Int. J. Multiphase Flow Vol. 7, pp. 271–291, 1981
Printed in Great Britain

0301-9322/81/030271-21$02.00/0
Pergamon/Elsevier

FLOW PATTERN TRANSITIONS IN VERTICAL AND UPWARDLY INCLINED LINES

J. WEISMAN and S. Y. KANG†
University of Cincinnati, Cincinnati, Ohio, U.S.A.

(*Received* 13 *December* 1979; *in revised form* 26 *September* 1980)

Abstract—Additional data has been obtained on flow pattern transitions during cocurrent gas–liquid flow in vertical and upwardly inclined lines. These data, together with those previously available in the literature, have enabled the development of improved dimensionless correlations for flow pattern boundaries. The individual boundary lines have been combined into simple overall flow pattern maps.

Although nearly all investigators agree that the flow pattern has a major influence on most two-phase (gas–liquid) transport phenomena, the influence of flow pattern is often ignored when predictions are made. This tendency may, in fact, be ascribed to the lack of generally accepted criteria for the transition between the various flow patterns. Considerable progress has recently been made in quantitatively characterizing the flow pattern transitions seen during cocurrent gas–liquid flow in horizontal (Weisman *et al.* 1979) pipelines. However, the behavior of cocurrent gas–liquid flow in inclined and vertical lines, still appears to need clarification. This study was therefore undertaken.

CURRENT PREDICTIVE METHODS

Study of the conditions at which flow pattern transition occur in horizontal lines has a long history. Quantitative predictions may be considered to begin with the pioneering work of Baker (1954). Baker's flow pattern map was widely used for many years despite the limited data on which it was based. With the availability of new data, the flow pattern map of Mandhane *et al.* (1974) and the semi-theoretical predictive equations of Taitel & Dukler (1976) were used fairly widely. More recently, studies at the University of Cincinnati have shown both of the foregoing approaches to have deficiencies.

The recent University of Cincinnati data (Weisman *et al.* 1979) covering a variety of fluids and the large-line data of Simpson *et al.* (1977) have enabled improved transition criteria to be established for horizontal pipelines. To simplify the flow pattern classification, Weisman *et al.* (1979) used a suggestion of Hubbard & Dukler (1966) and considered the flow to be described by the annular, intermittent, dispersed and separated flow patterns. Note that intermittent flow includes slug and plug. Separated includes wavy and stratified and dispersed covers both froth and mist flow. With this simplification, the flow pattern transitions of major interest are: transition to annular flow, transition to dispersed flow and the separated–intermittent transition. The occurrence of the transitions could be predicted by:

Transition to annular flow.

$$1.9(V_{SG}/V_{SL})^{1/8} = \mathrm{Ku}_G^{0.2}\mathrm{Fr}_G^{0.18}\,. \qquad [1]$$

Separated–intermittent transition.

$$(\mathrm{Fr}_G)^{1/2} = 0.25(V_{SG}/V_{SL})^{1.1}. \qquad [2]$$

†Current address: Taiwan Power Co., Taiwan.

Transition to dispersed flow.

$$\left[\frac{|dp/dx)|_{SL}}{(\rho_L-\rho_G)g}\right]^{1/2}\left[\frac{\sigma}{(\rho_L-\rho_G)gD^2}\right]^{-1/4}=9.7 \qquad [3]$$

where V_{SG}, V_{SL} = superficial gas and liquid velocities, respectively; Fr_G = Froude number = V_{SG}^2/gD; Ku_G = Kutadelaze number = $V_{SG}\rho_g/[g(\rho_L-\rho_G)\sigma]^{1/4}$; g = acceleration of gravity; $|dP/dx|$ = absolute value of pressure drop per unit length; D = pipe dia.; σ = surface tension; and ρ_G, ρ_L = gas and liquid densities, respectively.

It should be observed that [3] applies only to low and moderate qualities. At high qualities a revised formulation, which depends on the total flow rather than the liquid flow, seems to apply.

On the basis of the foregoing, an overall flow map was developed in terms of V_{SG}/ϕ_1 and V_{SL}/ϕ_2 (see figure 1). The transition boundaries shown are computed from [1] to [3], plus a correlation for the wavy flow transition (Weisman *et al.* 1979), for the air–water system in a 2.5-cm line. The functions ϕ_1 and ϕ_2 include the corrections needed to account for the effects of physical property and diameter variations from the standard values used in constructing the map. Expressions for these parameters are given in table 1.

Taitel & Dukler's (1976) predictions for horizontals lines were extended by them to cover slightly inclined lines. However, since these predictions did not represent the behavior in horizontal lines well, similar difficulties are to be expected in slightly inclined lines.

The flow patterns seen in vertical flow differ somewhat from those seen in horizontal lines. The annular (liquid around tube, gas core with or without entrained droplets) and dispersed (froth of bubbles in liquid or mist of droplets suspended in gas) flow patterns are still found but slug flow is no longer seen. At gas flow rates just below those giving rise to annular flow, "churn" flow encountered. This is a chaotic mixture of large packets of gas and liquid which appear to have a churning motion. At somewhat lower gas flow rates, "plug" flow appears. Here large bullet shaped plugs of gas, having a diameter approximately equal to that of the tube, rise through the liquid. At the lowest gas rates, bubble flow, in which small spherical bubbles rise through the liquid, is found. At high liquid rates, froth and mist (dispersed) flow appear again.

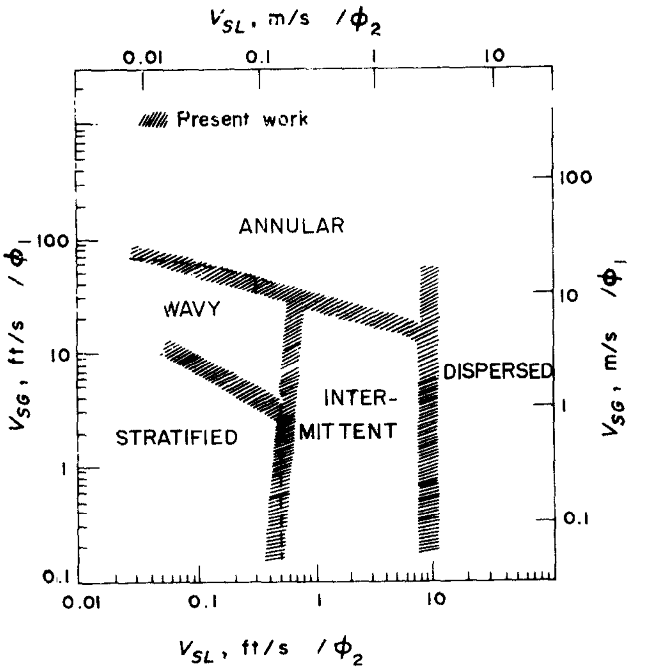


Figure 1. Overall flow pattern map for horizontal lines.

Table 1. Property and pipe diameter corrections to overall flow map

Flow orientation		ϕ_1	ϕ_2
Horizontal, vertical and inclined flow	Transition to dispersed flow	1.0	$\left(\frac{\rho_L}{\rho_{sL}}\right)^{-0.33}\left(\frac{D}{D_s}\right)^{0.16}\left(\frac{\mu_{sL}}{\mu_L}\right)^{0.09}\left(\frac{\sigma}{\sigma_s}\right)^{0.24}$
	Transition to annular flow	$\left(\frac{\rho_{sG}}{\rho_G}\right)^{0.23}\left(\frac{\Delta\rho}{\Delta\rho_s}\right)^{0.11}\left(\frac{\sigma}{\sigma_s}\right)^{0.11}\left(\frac{D}{D_s}\right)^{0.415}$	1.0
Horizontal and slightly inclined flow	Intermittent–separated transition	1.0	$\left(\frac{D}{D_s}\right)^{0.45}$
Horizontal flow	Wavy–stratified transition	$\left(\frac{D_s}{D}\right)^{0.17}\left(\frac{\mu_{sG}}{\mu_{sG}}\right)^{1.55}\left(\frac{\rho_{sG}}{\rho_G}\right)^{1.55}\left(\frac{\Delta\rho}{\Delta\rho_s}\right)^{0.69}\left(\frac{\sigma_s}{\sigma}\right)^{0.69}$	1.0
Vertical and inclined flow	Bubble–intermittent transition	$\left(\frac{D}{D_s}\right)^{n}(1\text{–}0.65\cos\alpha)$ $n = 0.26\,e^{-0.17(V_{SL}/V_{SL}^s)}$	1.0

s denotes standard conditions. $D_s = 1.0$ in. $= 2.54$ cm. $\rho_{sG} = 0.0013$ kg/l. $\rho_{sL} = 1.0$ kg/l. $\mu_{sL} = 1$ centipoise. $\sigma_s = 70$ dynes/cm. $V_{SL}^s = 1.0$ ft/s $= 0.305$ m/s.

Taitel & Dukler (1977) have extended their predictive modelling to vertical flow. They concluded that annular flow could not exist unless the gas velocity in the gas core was sufficient to lift any entrained liquid droplet. Their transition correlation is then given by

$$\frac{V_{SG}\rho_G^{1/2}}{[\sigma g(\rho_L - \rho_G)]} = 91\left\{\frac{\dfrac{\phi_G^2}{X} - 1}{\phi_G^2/X}\right\} \qquad [4]$$

where X = Lockhart–Martinelli parameter and ϕ_G^2 = two-phase friction factor based on gas phase flow. They predicted that the transition between bubble and plug is given by

$$V_{SL} = 2.33\,V_{SG} - 1.07\left[\frac{g(\rho_L - \rho_G)\sigma}{\rho_L^2}\right]. \qquad [5]$$

Their plug-churn transition prediction is based on the idea that the transition occurs when the liquid region separating two consecutive plugs is so short that the wake behind the plug destroys the liquid bridge between plugs. They concluded that the transition could be described by a relationship between (V_{SG}/V_S) and $(V_S/\sqrt{(gD)})$ with $(V_S D/\gamma_L)$ as a parameter {V_S = [volumetric gas flow rate + volumetric liquid flow]/total flow area, γ_L = kinematic viscosity of liquid.}

The transition to froth flow, which occurs at high liquid velocities, was assumed to be independent of orientation. The correlation previously developed by Taitel & Dukler (1976) was therefore assumed to apply.

