Int. J. Multiphase Flow Vol. 13, No. 4, pp. 549–563, 1987
Printed in Great Britain.

0301-9322/87 $3.00 + 0.00

EFFECT OF PIPE DIAMETER ON FLOW PATTERNS FOR AIR–WATER FLOW IN HORIZONTAL PIPES

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(*Received* 23 *May* 1985; *in revised form* 15 *October* 1986)

Abstract—New results are presented on interfacial patterns observed for air and water flowing in horizontal 2.54 and 9.53 cm pipelines close to atmospheric conditions. This work differs from previous studies in that measurements of pressure fluctuations at two locations separated in the streamwise direction are used to detect slugs. The liquid flow needed to initiate slugs at low gas velocities is strongly affected by pipe diameter and appears to depend on a linear instability. At high gas velocities the transition is approximately independent of pipe diameter and is explained by a nonlinear mechanism associated with the coalescence of roll waves. The initiation of slugs in the annular flow regime is determined to occur at much lower liquid flows than had been reported by previous investigators. The transition from stratified to annular flow is different in smaller-diameter pipes than in larger pipes because wave wetting plays a more important role.

1. INTRODUCTION

A number of different patterns are observed when gas and liquid flow through a horizontal pipe. At low liquid throughputs transitions from stratified-wavy to annular flow occur with increasing gas throughputs. An increase of liquid flow causes a transition to an intermittent slug flow, which is accompanied by large, undesirable pressure pulsations.

The most common correlation used to calculate the conditions for the transition from one flow regime to another is the Mandhane plot (Mandane *et al.* 1974). The general consensus is that this plot is most reliable for air and water flowing in a small-diameter horizontal pipe. There is, therefore, a need to carry out systematic studies of the effect of pipe diameter on the type of flow regime. This is underscored in the recent work of Taitel & Dukler (1976). They suggested a mechanistic approach, which uses dimensionless groups, and found a strong effect of pipe diameter on the transition from stratified to slug flow.

This paper presents results of a study on the flow patterns that exist for air and water in horizontal 2.54 and 9.53 cm i.d. pipelines at near atmospheric conditions. The goals were to examine the reliability of the Mandhane plot and to see if the mechanism of transition from one regime to another changes in a large-diameter pipe.

The regions of the Mandhane flow-pattern map for which there appears to be considerable disagreement amongst different investigators are the transition from annular to slug flow and the definition of the region near the intersection of the curves representing the annular slug, stratified slug and stratified annular transitions. This latter ambiguity has been recognized by Nicholson *et al.* (1977) by defining a "proto-slug" regime and by Barnea *et al.* (1980) by defining a "wavy-annular" pattern.

The reason for the apparent disagreement among various researchers arises, primarily, because flow regimes have been defined mainly by visual observations. Such determinations become subjective at high gas velocities. Some time ago, Dukler & Hubbard (1975) recognized this difficulty and suggested that measurements of pressure fluctuations be used to characterize flow regimes. An important aspect of this work is that a modification of the technique proposed by Dukler & Hubbard is used to define, in a precise way, the conditions under which slugs are present. Another paper by the authors (Lin & Hanratty 1987) gives a detailed description of this detection technique.

A slug is defined in this work as a mass of liquid (often highly aerated) which blocks the cross section of the pipe, which keeps its coherency throughout its passage in the pipe, and which moves approximately at the gas velocity. The pressure of the gas behind a slug is much larger than the pressure of the gas in the front. Therefore, the measurement of the time variation of the pressure at a given location in the pipe identifies a blockage by a sudden large increase in the pressure. The permanence of this blockage and the slug velocity are determined by making simultaneous measurements of the time-varying pressure at a location downstream.

2. DESCRIPTION OF EXPERIMENTS

The experiments were performed in the gas–liquid flow facility described by Laurinat *et al.* (1984). Tests were conducted in two horizontal pipes, with i.d. 2.54 and 9.53 cm and lengths of 15.5 and 24.6 m, that empty into a separator at atmospheric pressure. Both pipelines were constructed of clear Plexiglas sections in order to facilitate visual observation of how a flow evolves along the pipe. The pipes were carefully leveled because of the sensitivity of flow-regime transitions to pipeline inclination (Barnea *et al.* 1980).

The entry sections for the two phases were simple pipe tees with air introduced in the branch and water in the run. [Weisman *et al.* (1979), Reiman *et al.* (1981) and Simpson *et al.* (1981) found no effect of different entry designs on flow transitions.] In the present study some experiments were repeated with water introduced in the branch and air in the run. Results were the same except for the stratified/slug transition at $V_{SG} < 1$ m/s.

The heights of the waves on the stratified liquid layer were measured with parallel wire conductance probes similar to those used by Laurinat *et al.* (1984) except that the parallel wires extend vertically across the entire pipe section. A second set of parallel wires were located 26.9 cm downstream from the first set in the 9.53 cm pipe (25.4 cm downstream in the 2.54 cm pipe) to determine the wave/slug velocity. A similar technique was used to determine the variation of liquid film thickness around the circumference of the pipe. In this case, the parallel wires protrude for only a short distance into the pipe. A total of four such sets of probes were used for one pipe size, each being placed at 45° intervals along a half-pipe circumference starting from the top of the pipe. The signals from all four probes were recorded simultaneously.

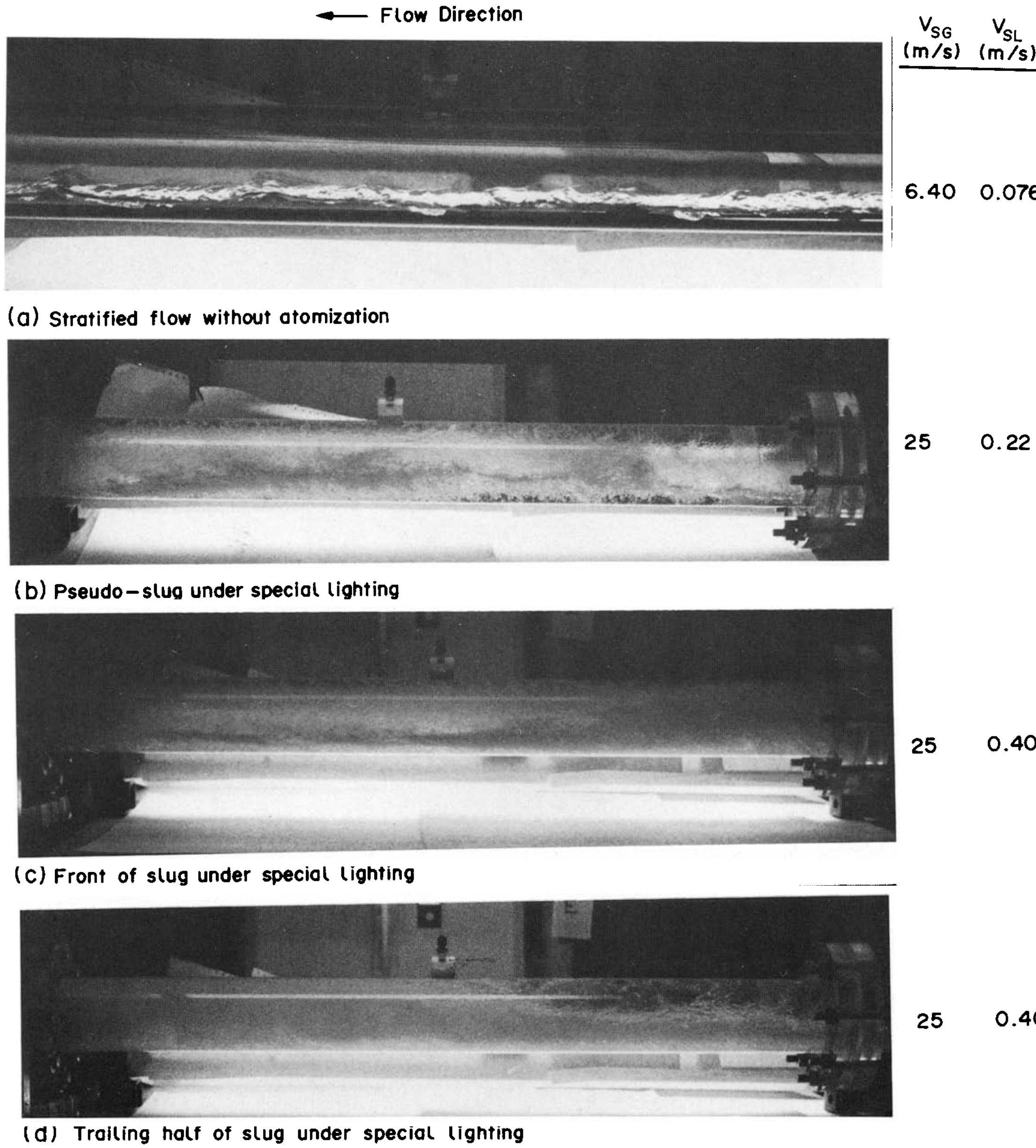
The occurrence of slug flow was detected with the use of two fast-response Viatran Corp. Model 218 strain gauge pressure transducers. The pressure transducers have a frequency response of up to 2 kHz. They were placed 1.3–5 m apart, depending on flow conditions. The pressure transducers were connected to the bottom of the pipe, filled with liquid and frequently purged of air bubbles. The procedure for using this technique to detect slugs is discussed by Lin & Hanratty (1987). A Honeywell Model 1508C Visicorder was used to record signal traces. This recorder produces traces by deflecting high-intensity light beams focused on a light-sensitive chart at frequencies up to 1 kHz. Analog signals from the electronic devices were also digitized and stored in a Digital Equipment Corp. LSI-11/25 microcomputer for later analysis. A/D conversions were performed by a Data Translation Inc. Model DT 2762 A/D module installed directly on the LSI-II computer bus. The A/D module is capable of performing conversions at a maximum rate of 35 kHz although the maximum sampling rate used in this study was 500 Hz per channel. The timing of the A/D coversion is controlled by a Digital Equipment Corp. KWV11-C programmable real-time clock with a crystal oscillator at 10,000 MHz base frequency.

