to occur at a lower liquid velocity at the same superficial gas velocity. This is due to the increased liquid shear stress because of higher gas density. So, the system pressure has some effects on the transitions from stratified to slug and slug to annular flow.

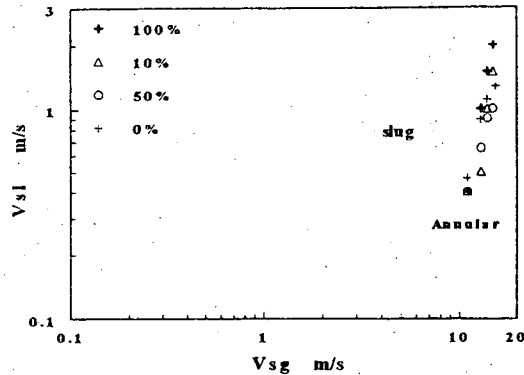


Fig. 10 Transition from slug to annular at different water cuts, +2 deg and 0.13 MPa

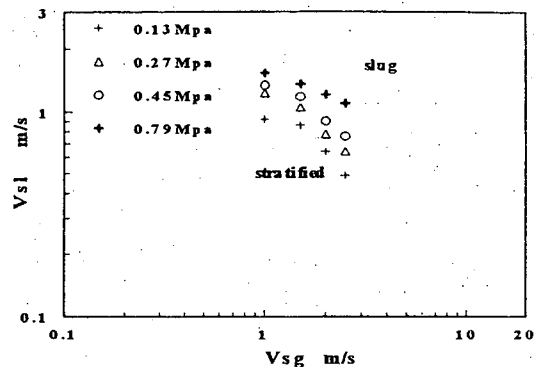


Fig. 11 Transition from stratified to slug at different pressures, -2 deg and 100 percent water cut

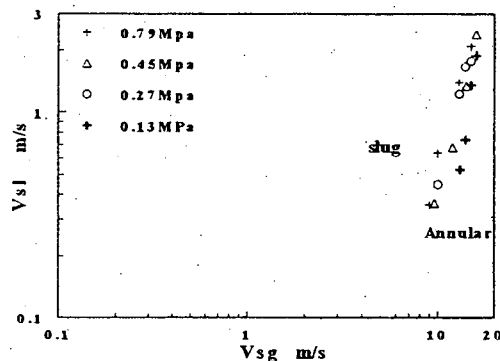


Fig. 12 Transition from slug to annular flow at different pressures, -2 deg and 100 percent water cut

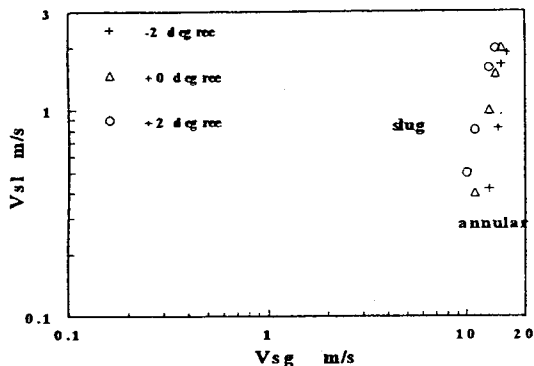


Fig. 13 Transition from slug to annular at different inclinations, 100 percent water cut and 0.13 MPa

**Effect of Inclination.** Figure 13 illustrates the transition from slug to annular flow at different inclinations, for a water cut of 100 percent and pressure 0.13 MPa. Increasing the inclination of the pipe results in the transition occurring at approximately same gas velocity at the same liquid superficial velocity. The inclination has little effect on the transition from slug to annular flow in large-diameter pipelines. Maley (1997) obtained the same conclusion from her experiments. This can be explained as follows: it is well known that the gas velocity is much faster than the liquid velocity in downward flow. Compared to the upward flow, at the same gas and liquid velocities, it is more difficult to reach slug flow in downward flow. This is because the height of the liquid film is reduced; consequently, it is more difficult for the liquid to touch the top of the pipe and block the pipe cross section. Also, gravity will accelerate the liquid and causes it to flow faster and prevent the liquid from accumulating. However, once slug flow is formed, the transition from slug to annular flow is controlled by gas entrainment, which is controlled by the maximum amount of gas that can be held within the slug. In this case, inclination has little effect on gas entrainment in slightly inclined pipelines. Crowley et al. (1986) also pointed out that the transition from slug to annular depended on gas velocity and was independent of inclination in horizontal and slightly inclined pipelines.