At the outset of this work, only limited experimental data was available to check the Taitel–Dukler (1977) predictions. In addition, nearly all of these data were at relatively low mass flow rates.

PRESENT EXPERIMENTAL STUDIES

The present tests were carried out in the University of Cincinnati air–aqueous solution facility and the U.C. boiling Freon loop. The air–aqueous solution test facility allowed flow patterns to be observed in 20 ft long glass lines which had nominal dia. of 1/2, 1 and 2 in. (actual dia. of 1.2, 2.5 and 5.1 cm). Air and water solution flows were measured by orifice meters. Air pressure was nearly atmospheric. The facility was constructed so that the test lines could be slightly inclined to the horizontal at upward inclinations up to 7°.

Tests in sharply inclined and vertical lines were conducted in the boiling Freon loop. Here, up to 120 l./min of Freon 113 was circulated through electric heaters producing a two-phase mixture which flowed through a 1.52-m length of vertical or inclined 2.5 cm glass pipe. In all cases the test section was preceeded by an additional 1.52 m length of steel pipe, having an i.d. very close to that of the test section, at the same inclination as the test section. Observations were made at the end of the glass test section. The fluid leaving the test section returned to a condenser and was recirculated. Total liquid flow was measured by an orifice meter and the two-phase mixture flow was measured with a drag disk preceeded by a fine screen. Previous studies (Weisman 1977) had shown that the drag disk signal was proportional to (G_T^2/ρ) where ρ is the homogeneous mixture density and G_T is the total mass flow. Since G_T is known from the liquid flow measurement, the value of ρ allows the quality to be determined.

A bladder type accumulator maintained the desired pressure. Tests were conducted at 1.02 and 3.07 bar. At the latter pressure, the vapor density is approx. 20 times that of air at atmospheric pressure.

The Freon and air–water test facilities are the same as those previously used by Weisman *et al.* (1979) and additional details on their construction may be obtained from this previous paper.

The experimental data obtained in the present tests were supplemented by the recent data of Spedding & Nguyen (1976). They conducted a series of tests with air and water in a 1.8-in. (4.5 cm) line at upward inclination angles ranging from 2.75 to 90°. However, all of the Spedding and Nguyen data were restricted to liquid flows below 5×10^6 kg/m^2 h and at several of the inclination angles only partial flow maps were determined.

In the present experimental program, the effect of small upward inclination angles was systematically investigated by conducting a series of air–water tests at upward inclination angles of 1/2, 2 and 7°. Flow patterns in all three line sizes (1.2, 2.5 and 5.1 cm) were examined. The availability of the recent Spedding & Nguyen (1976) air–water data at sharp inclination angles obviated the necessity of conducting air–water tests at these sharp inclination angles.

Based on the previous studies in horizontal lines, it was believed that liquid properties would have small effects. Nevertheless, since liquid viscosity can vary over a very wide range, tests were conducted using a 75-centipose glycerol–water solution. Tests in the 5.1-cm line were carried out at 1/2, 2 and 7° upward inclinations.

The tests with Freon-113 allowed the effect of gas density on flow patterns to be determined for sharply inclined and vertical lines. Tests were carried out at inclinations of 30, 45 and 90° in a 2.5-cm line. No similar data was available previously for the 30 and 45° inclinations.

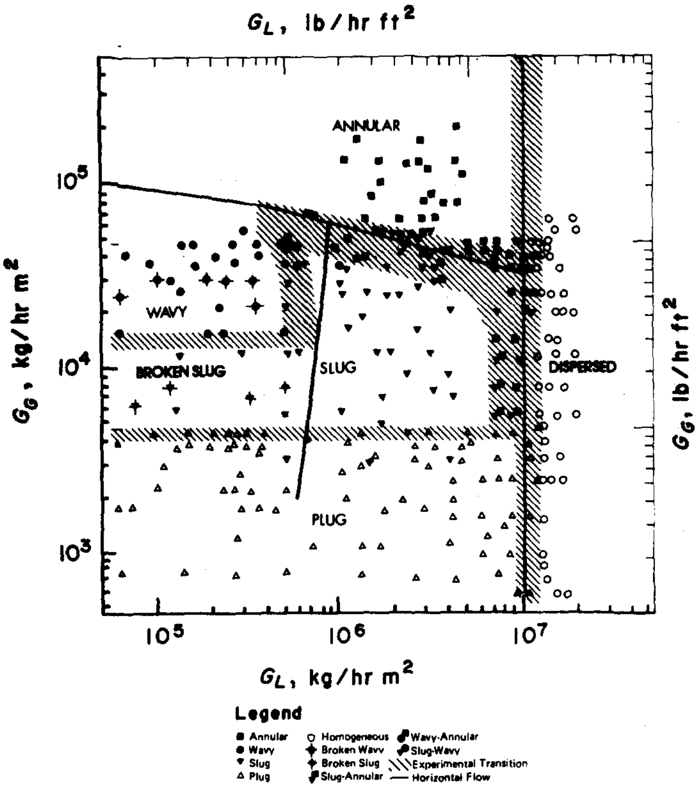
Table 2 summarizes the tests conditions examined in the present program. The data from the tests, plus the data available in the literature, allowed a comprehensive picture of flow-pattern behavior in upwardly inclined and vertical lines to be obtained.

RESULTS OF STUDIES IN SLIGHTLY INCLINED LINES

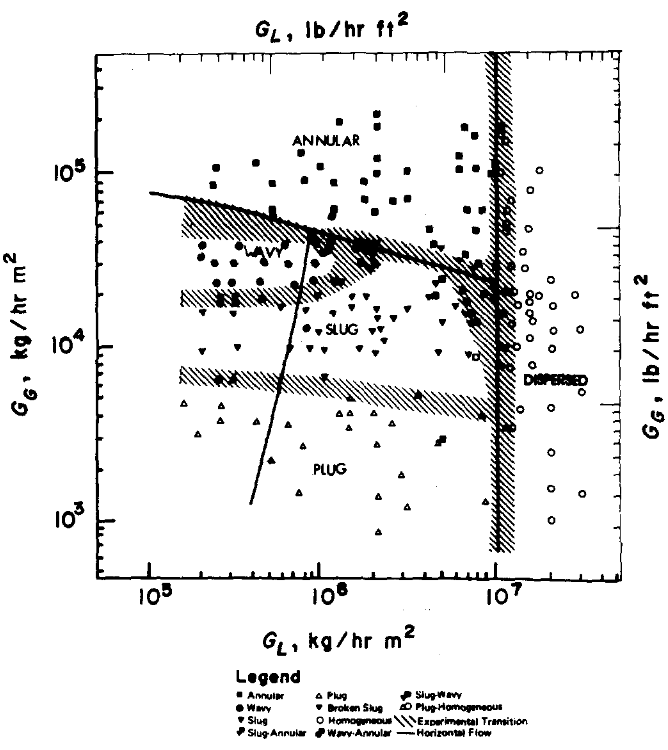
When a pipeline is only slightly inclined to the horizontal, the flow pattern behavior is very similar to that seen in a horizontal line. The major change observed is that stratified flow disappears at very low angles of inclination. The region formerly occupied by stratified flow is now occupied by plug flow. Wavy flow is still observed but the wavy flow region begins at a

Table 2. Conditions examined in university of Cincinnati flow pattern test program

Fluids	Line sizes	Inclination angles from horizontal (upward)
Air–water	1.2, 2.5, 5.1 cm	0, 1/2, 2, 7°
Air–glycerol ($\mu = 75$ cp)	5.1 cm	0, 1/2, 2, 7°
Freon-113–Freon 113 vapor	2.5 cm	0, 30, 45, 90°



(a)



(b)

Figure 2. Flow patterns in lines inclined 7° upwards (air–water system, line dia. 2.5 and 5.1 cm), (a) 5.1 cm, (b) 2.5 cm.

higher gas flow rate. The region formerly occupied by wavy flow is generally occupied by broken slug flow (slug flow in which the water slug does not reach to the top of the tube).

The flow pattern map of figure 2, showing the behavior in a 2.5- and 5.1-cm line inclined 7 degrees upward, is typical of what was observed. As in previous work, the individual points represent separate flow pattern observations and the shaded areas represent the region in which the flow pattern transition occurred. The solid lines correspond to the center of the transition region observed in horizontal flow. It will be observed that the transitions to annular and dispersed flow appear to be uninfluenced by the angle of inclination.

As noted above, stratified flow has disappeared and the lower boundary of the wavy flow region is located at higher gas flow rates than in horizontal flow. However, the position of the right-hand boundary between the separated and intermittant regions (wavy-slug boundary) has changed little from that seen in horizontal flow. The small changes in the 2.5 and 5.1 cm lines are in opposite directions and are probably within the scatter seen in most flow pattern data. The length of this boundary line has, of course, been decreased.

The behavior shown in figure 2 was typical for all the tests made in the 2.5 and 5.1 cm lines. However, the behavior in the 1.15 cm line was anomolous (see figure 3). Annular flow began at considerably lower gas flow rates than in horizontal flow and no wavy flow was observed.