The experimental apparatus and procedure are described in more detail in a paper by Lin (1985), which should be consulted for information not presented here.

3. DEFINITION OF FLOW PATTERNS

Stratified flow is defined as a pattern for which the liquid flows along the bottom of the pipe and air, over it. It can exist under conditions that the upper part of the pipe wall is dry, such as shown in figure 1a. At high enough gas velocities atomization of the liquid occurs and the top of the tube can be partially wetted by droplets or streaks, as shown in figures 2a, b. The wave pattern varies with liquid and gas flow rates; for low enough gas velocities the interface is smooth.

At low gas velocities slugs are easily identified from visual observations. However, as the gas velocity increases the slugs are highly aerated so it becomes difficult, from visual observations, to differentiate between a slug and a large-amplitude wave that almost, or only momentarily, touches the top of the pipe. At extremely high gas velocities the identification becomes even more difficult because droplets entrained in the gas wet the wall with a thick wavy film which impedes visual



Figures 1a–d. Flow patterns in a 9.53 cm pipe (side view).

observation. Therefore, at high gas velocities it was necessary to rely entirely upon the measurement of pressure pulsations to detect the presence of slugs.

Pseudo-slugs are identified as disturbances which have the appearance of slugs, but which do not give the identifying pressure pattern and do not travel at the gas velocity. The pseudo-slug regime resembles annular flow in that a continuous liquid film is formed on the pipe circumference; it resembles wavy-stratified flow in that a thick layer of liquid is present at the bottom of the pipe; it resembles slug flow in that large slug-like structures capable of reaching the top of the pipe are present.

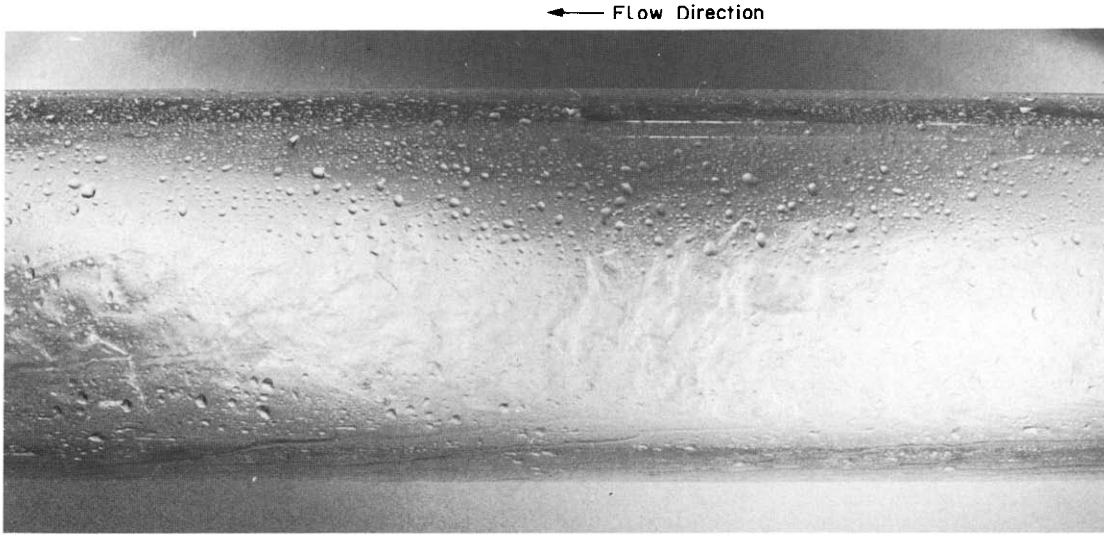
For the reasons cited above, pseudo-slugs were not easy to distinguish visually with ordinary room light. Therefore, a special lighting arrangement was used in this study. A strong light source was placed close to one side of the horizontal pipe and pictures of the flow were taken at a horizontal position on the opposite side of the pipe.

Figure 1b shows a pseudo-slug photographed in this manner in the 9.53 cm pipe at a superficial gas velocity, V_{SG}, of 25 m/s. The photograph suggests that the pseudo-slug consists of large, ill-defined waves which touch the top wall momentarily, but do not block the entire pipe cross section for an extended period of time. A large void can be seen in the upper portion of the pseudo-slug. Figures 1c,d show the front half and trailing half of a slug photographed with the same illumination. The system was operated at the same gas rate as for figure 1b, but at a high enough liquid flow rate for slugs to be present. These pictures show that slugs, unlike pseudo-slugs, fill up the entire pipe cross section.

