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Transition from stratified to intermittent flows in small angle upflows

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Abstract

The effect of small upward inclinations on the transition from stratified to slug flow was studied. Experiments were conducted with air and water at atmospheric pressure, flowing in a pipe with a diameter of 0.0763 m and a length of 23 m, at upward inclinations of 0°, 0.05°, 0.2°, 0.4° and 1.2°. Measurements were made of the location of the gas–liquid interface at several locations along the pipe and of the pressure gradient. A critical gas velocity, U_{SGC}, is determined below which an equilibrium stratified flow was not observed. The mechanism of slugging for upflows is found to differ from horizontal flows in a region in which the liquid layer in an equilibrium stratified flow cannot be supported by the interfacial shear of the gas phase. Within it, slugs are formed intermittently at the inlet. After slug formation, the depleted liquid layer builds up until the height at the inlet is such that a Kelvin–Helmholtz instability can trigger the formation of a new slug. Slugs carry liquid out of the pipe; the stratified flow that exists between slugs carries liquid in the opposite direction. The critical gas velocity is found to correspond to the maximum U_{SG} in the reversed flow region. Outside this reversed flow region, the transition to slugging can be predicted by the long wavelength viscous stability analysis, by the Kelvin–Helmholtz analysis, or by the slug stability analysis, but slug stability is the dominant mechanism for the system that was studied. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Gas–liquid pipe flow; Slug flow; Stratified–slug flow transition; Pipe inclination; Slug mechanism

1. Introduction

Slugs are commonly observed in near horizontal concurrent gas–liquid flows. They are formed when waves on the surface of a stratified liquid layer, intermittently, grow to reach the top of the

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pipe. The liquid then fills the whole cross-section, to produce highly aerated masses of liquid that propagate down the pipeline at a velocity close to that of the gas phase.

A consideration of the stability of a stratified flow has led to several predictions of the conditions at which slugs will be observed. Kordyban and Ranov (1970) suggested that slugs evolve from large amplitude waves through a Kelvin–Helmholtz instability. Wallis and Dobson (1973) used an inviscid linear stability analysis to define the gas velocity at which long wavelength waves are generated. They found that the predicted critical gas velocity is approximately twice that needed to form slugs. Taitel and Dukler (1976) provided a correction to the linear inviscid analysis, based on the notion that the stability of non-linear waves needs to be considered. Lin and Hanratty (1986) developed a linear analysis that includes viscous effects and obtained results that are similar to those of Taitel and Dukler for an air–water system at atmospheric pressure. They showed that the transition is best described by a plot of the influence of the superficial gas velocity, U_{SG}, on the critical height of the liquid layer, h, normalized by the pipe diameter, D. Good agreement was obtained with the observed transition for air and water flowing in a horizontal pipe at low gas velocities. This paper examines the differences between horizontal flows and upflows at small angles. Stratified flows in upwardly inclined pipes will have larger liquid heights than are less stable. Of particular interest are the definition of a criterion for transition and the establishment of a mechanism for slug formation, which can be used to develop a relation for the frequency of slugging.

A number of investigators have studied interfacial patterns in inclined pipes. Barnea et al. (1980) examined air–water flows with upward inclinations of 0.25°, 0.5°, 1°, 2°, 5° and 10° and with downward inclinations of 1°, 2°, 5° and 10°. Kokal and Stanislav (1989) carried out studies with air and water flowing in a pipe with upward inclinations of 0–9°. Grolman et al. (1996) developed flow regime maps for upflows at angles between 0.1° and 6° in pipes with diameters of 0.026 and 0.051 m for air–water and air–tetradecane systems at atmospheric conditions. These studies show that lower liquid flow rates are required to produce slugs in upflows. The stratified region in a flow regime map, that uses the superficial gas and liquid velocities, shrinks to a small bell-shaped area for an inclination of only +1° (Grolman et al., 1996). At angles above 10°, stratified flow is not observed (Barnea et al., 1980).