The disappearance of stratified flow appears to correspond to the disappearance of a clear gas passageway at zero flow. This in turn corresponds to the condition that

$$\sin\theta > D/L \quad [6]$$

where L = length of pipeline; D = pipeline dia.; and θ = angle of inclination. For a 5.1-cm line which is 20 ft (6.2 m) long, this corresponds to an angle of 0.475°. The absence of all stratified flow at tests with a 1/2° upward inclination is thus in accord with the criterion of [6].

As the angle of inclination is increased, the wavy flow region begins at higher gas flow rates.

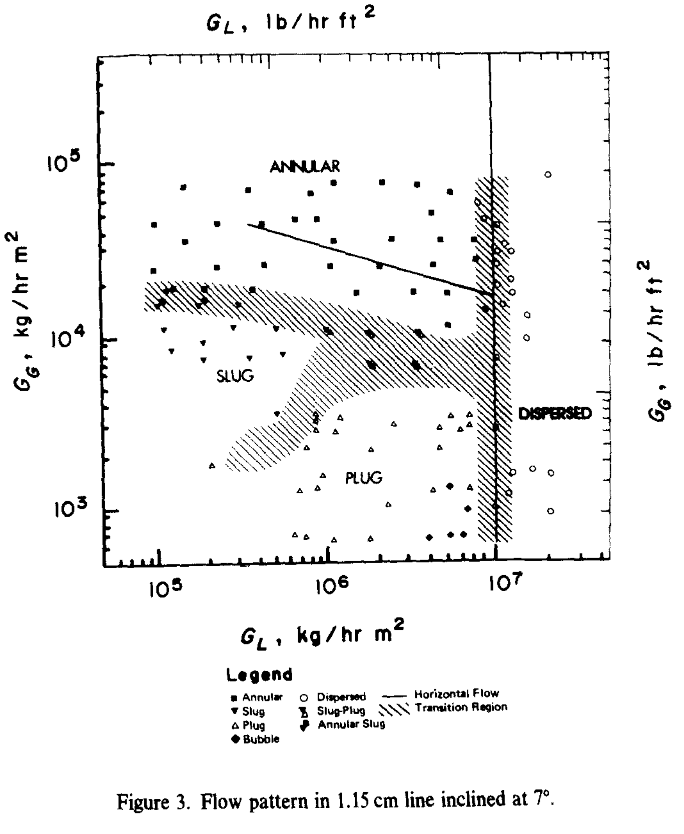


Figure 3. Flow pattern in 1.15 cm line inclined at 7°.

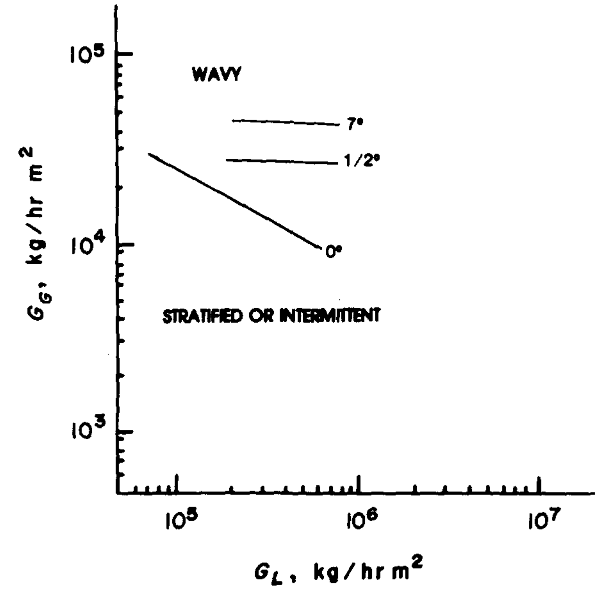


Figure 4. Effect of angle of inclination on lower boundary of wavy flow (air–water, 2.5 cm line).

This behavior is illustrated in figure 4 where the onset of wavy flow at 1/2 and 7° inclinations in a 1-in. (2.5 cm) line are compared to the onset in a horizontal line. Further increases in inclination angle lead to a disappearance of wavy flow. It should also be observed that the gas flow rate at which the transition occurs is essentially unaffected by the liquid flow rate. The transitions to wavy in inclined and horizontal lines differ in character and appear to require different correlating approaches.

It should be noted that at very low gas flow rates (below about 500 kg/m^2 h) the data of Spedding & Nguyen (1976) indicate that bubbly flow is observed (see figure 5). These gas flow rates were below the levels investigated in the present tests.

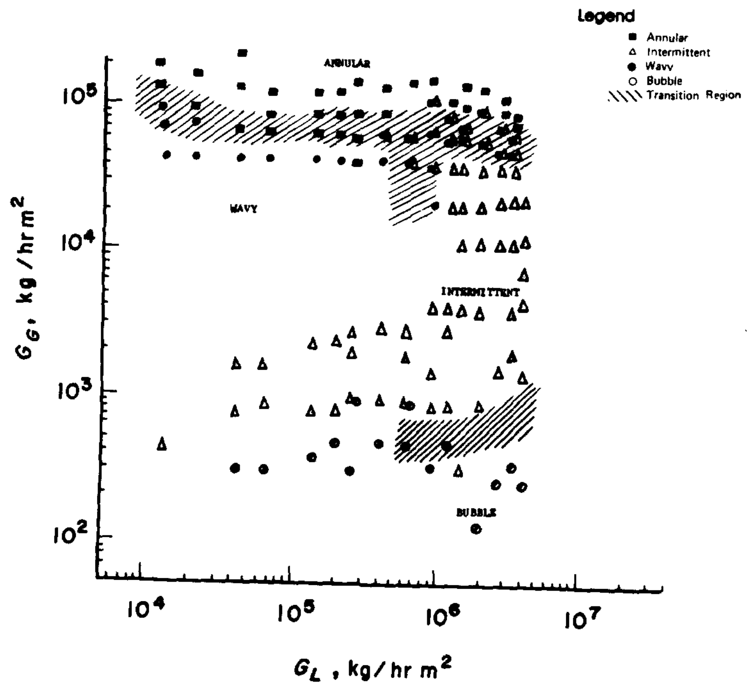


Figure 5. Flow patterns in line inclined 2.75° upwards (air–water system, data of Speddling *et al.*).

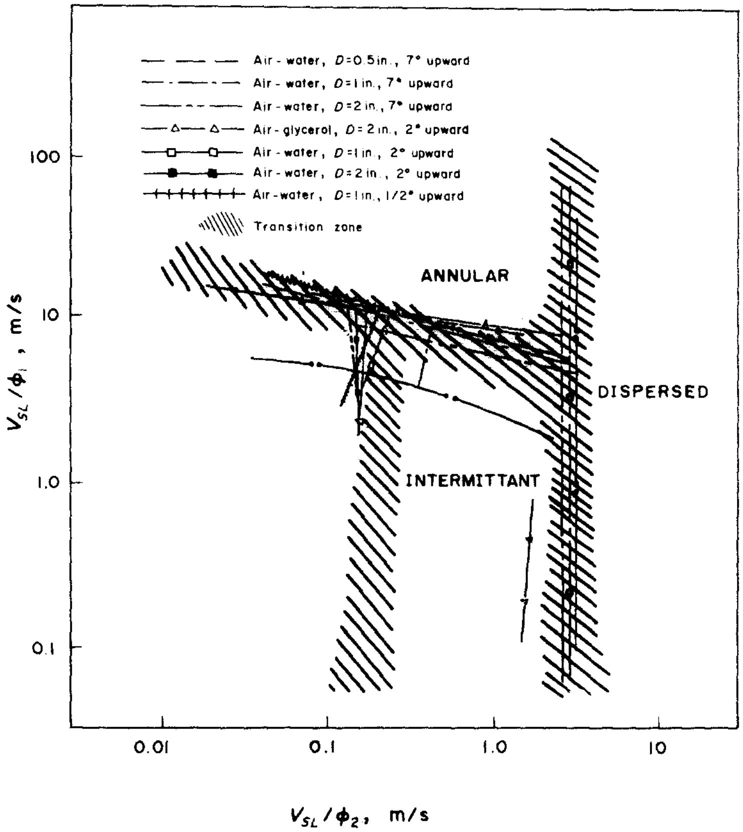


Figure 6. Comparison of transitions in slightly inclined pipelines with flow pattern map for horizontal lines.

In figure 6, the observed transitions between annular and separated flow, separated and intermittent flow and intermittent and dispersed flow are compared with the overall flow pattern map derived for horizontal pipelines. It is readily seen that, providing we restrict our consideration to pipelines of 2.5 cm or more, the horizontal flow pattern map represents the inclined flow observations very well. Of course, the vertical separated-intermittent boundary holds only for the reduced wavy flow region. A fully satisfactory general prediction of the lower boundary of the wavy flow region has yet to be determined.

To fully adapt the horozontal flow pattern map (figure 6) for use with slightly inclined pipelines, curves representing the transitions to wavy flow and bubbly flow need to be added. Figure 4 can provide the guidance needed in estimating the area of wavy flow. The bubbly flow transition may be determined by the correlation presented subsequently [9].

When we compare the present experimental data with Taitel & Dukler's (1976) predictions for slightly inclined pipelines, we find that the predictions generally indicate a somewhat greater change with inclination than was observed. Taitel & Dukler (1976) predict significant shifts of the transition to annular flow with varying angle of inclination while almost none were observed. The trend in the transition from intermittent to wavy flow was correctly predicted but the magnitude was greater than observed. Taitel & Dukler (1976) predict complete disappearance of wavy flow at angles of inclination of about 3° while substantial wavy areas were actually observed at considerably higher inclinations both in the present study and by Spedding & Nguyan (1976). In agreement with observations, the Taitel–Dukler predictions showed little change with inclination in the transition to dispersed flow.