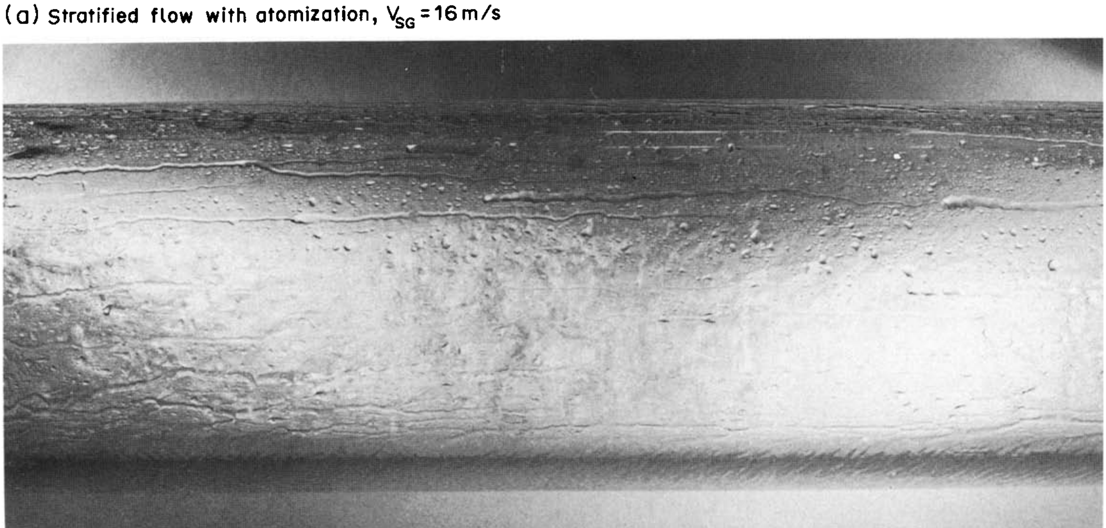
Figures 3c,d show a pseudo-slug and slug observed, with special illumination, in the 2.54 cm pipe at a lower gas velocity. Again, the pseudo-slug is observed to touch the top wall only momentarily and the slug is observed to block the entire pipe cross section. It is of interest to note that the picture of pseudo-slugs presented for the 2.54 cm pipe resembles the "disturbance wave" described by Butterworth & Pulling (1972) and the picture of a "slug" presented in figure 4 of the paper by Alves (1954).

Annular flow is considered to exist when a complete liquid annulus is formed and no slugs or pseudo-slugs are present. Figures 2c,d show the top and side views of annular flow in the 9.53 cm pipe very close to the transition gas velocity. Figure 2d shows a similarity to a stratified flow in that a thick liquid layer flows along the bottom of the pipe. Large-amplitude waves are noted, but these do not wrap around the pipe circumference. At larger liquid superficial velocities, V_{SL}, or at the same V_{SL} in a 2.54 cm pipe the waves are much larger and wrap around the entire pipe

← Flow Direction



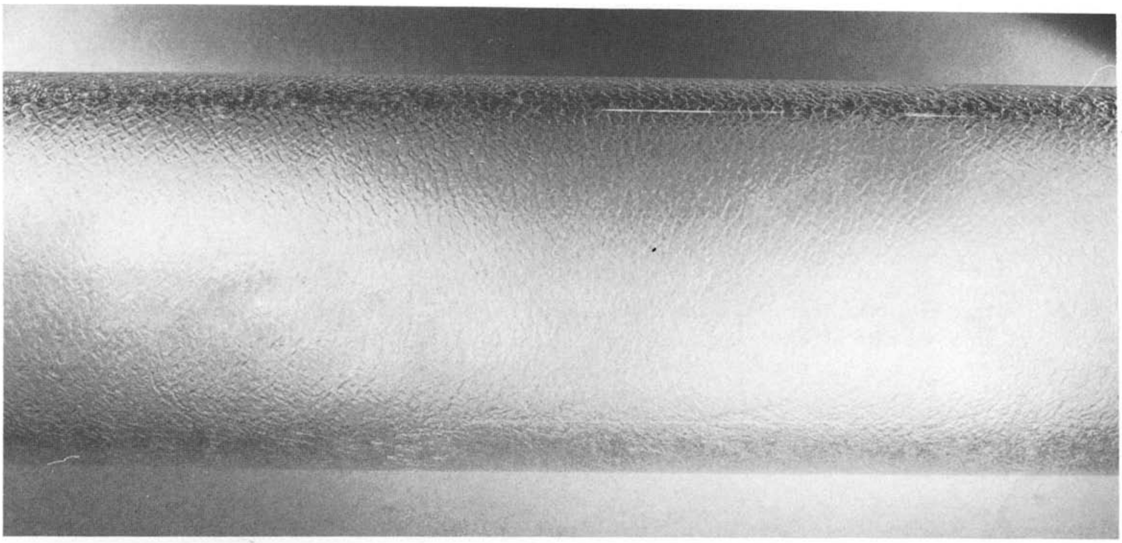
(a) Stratified flow with atomization, $V_{SG} = 16$ m/s



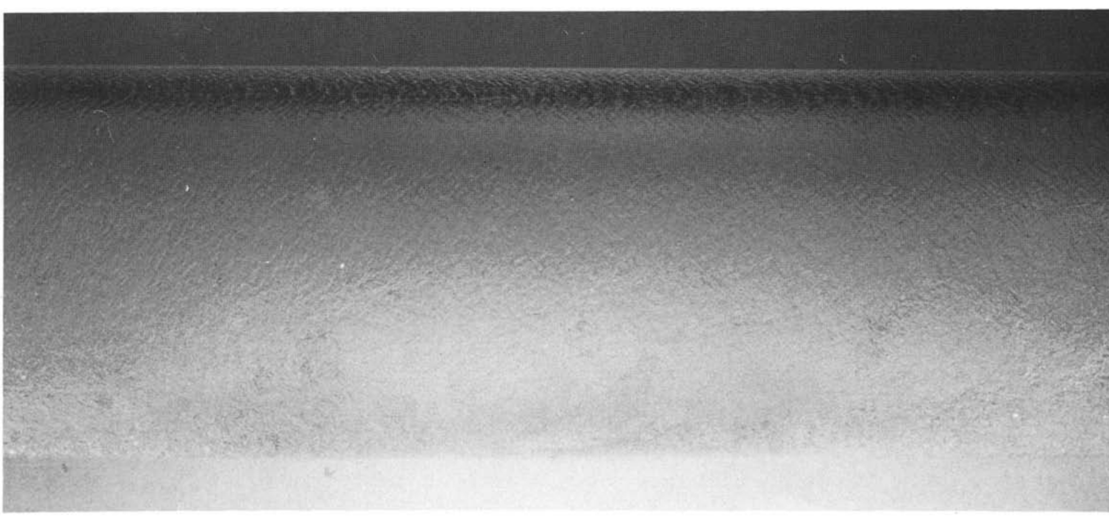
(b) Stratified flow with water streaks, $V_{SG} = 21$ m/s