These results have been interpreted by Barnea et al. (1980) and Kokal and Stanislav (1989) with the analysis of Taitel and Dukler for horizontal stratified flows by arguing that the critical h/D for a given U_{SG} would be the same in horizontal and inclined flows. The latter authors used a friction factor relation proposed by Chen (1984).

Stability analyses require an accurate model for a stratified flow. In particular, the influence of waves at the gas–liquid interface needs to be known. The effect is described in terms of the ratio of the interfacial friction factors to what would be observed at a smooth wall f_i/f_s. The analysis of Taitel and Dukler assumes a smooth interface, that is $f_i/f_s = 1$. Clearly, this introduces errors which are particularly important at transition, where large amplitude waves can be present. Andritsos and Hanratty (1987) and Andritsos (1986) have presented values of f_i/f_s that were obtained from measurements of the pressure gradient and the height of the liquid.

A slug propagating down the pipeline scoops up liquid at its front and sheds liquid from its tail. It will grow or decay depending on the relative magnitudes of the rates of these two processes. Woods and Hanratty (1996) showed that the ability of slugs to grow depends on the height of liquid in front of the slug and that, at a particular gas velocity, there is a minimum height of liquid in a stratified flow below which stable slugs cannot be formed. Slug stability is found to be the dominating mechanism for the transition to slug flow at high gas velocities.

The data presented in this paper were obtained at angles of 0°, 0.05°, 0.2°, 0.4° and 1.2° in a pipeline that has a diameter of 0.0763 m and a length of 23 m. The transition from stratified to slug flow was studied for each angle over a range of gas velocities 0.8–10 m/s. At transition, the liquid height was obtained from measurements with conductance probes at several locations along the pipe. The pressure gradient was also determined in order to obtain information on the interfacial stress.

At inclinations above 0.2°, liquid is carried out of pipe by slugs when conditions are such that a steady forward moving stratified flow cannot be maintained. Liquid pools at the inlet until its height is sufficient to form a slug, by a Kelvin–Helmholtz mechanism. This pooling occurs below critical gas velocities at which the shear of the gas phase is just sufficient to pull the liquid up the pipe. The region of reversed flows can be predicted from a momentum balance on a stratified flow. The maximum gas velocity in this region defines the critical conditions, U_{SGC}, below which an equilibrium stratified flows will not exist. Outside the reversed flow region, the onset of slugging can be predicted by the long wavelength viscous stability analysis of Lin and Hanratty (1986), the slug stability analysis of Woods and Hanratty (1996) or the Kelvin–Helmholtz analysis explored by Andritsos et al. (1989).

2. Theory

2.1. Stability of a stratified flow

The classical inviscid Kelvin–Helmholtz analysis of a stratified flow considers an infinitesimal neutrally stable wave at the interface. The following relation is derived between the wave velocity, C, and the wave number $k = 2\pi/\lambda$, for a gas with velocity U and a liquid with velocity u (Milne-Thomson, 1968):

$$k\rho_L(u - C)^2 \coth kh + k\rho_G(U - C)^2 \coth kH = g(\rho_L - \rho_G) + \sigma k^2. \tag{1}$$

Here, H is the height of the gas layer, h the height of the liquid layer, ρ_G the gas density, ρ_L the liquid density, g the acceleration of gravity, and σ is the surface tension. Instability is defined by a complex or imaginary value of C. This occurs when the destabilizing effects of liquid inertia and gas phase pressure variations 180° out of phase with the wave profile are larger than the stabilizing effects of gravity and surface tension. Eq. (1) gives the following relations for the neutral stability (or the onset of instability) of a stratified flow:

$$(U - u)^2 = [(g/k)\cos\theta(\rho_L - \rho_G)/\rho_G + \sigma k/\rho_G][\tanh(kH) + \rho_G/\rho_L \tanh(kh)], \tag{2}$$

$$C_R = (\rho_G Uh + \rho_L uH)/(\rho_L H + \rho_G h). \tag{3}$$

Eqs. (2) and (3) simplify if the gas is deep ($\tanh(kH) \cong 1$). Then, if ρ_G/ρ_L is small,