Considerably better agreement is obtained between present tests and the recent experimental air–water observations of Barnea *et al.* (1980) in a 2.5-cm line. To accomplish this comparison it must be recognized that Barnea *et al.'s* category of wavy-annular flow falls within the present authors' definition of wavy flow since a continuous liquid film was not maintained at the top of the tube. With this modification, we find that the present observations of the transition to annular flow are in general agreement with those of Barnea *et al.* (1980). Both sets of observations show the transition at about the same gas velocity and little change with increasing angle of inclination. The only area of disagreement is in the chaotic region near the intersection of the dispersed and annular transitions. There Barnea *et al.* report a region of slug flow while annular flow is indicated by present observations. Both Barnea *et al.* and the present study see little difference in the onset of dispersed flow with increasing angle of inclination although Barnea *et al.* report dispersed flow at slightly lower velocities than the present study indicates.

In the transition between intermittent and wavy flow [with Barnea *et al.'s* wavy-annular taken as wavy], Barnea *et al.*'s observations at 1/4° upward are in the region of the present observation at 1/2° upward. Similarly, the observations of Barnea *et al.* at 10° upward are in general agreement with present tests since they are at slightly higher gas rates than the present observations at a 7° upward inclination. The Barnea *et al.* observations at 2° are anomolous since they are in the same region as the present observations taken at 7° upward inclination.

BEHAVIOR IN VERTICAL AND SHARPLY INCLUDED LINES

The flow pattern behavior of the Freon 113 vapor–liquid system in vertical flow in a 2.5-cm tube is illustrated in figure 7(a) and 7(b). Slug flow has disappeared and churn and bubble flow now appear. Annular and dispersed flows appear to be in approximately the same positions as seen in horizontal flow. The effect of increased vapor density (higher gas pressure) is to move the bubble-plug, churn-plug and churn-annular transitions to higher gas mass flow rates.

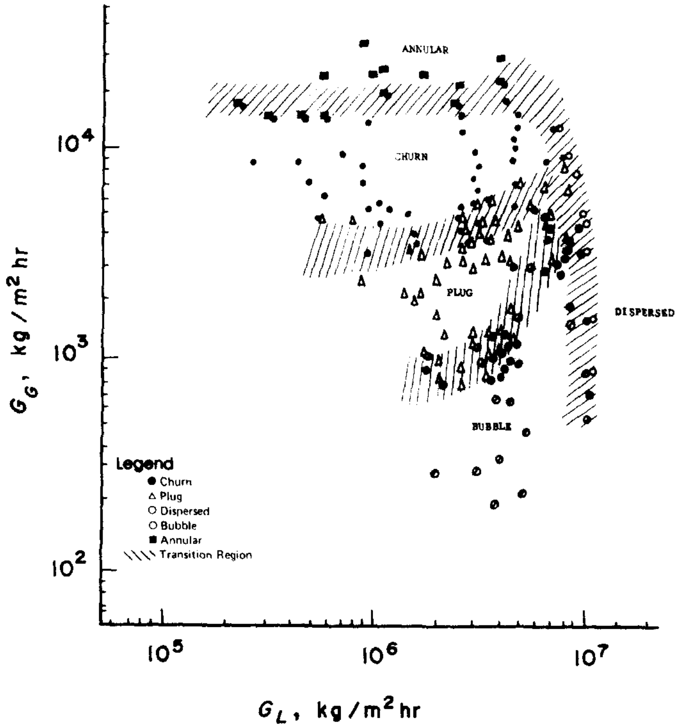
The effect of decreasing the angle of inclination in the Freon system is shown in figures 8(a) and 8(b). Comparison of the full map taken at 45° (figure 8a) with the vertical map, indicates that the angle of inclination has little effect on the transitions to annular and dispersed flow. However, the churn flow region has disappeared and has been replaced by slug flow. The bubble flow region is now restricted to somewhat lower gas flow rates. The effect of angle of inclination on the bubble flow region is further clarified by the partial map taken at a 30° inclination (figure 8b). Here bubble flow is restricted to substantially lower gas rates.

The effect of vapor density and angle of inclination may be confirmed by examination of the data of Spedding & Nguyen (1976) for the air–water system in a 4.5-cm tube. Plots for the observation at inclination angles of 20.75 and 90° are shown in figures 9(a) and 9(b). To simplify the discussion, we have not distinguished between churn, plug and slug flow but have characterized all of the flow patterns as "intermittent" flow. This is consistent with the procedure followed in developing the horizontal pipeline flow maps.

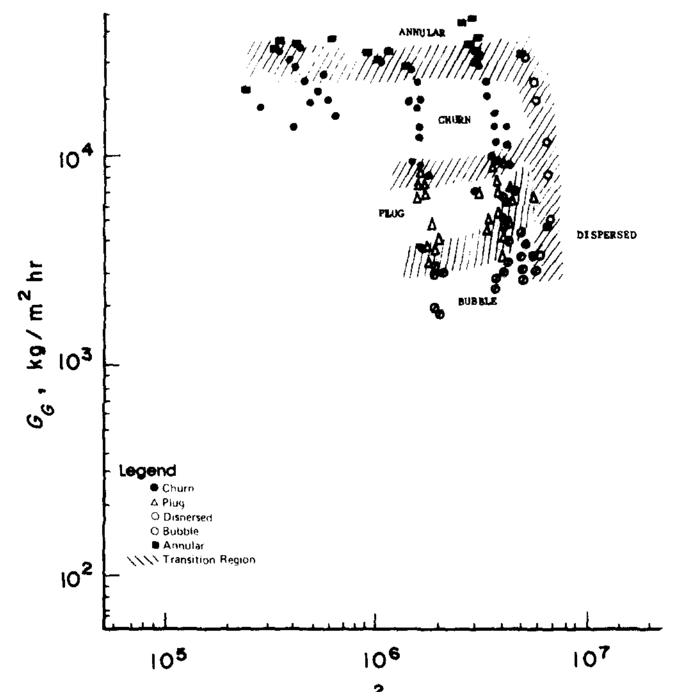
Examination of figures 9(a) and 9(b) show that, as expected, the annular flow transition is affected only very slightly by the angle of inclination. However, the bubble flow transition is shifted to lower gas flow as the inclination angle is decreased. Comparison of these maps with the Freon maps shows that the decreased vapor density has shifted both the annular and bubble transitions to substantially lower gas mass flow rates. The tests were not carried out at sufficiently high total flow rates to encounter dispersed flow.

ANALYSIS OF OBSERVATIONS IN VERTICAL AND SHARPLY INCLINED LINES

The vertical flow data on the transition between plug and churn flow were compared to Taitel & Dukler's (1977) prediction. In addition to the data from the present study, the air–water data of Hewitt & Rodgers (1969) and the high pressure (33.5 and 67 bars) data of Benett *et al.* (1965) were included. A very poor comparison was obtained. Rough agreement between the

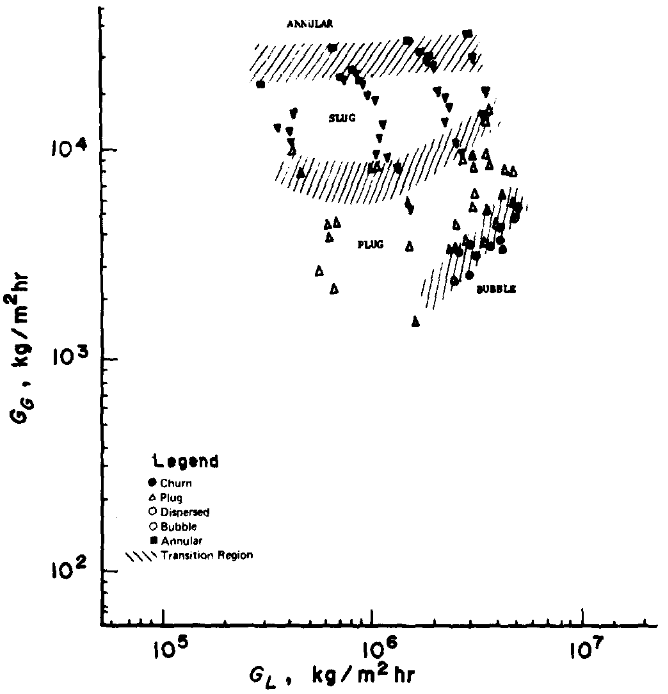


(a)

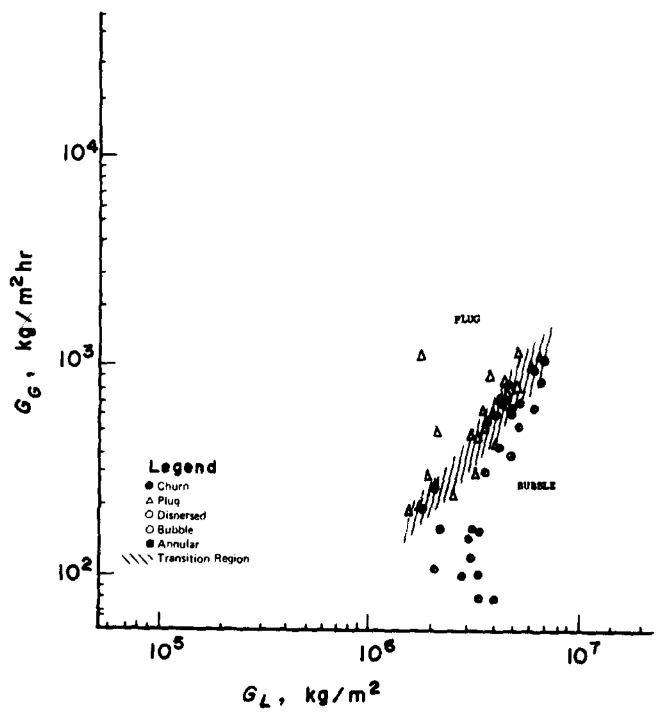


(b)

Figure 7. Flow patterns for Freon 113 in vertical lines ($P \simeq 2$ bar and ~ 4 bar), (a) $p = 2$ bar, (b) $p = 4$ bar.