Figures 2a, b

← Flow Direction



(c) Annular flow, top view, $V_{SG} = 31 m/s$



(d) Annular flow with waves at bottom portion, side view, $V_{SG} = 35 m/s$

Figures 2c, d

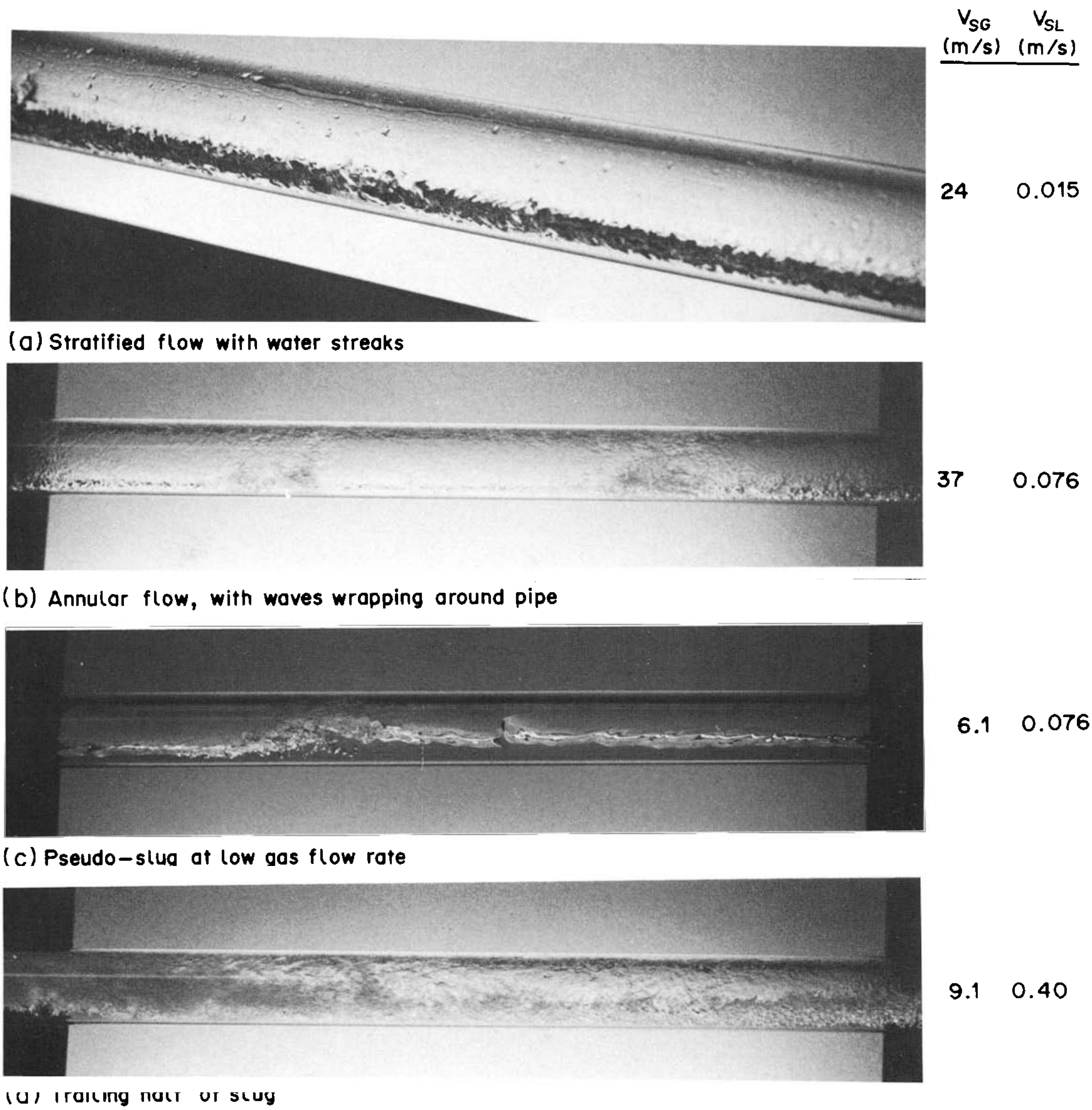
Figures 2a–d. Transition to annular flow in a 9.53 cm pipe at a superficial liquid velocity of 0.076 ms (top view).

circumference. (See, for example, figure 3b.) For very high gas velocities or for the 2.54 cm pipe, the liquid is less stratified at all liquid flow rates at which an annular pattern exists.

4. MAPS OF FLOW REGIMES

The curves representing the observed flow-regime transitions for air and water in horizontal 2.54 and 9.53 cm pipes are given in figure 4, where the ordinate is the superficial liquid velocity, V_{SL}, and the abscissa is the superficial gas velocity, V_{SG}.

No influence of pipe diameter on the transition to slug flow is observed at high gas velocities. However, in contrast to the Mandhane correlation, a very strong effect is observed at low gas velocities [as already suggested by Taitel & Dukler (1976)]. Under these conditions, hydraulic gradients exist in the liquid flowing along the bottom of the pipe (Bergelin & Gazley 1949), so the height of the liquid, h, is smaller than would exist for a fully-developed flow at given values of V_{SG} and V_{SL}. Consequently, it is probably better to correlate the results in terms of the ratio of the liquid height to the pipe diameter, h/D, rather than V_{SL}. This is done in figure 5 for $V_{GS} < 3$ m/s



Figures 3a–d. Flow patterns in a 2.54 cm pipe (side view).

for the 2.54 cm pipe and for $V_{GS} < 7$ m/s for the 9.53 cm pipe. Here it is to be noted that a plot of h/D vs $(V_{SG}/\sqrt{gD})$ $(\sqrt{\rho_G/\rho_L})$ correlates the transition results for both pipe diameters [see Lin & Hanratty (1987) for further discussion about this].

The pseudo-slug region is noted to decrease markedly in size with an increase in pipe diameter. The transition to annular flow in the 9.53 cm pipe occurs in the range of 35–70 m/s. A decrease in pipe diameter to 2.54 cm causes transition to annular flow at slightly lower gas velocities.

Two types of waves were observed in the stratified regime. At low enough gas velocities the interface is smooth. The first interfacial disturbances that appear with increasing gas velocity are long crested capillary–gravity waves. With a further increase in gas velocity roll waves, of the type described by Hanratty & Engen (1957) and Hanratty (1963), appear. Eventually, at very high gas velocities, droplets are torn from the crest of the roll wave (Woodmansee & Hanratty 1969).

If the Mandhane transitions from stratified to wavy-stratified and from wavy-stratified to annular patterns are associated with the initiation of roll waves and of atomization an approximate average agreement is noted between observations made in this laboratory (Lin 1985; Andritsos 1986) and the Mandhane correlation, except for the transition to slug flow at large gas velocities. This transition is observed at much lower liquid flows than suggested by Mandhane (or, to our knowledge, by anyone else). The reason for this is that a different method of detection was used.

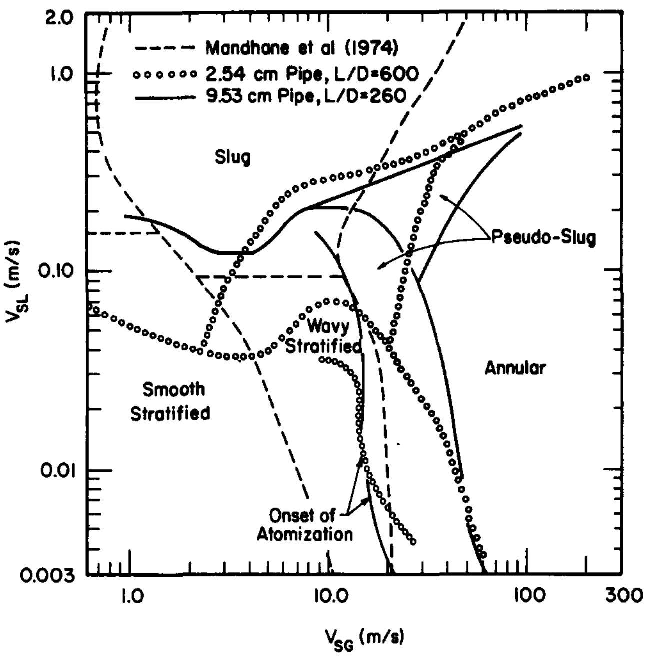


Figure 4. Flow regime map for air and water flowing in horizontal 2.54 and 9.53 cm pipes.

The chief ambiguities in figure 4 are the definition of the transitions from pseudo-slug and stratified flows to annular flow. The wetting of the wall to form a laminar annulus with capillary ripples depends on the materal of construction. Differences of about 10% in the superficial gas velocities needed to cause the top wall to become wetted were observed between old and new plastic pipes. Therefore, the transition to annular flow was identified in this study by the appearance of a turbulent film on the top wall, in the hope that this criterion would be independent of the piping material. This "turbulent" film was identified as one which has a 3-D wave pattern, rather than long-crested capillary ripples (see figure 2c).

Figures 6 and 7 show the film height distribution for annular flow in a 2.54 cm pipe at high liquid flows. The high degree of correlation among the wave heights at all angular locations suggests the existence of waves in the form of rings wrapping around the pipe circumference. This behavior of the film persists at least up to $V_{SG} = 100$ m/s in the 2.54 cm pipe. However, it was not observed in the 9.53 cm pipe.