$$(U - u)^2 = (g/k)\cos\theta(\rho_L - \rho_G)/\rho_G + \sigma_k/\rho_G, \tag{4}$$

$$C_R = u. \tag{5}$$

The minimum relative velocity at which (4) is satisfied gives a critical relative gas velocity, $(U-u)_{\mathrm{Crit}}$ and a critical wave number,

$$k_{\mathrm{Crit}} = (\rho_{\mathrm{L}} g \cos\theta/\sigma)^{0.5}. \tag{6}$$

The critical relative velocity predicted for flow in a channel is a close approximation to the critical relative velocity for a stratified flow in a round pipe. For air and water at atmospheric pressure, (4) and (6) predict instability to occur at $(U-u)_{\mathrm{Crit}} = 6.6$ m/s and $\lambda = 1.7$ cm.

If one considers long wavelength waves, for which $kh \ll 1$ and $kH \ll 1$, Eq. (1) gives the following relation for the initiation of an instability if $\rho_{\mathrm{G}}/\rho_{\mathrm{L}}$ is small:

$$\rho_{\mathrm{G}}(U-u)^2 = \rho_{\mathrm{L}} g H, \tag{7}$$

As already mentioned, Wallis and Dobson (1973) found that (7) overpredicts the critical gas velocity by a factor of about 2. From (7), (4) and (1), it is seen that the inviscid analysis predicts that liquid inertia is neither stabilizing nor destabilizing. Taitel and Dukler (1976) suggested that a factor of the form $(1-h/D)$, should be included in the right-hand side of (7). For a round pipe with an inclination of θ, and for $U \gg u$, they proposed the following relation:

$$\rho_{\mathrm{G}} U^2 = \frac{(1-(h/D))\rho_{\mathrm{L}} g \cos\theta A_{\mathrm{G}}}{\mathrm{d}A_{\mathrm{L}}/\mathrm{d}h}, \tag{8}$$

where A_{G} and A_{L} are the cross-sectional areas occupied by the gas and liquid, respectively, Lin and Hanratty (1986) and Wu et al. (1987) used a long wavelength analysis which introduces the influences of a shear stress at the gas–liquid interface and a resisting stress at the wall. An extra term representing the destabilizing effect of liquid inertia is then introduced into (7) because $C_{\mathrm{R}} \neq u$

$$A_{\mathrm{G}}\rho_{\mathrm{G}}(U-C_{\mathrm{R}})^2 + A_{\mathrm{L}}\rho_{\mathrm{L}}(C_{\mathrm{R}}-u)^2 = \frac{g A_{\mathrm{L}}\rho_{\mathrm{L}}\cos\theta}{\mathrm{d}A_{\mathrm{L}}/\mathrm{d}h}. \tag{9}$$

Lin and Hanratty (1986) found that similar results are obtained from (8) and (9) for air–water systems at atmospheric pressure if $f_{\mathrm{i}}/f_{\mathrm{s}} = 1$. They concluded that the correction made by Taitel and Dukler (1976) accounted for effects of liquid inertia. However, for other fluid pairs, Eq. (8) was found to be unsatisfactory since the correction for inertia is a complicated function of the fluid viscosity, as well as of h/D.

Detailed observations of interfacial behaviour at the transition to slug flow in a horizontal pipe at low U were made by Fan et al. (1993). These revealed an appearance of small amplitude long wavelength waves at gas velocities close to the critical. However, slugs were observed to evolve from waves with lengths of 16–20 cm which evolve from smaller wavelength waves by a non-linear growth mechanism. Woods et al. (2000) observed that, if the pipeline is inclined slightly downward, these smaller wavelength waves are damped and that the slugs evolve directly from small amplitude long wavelength waves. The viscous linear stability analysis of Lin and Hanratty (1986) also predicts the onset of slugging in a horizontal pipe, even though physical observations suggest a non-linear mechanism.