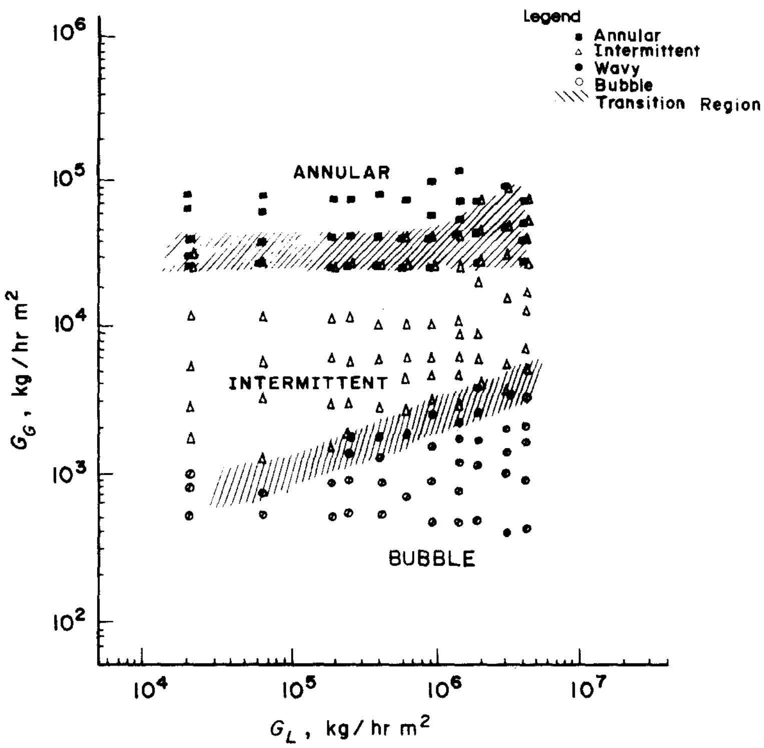


(a)

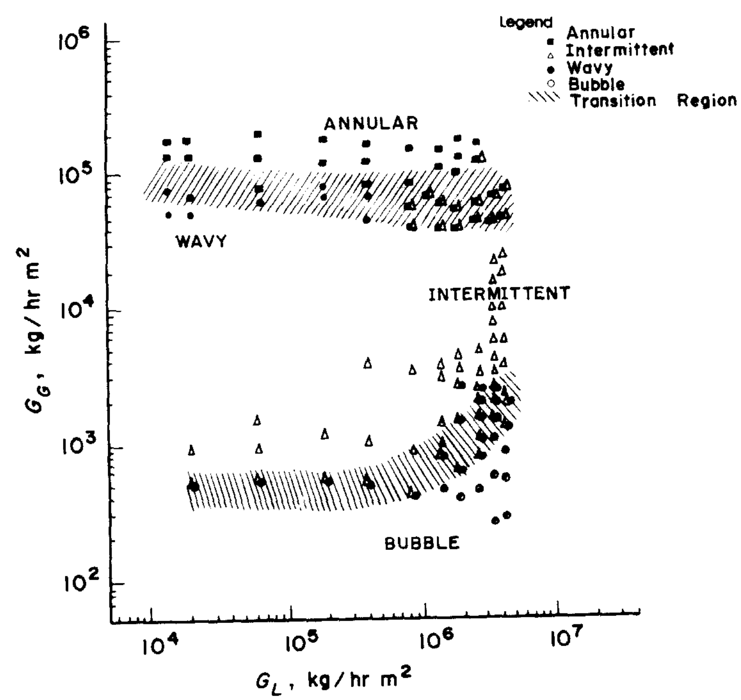


(b)

Figure 8. Flow patterns for Freon 113 in inclined flow ($\theta = 45°$ and 30°, $P \simeq 2$ bar), (a) $\theta = 45°$, (b) $\theta = 30°$.



(a)



(b)

Figure 9. Flow patterns for air–water in vertical and sharply inclined lines ($\theta = 90°$ cm 20.75°, line dia. = 4.5 cm, data of Spedding *et al.*), (*a*) $\theta = 90°$, (b) $\theta = 20.75°$.

various data sets could be obtained by plotting V^*_{SG} vs V^*_{SL} where

$$V^*_{SG} = V_{SG}\{\rho_g/[gD(\rho_l - \rho_g)]\}^{1/2}$$
$$V^*_{SL} = V_{SL}\{\rho_l/[gD(\rho_l - \rho_g)]\}^{1/2}.$$

The results obtained are shown in figure 10.

In view of the limited agreement shown in figure 10 as well as the desire to be consistent with the approach taken for horizontal lines, it was decided to follow the procedure used in figure 9 and combine "plug" and "churn" flow as "intermittent" flow. As before, the intermittent region also includes the "slug" flow pattern seen in inclined lines. With this simplification, there are only three transitions of concern; transition to annular flow, transition to dispersed flow and the intermittent–bubble transition.

At high mass velocities it is to be expected that inertial forces will greatly exceed gravitational forces and hence the orientation of the test section should have little effect. Accordingly, the dispersed transition data obtained in the present tests were compared with the predictive method[3] found successful for horizontal and slightly inclined lines. The comparison is shown in figure 11 where the quantity

$$\left[\frac{|(\mathrm{d}p/\mathrm{d}x)|_{SL}}{(\rho_L - \rho_G)g}\, g_c\right]^{1/2}\left[\frac{g_c\sigma}{(\rho_L - \rho_G)gD^2}\right]^{1/4}$$

is plotted vs X, the Martinelli parameter. Equation [3] predicts that the transition should be

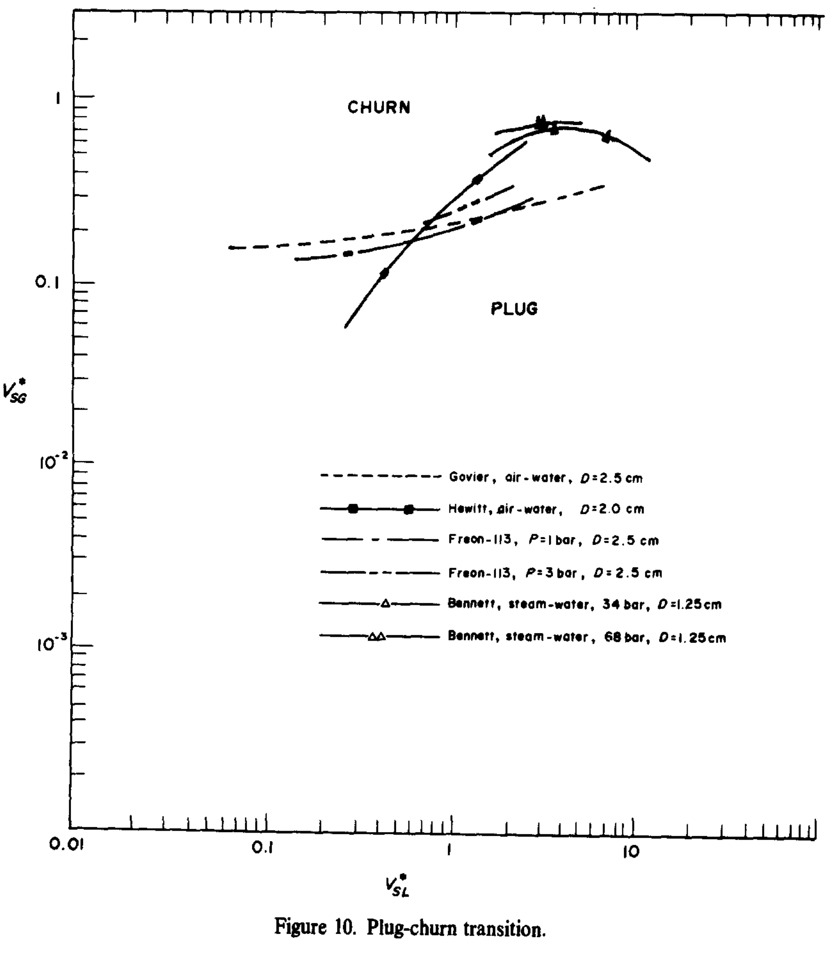


Figure 10. Plug-churn transition.