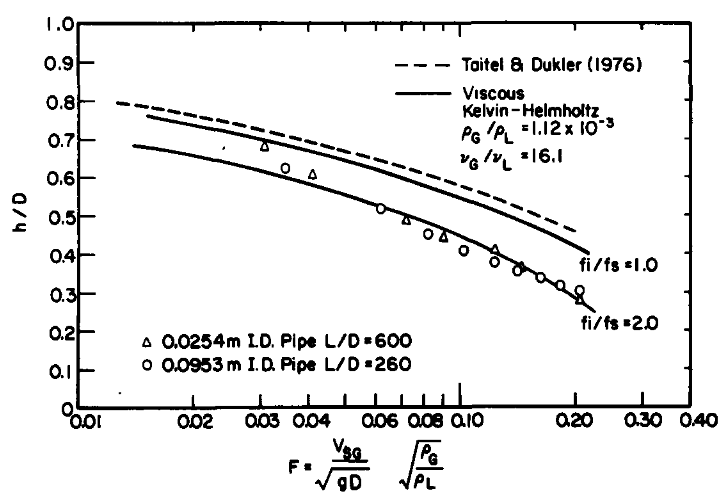


Figure 5. Observed transition to slug flow at gas velocities <3.3 m/s.

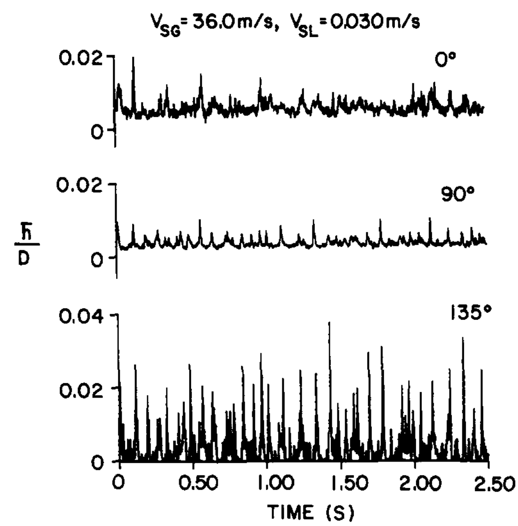


Figure 6. Film thickness distribution in annular flow at high liquid flow rates in a 2.54 cm pipe.

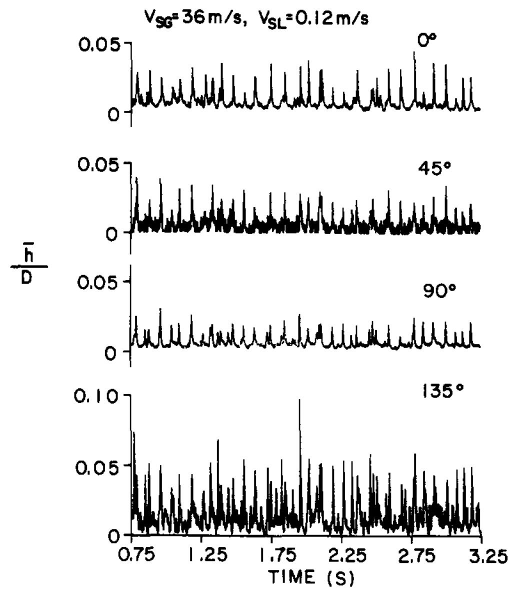


Figure 7. Film thickness distribution in annular flow at high liquid flow rates in a 2.54 cm pipe.

Figure 8 shows film height distributions for pseudo-slugs at the same V_{SL} as for figure 7. Figure 9 depicts pseudo-slugs in the 9.53 cm pipe. It is noted that pseudo-slugs also wrap around the pipe circumference. The waves in figure 9, however, occur on a thicker film, and with lower frequency than the waves in annular flow. They give a slug-like appearance when observed visually.

The transition from a pseudo-slug to annular flow in the 9.53 cm pipe was simply defined by the disappearance of large-amplitude waves which temporarily touch the top wall and of waves which are coherent around the pipe circumference. The transition from a pseudo-slug to an annular flow in the 2.54 cm pipe is more complicated. Consider an increase of V_{SG} at fixed V_{SL}. In the

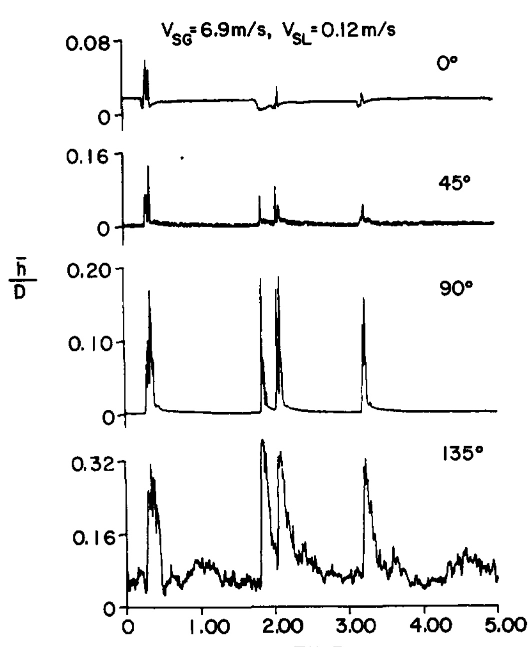


Figure 8. Film thickness distribution in pseudo-slug flow in a 2.54 cm pipe.

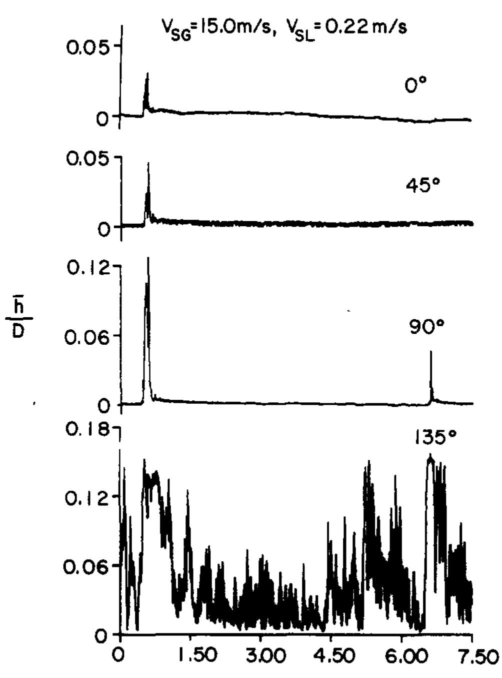


Figure 9. Film thickness distribution in pseudo-slug flow in a 9.53 cm pipe.

pseudo-slug region waves ring the pipe and waves from the bottom occasionally touch the top wall. With an increase in gas velocity the roll waves, which occur more frequently then the pseudo-slugs, are observed to start to ring around the pipe circumference. This causes the liquid layer on the bottom of the pipe to thin out and large-amplitude pseudo-slugs to disappear.

5. TRANSITION MECHANISMS

(a) Wavy-stratified/pseudo-slugs to annular flow

Two mechanisms have been suggested for the transition from stratified to annular flow. Butterworth & Pulling (1972), Govier & Aziz (1972) and Taitel & Dukler (1976) have all argued that wetting of the top wall of the pipe is initiated by large-amplitude waves which ring around the pipe circumference. Hoogendoorn (1959), however, concluded that annular flow is caused by an entrainment–deposition mechanism.

Our observations in the 9.53 cm pipe indicate that the transition from stratified to annular flow occurs primarily through the deposition of droplets on the top of the pipe. Figure 1a and figures 2a–d illustrate the events that occur in the 9.53 cm pipe when the gas flow rate is increased at a constant superficial liquid velocity of 0.076 m/s. Figure 1a shows the pattern observed at $V_{SG} = 6.4$ m/s. It can be said that it is a stratified flow with 2-D roll waves. No atomization was observed and the top portion of the pipe wall remained dry. As the gas velocity increases atomization begins. Droplets torn from the liquid film are observed to impinge on the top of the pipe (figure 2a). At high gas velocities the atomization rate increases and more droplets are deposited. Some droplets on the pipe wall eventually coalesce together to form water streaks that run downstream along the wall and pick up droplets which had been deposited in front of them (figure 2b). At still higher gas velocities more droplets are deposited and more water streaks are formed. Eventually, a continuous liquid film with a pebbled surface is formed covering the entire pipe surface (figure 2c). Annular flow has begun. Figure 2d shows a slide view of the pipe just after the transition to annular flow. Large-amplitude wave are noted on the thick liquid layer flowing along the bottom but these do not wrap around the pipe circumference. This same sequence of events can be observed for the transition from stratified to annular flow in the 9.53 cm pipe at any superficial liquid velocity <0.1 m/s. At superficial liquid velocities >0.1 m/s the transition to annular flow in the 9.53 cm pipe was defined by a change from a condition where the top wall was wetted only by atomized droplets to a condition where atomization and large-amplitude waves or pseudo-slugs were wetting the top wall.