**Comparison With Models.** Figure 14 illustrates the comparison between the experimental results and Wilkens' model (1997) and Taitel-Dukler's model (1976) at the conditions of water cut 100 percent, system pressure 0.13 MPa, and pipe inclination  $-2$  deg. At low gas flow rates (less than 3 m/s), both models predict the transition reasonably well. Above a superficial gas velocity of 3 m/s, Taitel-Dukler's model (1976) significantly underpredicts the transition line. For exam-

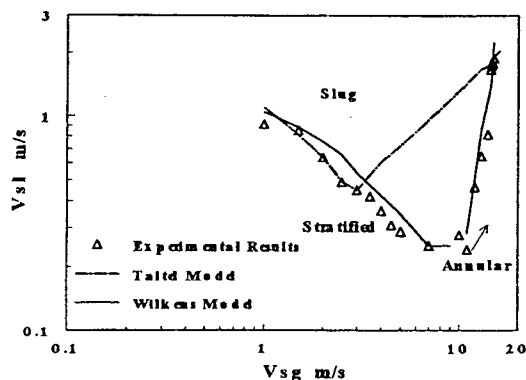


Fig. 14 Comparison of experimental results with the predicted models at 100 percent water cut,  $-2$  deg and 0.13 MPa

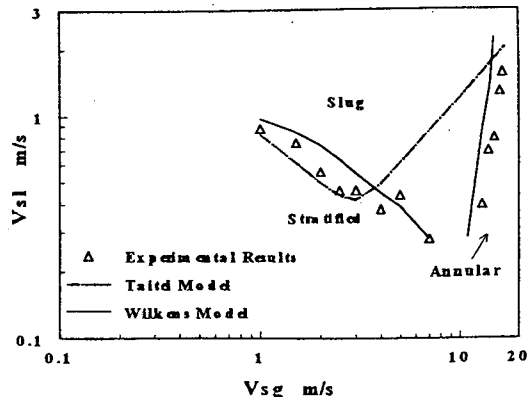


Fig. 15 Comparison of experimental results with the predicted models at 50 percent water cut,  $-2$  deg and 0.13 MPa

ple, the transition to slug flow is predicted at a superficial liquid velocity as low as 0.25 m/s at a superficial gas velocity of 7 m/s. Slug flow would clearly not occur at a lower liquid flow rate than it did in horizontal flow. Kokal et al. (1989) also pointed out that Taitel-Dukler's model was not suitable for predicting the transition from stratified to slug flow at higher gas flow rate. The Wilkens (1997) model, however, adequately predicts the transition line in all cases. The Taitel-Dukler (1976) model poorly predicts this transition from slug to annular flow. This is a well-known limitation of the Taitel-Dukler model (1976). The Wilkens (1997) model compares with the experimental results very well.

Figure 15 shows the comparison between the experiments and the results predicted by Taitel-Dukler's model and Wilkens' model at the conditions of 50 percent water cut, 0.13 MPa, and  $-2$  deg inclination. The experiments compare with the results predicted by both models at low gas rates. Above a gas flow rate 3 m/s, the experiments deviate from the results predicted by the Taitel-Dukler (1976) model. For example, stratified-slug transition is predicted at a superficial liquid velocity as low as 0.23 m/s at a superficial velocity of 7 m/s. The Wilkens (1997) model, however, predicts the transition reasonably. For the transition from slug to annular flow, the experiments compare well with the results predicted by the Wilkens (1997) model, and deviate from that predicted by the Taitel-Dukler model (1976).

## Conclusion

New experimental results were obtained for oil/water/gas three-phase flow in large-diameter inclined pipelines. Based on the experimental data, the following conclusions are made.

The water cut of the liquid has some effects on the transitions from stratified to slug. Increasing the water cut causes the transition to occur at higher liquid velocity at the same gas velocity. However, water cut has little effect on the slug-annular transition for this oil/water mixture.

The system pressure has a moderate effect on the transition from stratified to slug and slug to annular. For the transition from stratified to slug, increasing the system pressure causes the transition to occur at higher liquid velocity at the same gas velocity. The transition from slug to annular flow occurs at lower gas velocity at the same liquid velocity. The inclination of pipe has little effect on the transition from slug to annular flow. Increasing the inclination causes the transition to occur at approximately the same gas velocity at the same liquid velocity.

The Wilkens model compares with the experimental results very well. The Taitel-Dukler model (1976) predicts the transition from stratified to slug well at low gas and liquid velocities, but not well for higher gas and liquid velocities, and it predicts poorly the transition of slug to annular flow.

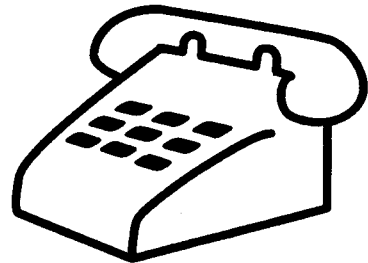
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