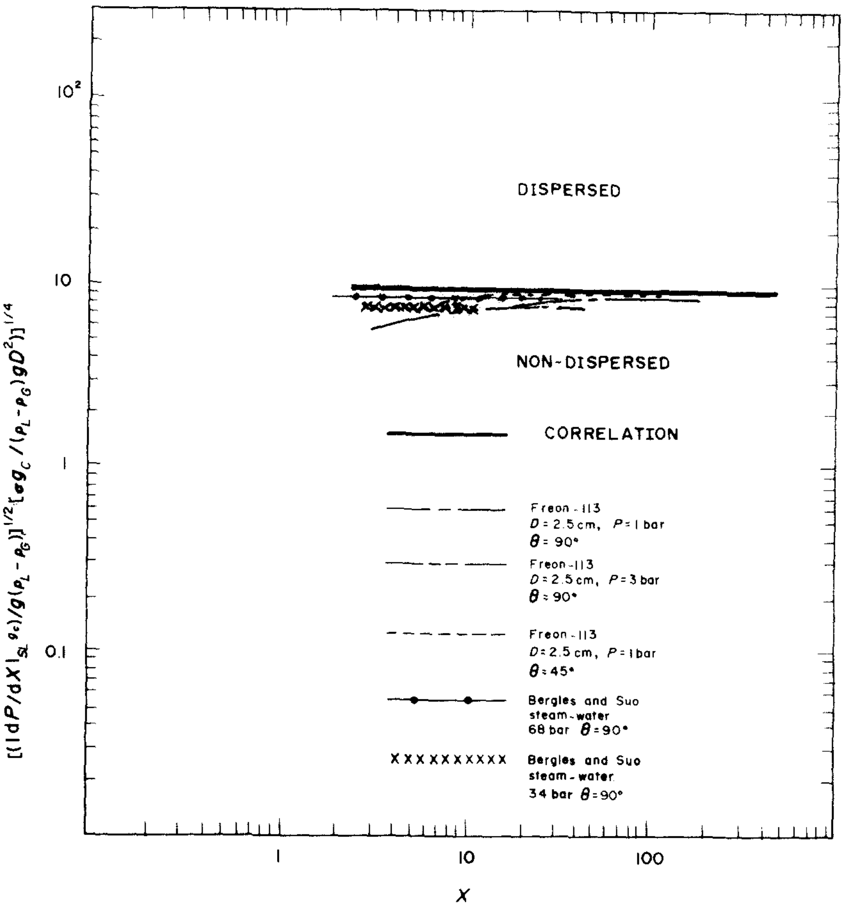


Figure 11. Comparison of observed dispersed flow transition in vertical and sharply inclined lines with prediction.

independent of X and that is what is observed. No effect of orientation is seen, the Freon data from vertical and 45° inclined lines agree well with the prediction based on horizontal lines. This is consistent with the observations at slight angles of inclination where the same agreement was observed (see figure 6). It is unfortunate that most of the data in the literature obtained in sharply inclined and vertical lines were obtained at mass velocities below those at which dispersed flow occurs. However, the data of Bergles & Suo (1966) were in the correct range and are included in the comparison.

The available data on the transition to annular flow in vertical lines was compared to both the predictions of Taitel & Dukler (1977) and those of Weisman *et al.* (1979). Figure 12 shows that the prediction of Taitel & Dukler (1977) agrees reasonably well with the data. It is also found that the prediction of Weisman *et al.* (1979) [1], agrees well with the available data (see figure 13). This latter approach has the advantage that it is consistent with the approach found successful in correlating the behavior in horizontal and slightly inclined lines.

The ability of [1] to predict the transition to annular flow in inclined lines is shown in figure 14(a) and 14(b). The data include inclination angles varying from 2 to 90° and Freon systems as well as air–water systems. It would thus appear that the predictions of [1] holds for all angles of inclination. It should be noted that [1] may be simplified by using the same exponent for both Fr and Ku. We then may write

$$\mathrm{Fr\,Ku} = 25\left(\frac{V_{SG}}{V_{SL}}\right)^{5/8} \qquad [7]$$

with very little loss in accuracy.

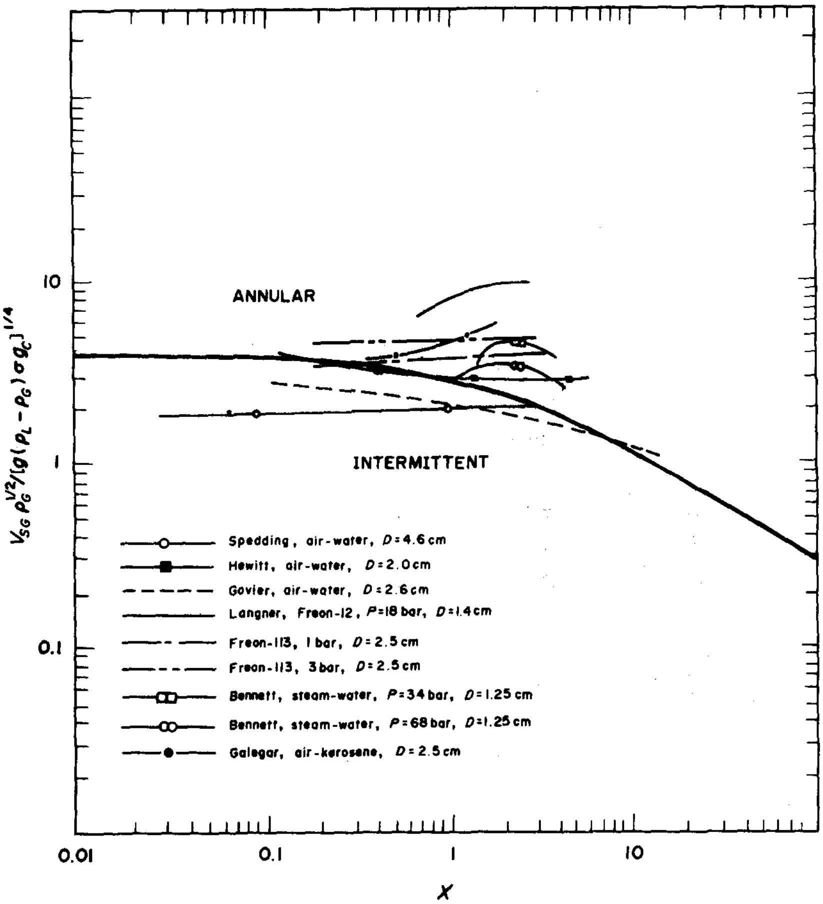


Figure 12. Comparison of observed annular flow transition in vertical lines with Taitel–Dukler prediction.

When Taitel & Dukler's (1977) prediction of the transition between intermittent and bubble flow [5] was compared to the data, very poor agreement was obtained. Examination of the available data for the intermittent vertical flow indicated that a simple relationship existed between the gas-phase Froude number and the Froude number based on total volumetric flow.† This may be seen in figure 15. The data may be represented by

$$\frac{V_{SG}}{\sqrt{(gD)}} = 0.45\left(\frac{V_{SG}+V_{SL}}{\sqrt{(gD)}}\right)^{0.78} \qquad [8a]$$

or

$$\mathrm{Fr}_G = 0.2(\mathrm{Fr}_t)^{1.56}. \qquad [8b]$$

Figure 8 includes data from Freon steam–water at varying pressures and air–water systems. Line diameters range from about 1 to 4 cm. It is believed that the property and line size variations are sufficient to confirm the proposed correlation.

As previously noted, the transition to bubble flow is shifted to lower gas flows as the angle of inclination to the horizontal is decreased. This effect was seen both in the present study with Freon 113 and the Spedding & Nguyen (1976) study with air–water. Reasonable agreement between the various data sets was obtained by modifying [8] so that it included a function of θ, the angle

†Kozlov (1954) first suggested that this parameter be used for flow pattern mapping.

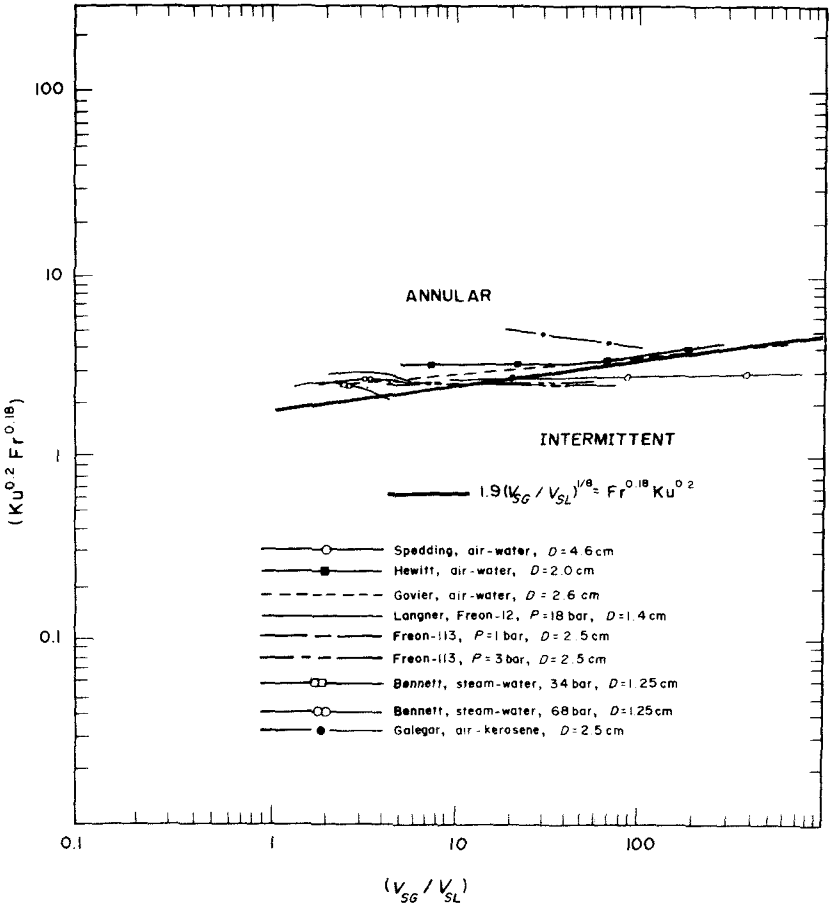


Figure 13. Comparison of observed annular flow transition in vertical lines to proposed correlation.