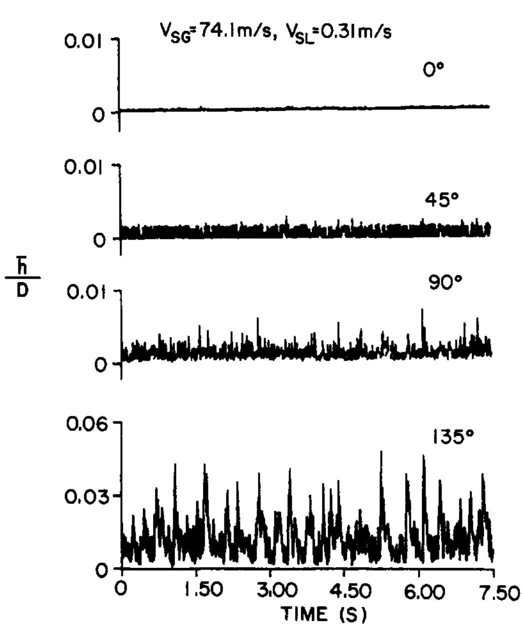


Figure 10. Film thickness distribution in annular flow in a 9.53 cm pipe.

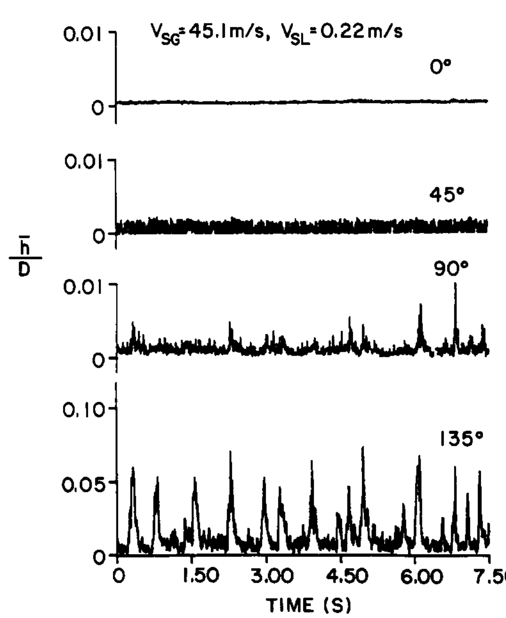


Figure 11. Film thickness distribution in annular flow in a 9.53 cm pipe.

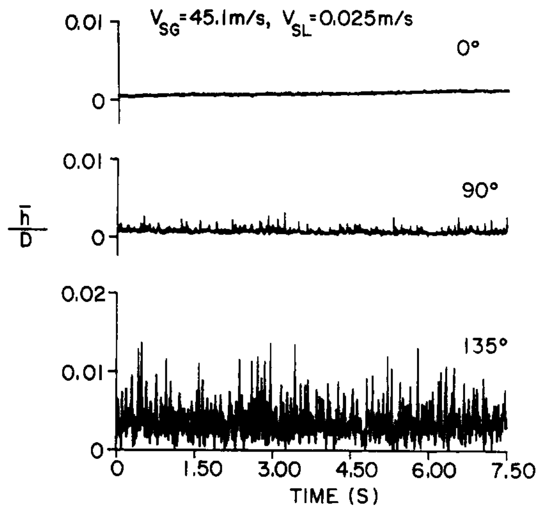


Figure 12. Film thickness distribution in annular flow in a 9.53 cm pipe.

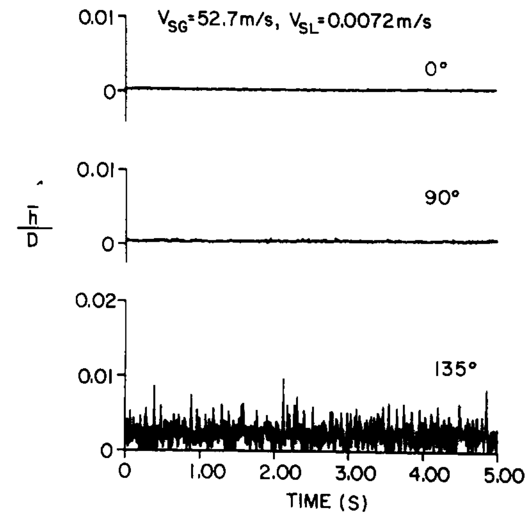


Figure 13. Film thickness distribution in annular flow in a 9.53 cm pipe.

The conclusion that waves are not causing the wetting of the top part of the pipe is also supported by the film height measurements shown in figures 10–13. These were obtained just after the transition to annular flow. Wave are observed only at the bottom of the pipe.

The same type of mechanism for the transition from a stratified to an annular pattern also is found for the 2.54 cm pipe at low liquid velocities ($V_{SL} \leqslant 0.015$ m/s). Figure 3a shows a view, at an angle, of wavy-stratified flow in the 2.54 cm pipe at $V_{SL} = 0.015$ m/s. Atomization is occurring and water streaks can be clearly seen on the top of the pipe. At higher liquid rates, however, waves play a more important role in wetting the top of the pipe and in determining the transition to annular flow. Figure 3b shows a side view of the 2.54 cm pipe just after transition to annular flow and at the same V_{SL} as for figure 2a for the 9.53 cm pipe. The waves in the smaller pipe are much larger and appear to wrap around the entire pipe circumference.

The possible role played by waves in transition to annular flow can be explored by examining the distribution of film thickness around the pipe circumference in the 2.54 cm pipe just after the transition. Figures 14 and 15 illustrate the film distribution for $V_{SL} < 0.015$ m/s for which the atomization–deposition mechanism is controlling. No wave peaks are observed at the upper probes. Figures 6 and 7 show, however, that ring-shaped waves do appear at higher liquid flows.

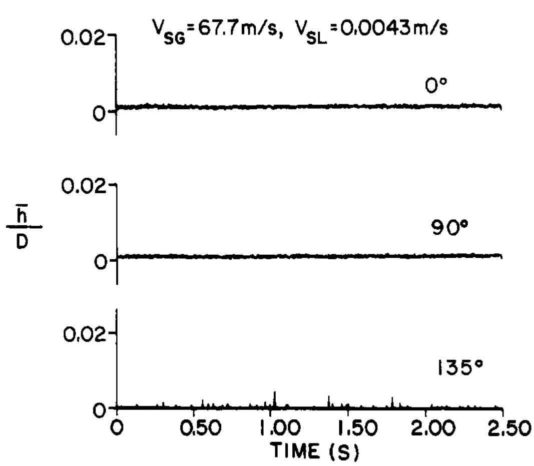


Figure 14. Film thickness distribution in annular flow at low liquid flow rates in a 2.54 cm pipe.

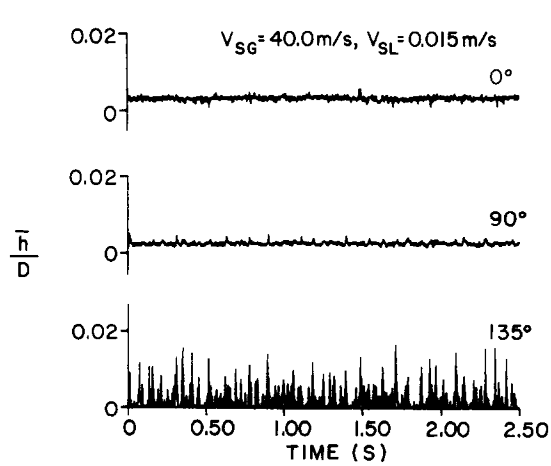


Figure 15. Film thickness distribution in annular flow at low liquid flow rates in a 2.54 cm pipe.

Our observations, therefore, indicate that both the entrainment–deposition and the wave-mixing mechanism are operative. Their relative importance depends on the pipe size and the liquid flow rate. For the large pipe, entrainment–deposition is dominant. For the small pipe entrainment–deposition controls only for $V_{SL} \leqslant 0.015$ m/s. Wave-mixing is dominant at flows that are high enough for the transition from a pseudo-slug to an annular regime to occur. An examination of the flow conditions under which Butterworth & Pulling (1972) conducted their experiments indicates that all but one of their data points lie at or near the pseudo-slug/annular transition. Their conclusion is, therefore, not surprising.

The transition from a pseudo-slug to an annular regime occurs in the following manner: pseudo-slugs are formed primarily by the coalescence of roll waves. At low gas velocities these roll waves are approximately 2-D, as shown in figure 1a. At high gas velocities the frequency of the roll waves increases, the thickness of the liquid layer decreases because of atomization and the increased gas drag, and the roll waves tend to move higher around the pipe circumference. These factors cause the roll waves to be thinner and make coalescence to form pseudo-slugs more difficult. In the 2.54 cm pipe, at conditions where pseudo-slugs no longer appear the roll waves wrap around the circumference and form an annular flow.

(b) Wavy-stratified to slug/pseudo-slug flows

At gas velocities that are low enough such that roll waves do not appear at the interface ($V_{SG} < 5$ m/s for the 9.53 cm pipe; $V_{SG} < 3$ m/s for the 2.54 cm pipe), the transition process appears consistent with a stability mechanism. [See Andritsos & Hanratty (1987) for a discussion of wave patterns in stratified flows.] For these low gas velocities, the first observed slugs appear at the downstream end of the pipe and could, therefore, be associated with the growth of infinitesimal

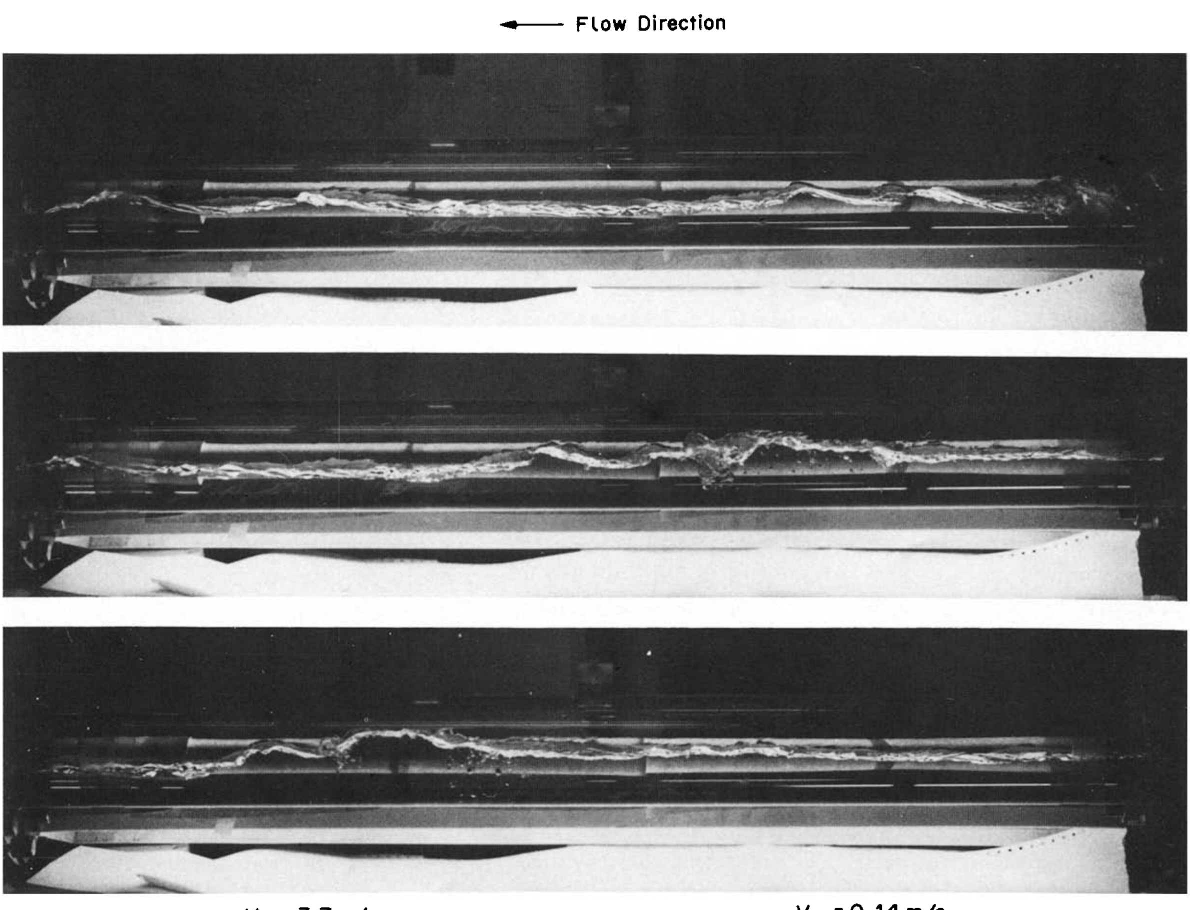


Figure 16. Coalescence of roll waves in a 9.53 cm pipe (side view).

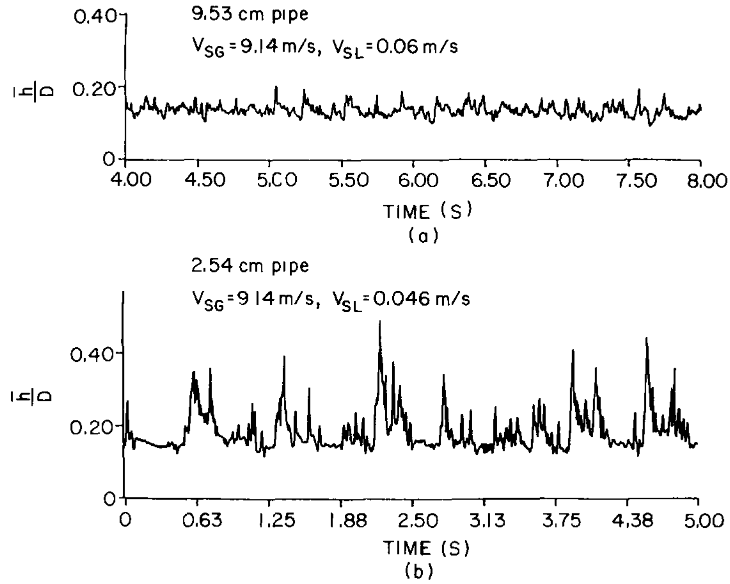


Figure 17 Heights of roll waves in stratified flow in 2.54 and 9.53 cm pipes

long-wavelength disturbances. The curves shown in figure 5 are the results of a linear stability analysis carried out by Lin & Hanratty (1987). Note that excellent agreement is obtained if the ratio of the interfacial friction factor at transition to the friction factor for flow in a smooth pipe is taken to be equal to 2.0.

At higher gas velocities the interface in the stratified flow region is covered by large-amplitude roll waves rather than by 2-D capillary–gravity waves. Roll waves are observed to coalesce and form a larger wave. This larger wave can subsequently break up or it can coalesce with another large-amplitude roll wave to form a pseudo-slug or a slug.