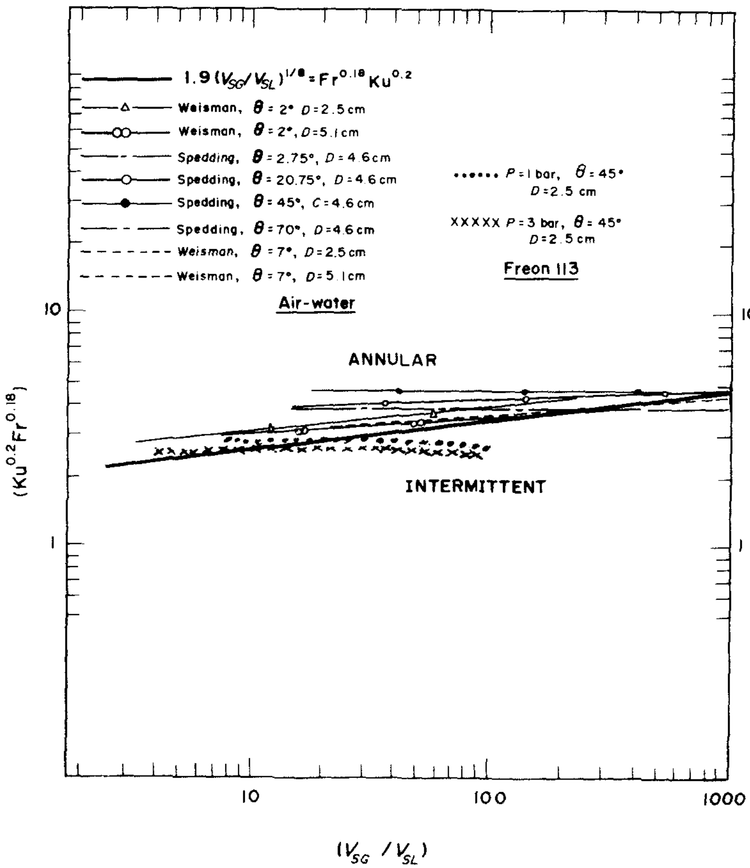


Figure 14. Comparison of observed annular flow transition in inclined lines to proposed correlation.

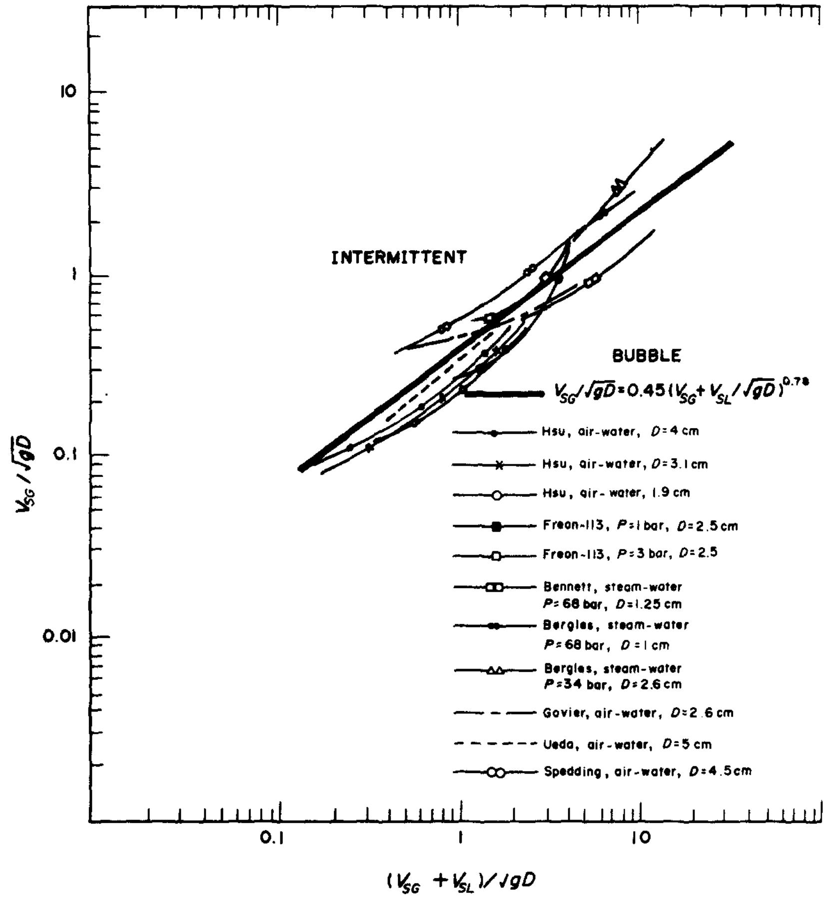


Figure 15. Comparison of observed transition between intermittent and bubble flow in vertical lines to proposed correlations.

of inclination. As shown in figure 16 good agreement was obtained by using

$$\frac{V_{SG}}{\sqrt{(gD)}} = 0.45\left(\frac{V_{SG}+V_{SL}}{\sqrt{(gD)}}\right)(1-0.65\cos\theta). \qquad [9]$$

Note that [9] reduces to [8] when $\theta = 90°$.

It should be observed that data at inclination angles as low as 2.75° were fitted by [9]. Further, reasonable agreement is obtained when [9] is compared with the appearance of bubble flow seen by Choe *et al.* (1978) at very low gas flows in a 5.1-cm horizontal line. Thus, the bubble–intermittent transition line should be added to the horizontal and slightly inclined flow pattern maps if these are extended to lower gas flow rates.

OVERALL FLOW PATTERN MAP FOR VERTICAL AND SHARPLY INCLINED LINES

The overall flow pattern map previously shown useful for horizontal and slightly inclined lines, may be readily adopted to vertical and sharply inclined lines. The transitions to annular and dispersed flow remain unchanged and hence can be represented in terms of V_{SG}/ϕ_1 and V_{SL}/ϕ_2 where ϕ_1 and ϕ_2 provide the necessary corrections for fluid properties and geometry (see table 1). Since wavy flow is not seen (or is seen only very briefly in the annular-intermittent transition region) in vertical or very sharply inclined lines, the intermittent–bubble transition is the only line which must be added to this map.

Since the transition between bubble and intermittent flow is governed by the Froude number

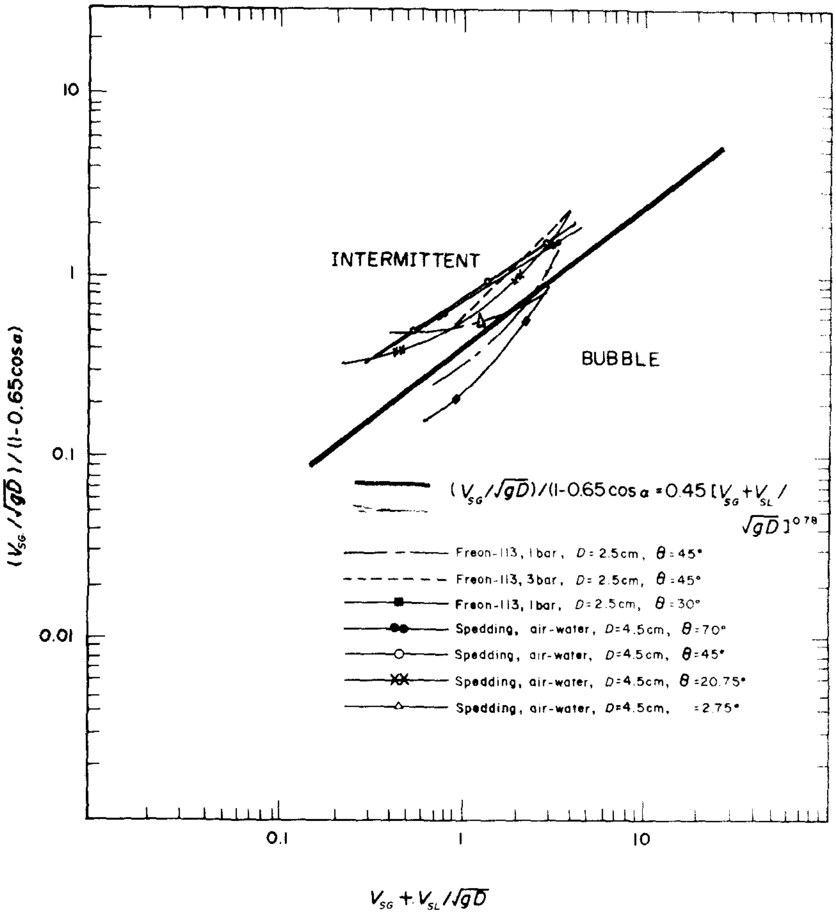


Figure 16. Comparison of observed transition between intermittent and bubble flow in inclined lines to proposed correlations.

based on total volumetric flow rather than liquid flow, the correlation of [9] cannot be directly placed on the proposed map. However, a close approximation is readily obtained if we set the diameter correction to be $(D/D_s)^n$ where n is a function of the liquid velocity. We find that for this transition

$$\phi_2 = 1.0 \quad \phi_1 = (D/D_s)^n(1 - 0.65\cos\theta) \qquad [10]$$

where $n = 0.26\,e^{-0.17(V_{SL}/V_{SL}^s)}$; V_{SL}^s = reference liquid velocity = 0.3 m/s; and D_s = standard pipe dia. (2.54 cm). The overall flow map obtained is shown in figure 17 and values of ϕ_1 and ϕ_2 given for each of the transitions in table 1.

Care should be observed in using figure 17. The map is limited to the vertical and sharp angles of inclination. Wavy flow will appear at low angles of inclination and at angles of inclination below that specified by [6]; stratified flow will appear. Further, the map should probably be used only for lines of 2.5 cm and larger in view of the anomalous behavior seen in slightly inclined 1.2-cm lines.

The transition to dispersed flow should not be extrapolated to significantly higher gas velocities than those shown in figure 18. Previous work on horizontal lines (Weisman *et al.* 1979) has indicated that this transition is dependent on the total mass flow rate rather than on the liquid flow rate alone. Although at the low qualities for which the map is drawn there is very little difference between the total and the liquid flow rates, this is obviously not true at higher qualities.