Figure 16 shows a time sequence of pictures taken at 4 frames/s illustrating the coalescence of roll waves in a 9.53 cm pipe. Three separate roll waves are seen in figure 16a. The roll wave in the rear quickly captures the wave in the middle (figure 16b) and the resulting combined wave is about to overtake the first wave in figure 16c. The resulting wave has a larger amplitude than any of the original roll waves of which it is composed and travels at a higher velocity. At a point farther downstream this large-amplitude roll wave coalesces with another large-amplitude roll wave. This coalescence results in the formation of either a slug or pseudo-slug, depending on whether enough liquid is present in front of the point of coalescence to sustain a fast-moving slug.

At a liquid flow necessary to initiate slugging, the slugs are observed at the downstream end of the pipe. As the liquid flow increases, initiation is possible farther upstream. At high enough liquid flows ($V_{SL} > 0.5$ m/s), slugs form a short distance from the entry. For such cases, the average liquid height at the entry is considerably higher than in the rest of the pipe. Slugs can then occur by the growth of a solitary wave, although slug formation by coalescence still occurs. This is the mechanism proposed by Dukler & Hubbard (1975); it appears to be valid at liquid flows much larger than that needed for the initiation of slugging.

Figure 4 shows that the pseudo-slugs occur at lower liquid flow rates in the smaller pipe. This could be associated with the observation that roll-wave heights are larger in the smaller-diameter pipe. This is illustrated by the liquid height tracings in figures 17a,b for stratified flows in the 2.54 and 9.53 cm pipes [obtained by Andritsos (1986)], at roughly the same superficial velocities. This effect of pipe diameter on wave heights has also been observed by Hoogendorn (1959).

(c) Slug to annular flows

The transition from slug to annular flows is associated with essentially the same mechanisms that control the transition from pseudo-slug to annular flow. The slug/annular transition actually consists of a very narrow transition zone in which pseudo-slugs exist. Higher gas velocities cause a thinning in the liquid layer due to increased drag and atomization. The frequency of roll waves also increases with increasing gas velocity. As a result, coalescence to form slugs become less favorable at high gas velocities.

6. CONCLUDING REMARKS

Air and water flowing in a horizontal pipe can assume different interfacial configurations. The physical processes governing the transitions are not completely understood. Two factors have impeded progress in this direction: (1) different researchers have disagreed regarding the influences of fluid flow rates and of pipe diameter; (2) the mechanisms have not been well-documented. This research was done to help remedy this situation. A key factor is the use of an instrumental technique, described by Lin & Hanratty (1987), to detect the presence of slugs.

A common approach over the past three decades has been to construct empirical flow-regime maps based on visual observations, in most cases, in pipes <5 cm dia (Baker 1954; Govier & Aziz 1972; Mandhane *et al.* 1974; Weisman *et al.* 1979). The map by Mandhane is based on the largest amount of data and is the most widely used. It assumes that the transition curves are least sensitive to changes in pipe diameter and in fluid properties if superficial gas velocity and superficial liquid velocity are used as ordinates.

The plot used in this study to present the results is the same as that of Mandhane, except that a pseudo-slug pattern is added to define the ambiguous region that exists close to the intersection of the curves representing the slug/annular, the slug/stratified and the stratified/annular transitions. Measurements of pressure fluctuations at two locations along the pipe showed that the transition to a slugging condition can be sharply defined and, consequently, no problem is encountered in differentiating slugs from pseudo-slugs.

The results support the approach of Mandhane in that the effect of pipe diameter on all transitions, with the exception of the stratified/slug, is small when presented on a plot of V_{SL} vs V_{SG}. The strong effect of pipe diameter on the stratified/slug transition, at low gas velocities, shown in our results, confirms what we had already been suggested by Taitel & Dukler (1976) in their recent mechanistic approach toward predicting flow regimes.

The Mandhane curves representing the different transitions (here, we interpret his stratified/stratified-wavy and stratified-wavy/annular as transitions to roll waves and to an atomizing condition) are a good average representation of the results obtained in this laboratory, except for the transition from slug to annular flow.

Figure 4 is in approximate agreement with the overall predictions of Taitel & Dukler (1976) for air–water flows, except for the transition to slugs at large gas velocities. This transition appears to be much more complicated than can be represented by the criterion of h/D being $\gtrless 0.5$. The Taitel–Dukler prediction for the stratified/annular transition for a 9.53 cm pipe is suprisingly good, considering that their mechanism appears inconsistent with observations in this study.

The influence of gravity on the flow can be represented by the dimensionless group, $gh/V_G^2 = G$. For fixed h/D, V_{GS}, V_{LS}, the stabilizing effect of gravity, represented by G, will be larger for a larger-diameter pipe because the term gh varies with the absolute liquid thickness rather than the h/D ratio. This shows up in the stratified/slug transition in that a strikingly large V_{SL} is needed in a larger-diameter pipe. However, it also affects the other flow patterns in a, perhaps, less dramatic way. Because the stabilizing effect of gravity in small-diameter pipes is less, larger amplitude waves (with respect to pipe diameter) are formed more easily and the pseudo-slug region is larger. Also, the smaller stabilizing effect of gravity in smaller pipes allows roll waves to wrap around the circumference. This provides a mechanism for bringing liquid to the top of the pipe. Thus, the transition to annular flow is facilitated, and a more uniform film distribution occurs in annular flow in small-diameter pipes.

The initiation of slugs at low enough gas velocities that roll waves are not present in the stratified flow can be interpreted by a stability mechanism involving the growth of small disturbances. At large gas velocities a non-linear mechanism is operative, which has not been addressed by any model for the onset of slugging. Large-amplitude roll waves were observed to coalesce occasionally to form a slug or a pseudo-slug.

A possible explanation as to why coalescence is necessary to form a slug at high gas velocity is as follows. For a stratified flow with 2-D waves, an increase in gas velocity at a constant liquid flow produces roll waves. Associated with the appearance of roll waves is a dramatic decrease in the liquid thickness over which the roll waves move. Apparently the thinner liquid carpet cannot supply enough liquid for a single solitary wave to form a slug. Slugs form through the coalescence of these roll waves or, for large liquid flows and large roll-wave frequencies, by an interaction of roll waves in such a way as to form a thick enough carpet. The local maximum in the wavy-stratified/pseudo-slug transition observed in the 2.54 cm pipe deserves further explanation. At low gas velocities in the pseudo-slug region, large-amplitude roll waves coalesce to form pseudo-slugs. As the gas velocity is increased, the liquid layer at the pipe bottom begins to thin so that even after coalescence the waves cannot touch the top wall. This is easily observed by a drying out of the top wall of the pipe. This region is wavy-stratified flow according to definitions used in this study. As gas velocity is increased further, the roll waves begin to ring around the pipe circumference so that pseudo-slugs appear again. (These pseudo-slugs have a different appearance from those at lower gas velocities, but can touch the top wall nonetheless.)

The transition from wavy-stratified to annular flow in the 9.53 cm pipe occurs primarily through the deposition of droplets. This mechanism is dominant in the 2.54 cm pipe only for superficial liquid velocities <0.015 m/s. At higher liquid flow rates, a wave-mixing mechanism is important.

NOMENCLATURE

D = Pipe diameter
$F = (V_{SG}/\sqrt{gD})(\rho_G/\rho_L)^{1/2}$
g = Acceleration of gravity
$G = gh/V_G^2$
h = Height of the liquid film
V_G = Actual gas velocity
V_{GS} = Superficial gas velocity
V_{SL} = Superficial liquid viscosity
ρ_G = Gas density
ρ_L = Liquid density

Acknowledgements—This work has been supported by the AIChE Design Institute for Multiphase Processing and by the Shell Companies Foundation.

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