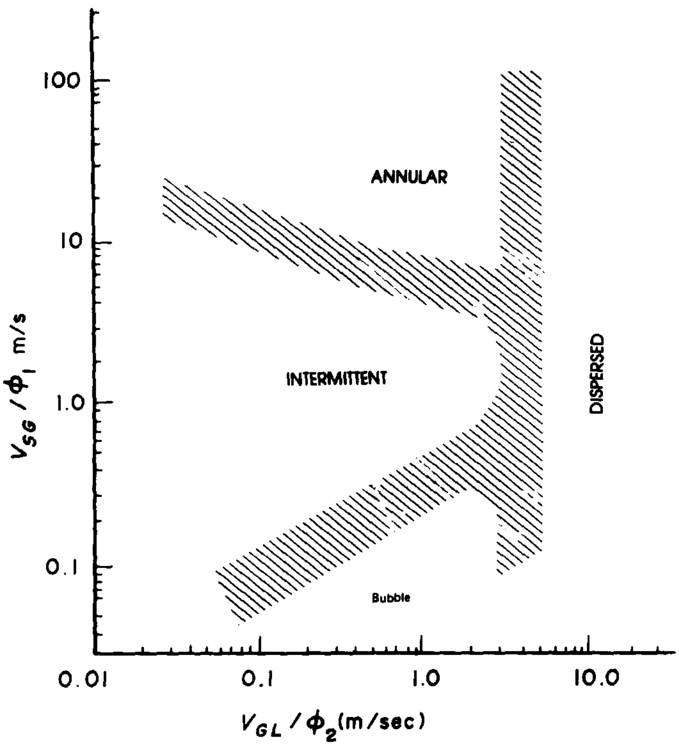


Figure 17. Overall flow pattern map for vertical and sharply inclined lines.

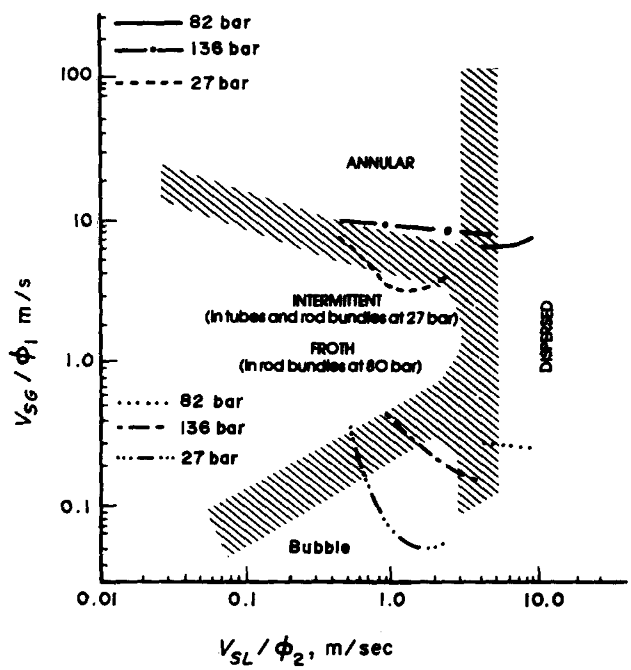


Figure 18. Comparison of overall flow pattern map with rod bundle data.

It is interesting to compare the overall flow pattern map of figure 17 with the recent rod bundle data of Petersen & Williams (1978). In the Petersen and Williams' tests, steam–water mixtures at pressures of 27, 81 and 135 bar flowed upward through a 4-rod bundle. The rods were 0.64 cm o.d. arranged in a single row on a 0.87-cm pitch and grid spacers were placed every 12.7 cm in the axial direction.

Intermittent, bubble and annular flow were observed. The observed transitions between these flow patterns are compared to the flow map for round tubes in figure 18. The data taken at 27 bar show the same sequence of events as expected on the basis of round tube data; bubble, intermittent and annular flow successively appear with increasing gas flow rate. The bubble, intermittent and the annular flow transitions are in the general regions of the round tube transitions. At the higher pressures, the transitions are again in the regions expected but intermittent flow has been replaced by froth flow. It is known that a screen present in a line tends to homogenize the flow immediately downstream of the screen. It may be postulated that (a) the grids act like a screen and tend to homogenize the flow, and (b) that this homogenization is easier at high pressures where there is less of a density difference between the phases.

CONCLUSION

The data obtained in this investigation, in conjunction with the data available in the literature, have provided a clear picture of flow pattern behavior in upwardly inclined and vertical lines. The behavior is consistent with that seen in horizontal lines. Indeed, for line sizes of 2.5 cm and above, both the annular and dispersed transitions are the same as those determined for horizontal lines.

By considering plug, slug and churn flow as intermittent flow, the annular and dispersed transition lines, together with one new transition line (bubble–intermittent), are sufficient for characterization of the flow in sharply inclined and vertical lines. The bubble–intermittent transition can be described by a relationship between the gas phase and total Froude numbers. This transition correlation has been shown to apply to liquids and gases of widely varying properties.

The data obtained for slightly inclined lines show that the only changes from the horizontal flow pattern map are the disappearance of stratified flow, restriction of the wavy flow region and expansion of the bubbly flow region. A criterion has been devised for the disappearance of stratified flow. The bubble–intermittent transition correlation devised for sharply inclined lines is also applicable at low upward inclinations.

Behavior in downwardly inclined lines may be expected to be somewhat different than that seen here; particularly the behavior of the separated intermittent transition. Experimental studies of this behavior would be desirable.

REFERENCES

BAKER, O. 1954 Simulatious flow of oil and gas. *Oil & Gas J.* **53**, 185–190.

BARNEA, D., SHOHAM, O., TAITEL, Y. & DUKLER, A. E. 1980 Flow pattern transition for gas–liquid flow in horizontal and inclined pipes. *Int. J. Multiphase Flow* **6**, 217–225.

BENNETT, A. W., HEWITT, G. F., KEARSEY, H. A., KEEYS, R. K. F. & LACEY, P. M. C. 1965–66 Flow visualization studies of boiling at high pressure. *Proc. Inst. Mech. Engrs* Part 3C, 1–13.

BERGLES, A. & SUO, M. 1966 Investigation of boiling water flow regimes at high pressure. In *Proc.* 1966 *Heat Trans. & Fluid Mech. Inst.* (Edited by M. A. Saad & J. A. Miller), pp. 79–88. Stanford Press, California.

CHOE, W. G., WEINBERG, L. & WEISMAN, J. 1978 Observation and correlation of flow pattern transition in horizontal, cocurrent gas liquid flow. In *Two Phase Transport and Reactor Safety* (Edited by T. N. VEZIROGLU and S. KAKAC), pp. 1357–1375. Hemisphere, Washington.

GALEGAR, W. C., STOVALL, W. B. & HUNTINGTON, R. L. 1954 More data on two-phase vertical flow. *Petroleum Refiner* **33**, 208.

GOVIER, G. W., RADFORD, B. A. & DUNN, J. S. C. 1957 Upwards vertical flow of air–water mixtures. *Can. J. Chem. Engng* **35**, 58–70.

HEWITT, G. E. & RODGERS, D. N. 1969 Studies of two-phase flow patterns by simultaneous X-ray and flash photographs. U.K.A.E.A. Rep. AERE-M2159.

HSU, Y. C. & DUDOKOVIC, M. P. 1980 Liquid recirculation in gas-lift Reactors. *Proc. 2nd Multiphase Flow and Heat Transfer Symp.*, Miami, FL. Hemisphere, Washington.

KOZLOV, B. K. 1954 Forms of flow of gas–liquid mixtures and their stability limits in vertical tubes. *Zh. Tekh. Fiz.* **24**, 2285–2288.

LANGNER, H., VIECENZ, H. J. & ZETZMAN, K. 1978 Some special investigation of fluid behavior in two-phase flow. In *Two-Phase Transport and Reactor Safety* (Edited by T. VEZIROGLU and S. KAKAC), pp. 225–252. Hemisphere, Washington.

MANDHANE, J. M., GREGORY, G. A. & AZIZ, K. A. 1974 A flow pattern map for gas–liquid flow in horizontal pipes. *Int. J. Multiphase Flow* **1**, 537–551.

PETERSEN, A. C., JR. & WILLIAMS, C. L. 1978 Two-phase flow patterns with high pressure water in a heated four rod bundle. *Nucl. Sci. Engng* **68**, 155–169.

SIMPSON, H. E., RONNEY, D. H., GRATTON, E. & AL-SAMARRAL, F. 1977 Two-phase flow in large diameter horizontal lines. Paper H6, *European Two-Phase Flow Group Meeting*, Grenoble.

SPEDDING, P. L. & NGUYEN, V. T. 1976 Data on holdup, pressure loss and flow pattern for two-phase air–water flow in an inclined pipe. Rep. 122, Univ. of Auckland, Auckland, New Zealand. (Also published as, Regime maps for air–water two-phase flow. *Chem. Engng Sci.* **35**, 779–793.)

TAITEL, Y. & DUKLER, A. E. 1976 A model for predicting flow regime transitions in horizontal and near-horizontal gas–liquid flow. *AIChE J.* **22**, 147–155.

TAITEL, Y. & DUKLER, A. E. 1977 Flow regime transitions for vertical upward gas–liquid flow. Paper presented at *70th Ann. Meeting AICHE,* New York.

UEDA, T. 1958 Studies of the flow of air–water mixtures. *JSME* **1**.

WEISMAN, J. 1977 Experimental data on two-phase pressure drop across area changes during flow transients. U.S.N.R.C. Rep. NUREG-0306, Vol. 2.

WEISMAN, J., DUNCAN, D. & GIBSON, J. 1979 Effect of fluid properties and pipe diameter on two-phase flow patterns in horizontal lines. *Int. J. Multiphase Flow* **5**, 437–462.