2.2. Modelling of a stratified flow

A steady-state stratified flow is modelled by considering a fully developed cocurrent flow of gas and liquid in a channel of width, B, inclined from the horizontal at an angle, θ. A momentum balance describes the shear stress, τ, at any point in the liquid as follows:

$$\tau = (y - m)\frac{\mathrm{d}p}{\mathrm{d}x} - \rho_L(y - m)g_x + \tau_i. \tag{10}$$

The gas flow is assumed to be turbulent and to travel as a plug. A similar balance for the gas phase gives

$$(B - m)\left[\frac{\mathrm{d}p}{\mathrm{d}x} - \rho_G g_x\right] = -\tau_i - \tau_{WG}, \tag{11}$$

where $g_x = g\cos\theta$ and $\tau = \tau_{WL}$ at $y = 0$. Here, m is the thickness of the liquid layer in the channel and y is the distance from the wall. The pressure gradient is designated as $\mathrm{d}p/\mathrm{d}x$. For a turbulent flow, the shear stress at any point in the liquid can be related to the velocity gradient by using an eddy viscosity concept

$$\tau = \rho_l(\varepsilon_L + \upsilon_L)\frac{\mathrm{d}u}{\mathrm{d}y}, \tag{12}$$

where the eddy viscosity is ε_L, the kinematic molecular viscosity is υ_L, and $\mathrm{d}u/\mathrm{d}y$ is the velocity gradient. Henstock and Hanratty (1976) and Andritsos (1986) used the van Driest mixing length relation, derived for single-phase flows, to represent ε_L

$$\varepsilon_L = l^2\left|\frac{\mathrm{d}u}{\mathrm{d}y}\right|, \tag{13}$$

where

$$l = \kappa y\left[1 - \exp\left(-\frac{y}{A\upsilon_L}\left(\frac{\tau}{\rho_L}\right)^{1/2}\right)\right] \tag{14}$$

and κ and A are constants. van Driest suggested values of $\kappa = 0.4$ and $A = 26$.

By specifying the gas velocity and the height of liquid in the channel, the velocity profile in the liquid can be found by equating (10) and (12) and integrating. The flow rate per unit width, Γ, is then given by

$$\Gamma = \int_{y=0}^{y=m} u\,\mathrm{d}y. \tag{15}$$

To maintain a steady-state stratified flow in an upward orientation, the gas to impart sufficient force to the liquid phase, via the interfacial shear, to prevent the liquid from falling back towards the inlet due to gravity. Below a certain gas velocity, it is possible for the liquid layer to reverse direction when the influence of gravity is not balanced by the interfacial shear.

This critical condition was defined by solving the channel flow equations to determine when $\Gamma < 0$. The velocity profile obtained for $\Gamma = 0$ is shown by the dashed line in Fig. 1. Calculation of liquid flow rate for a range of U_{SG}, at constant h/D, are presented in Fig. 2. These show a very

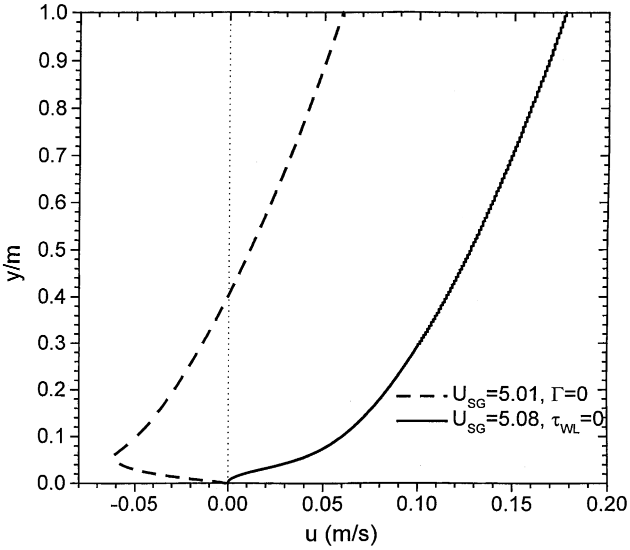

Fig. 1. Computed liquid film velocity profiles for a half-channel ($f_i/f_s = 4$, $\theta = 0.4°$ upflow).

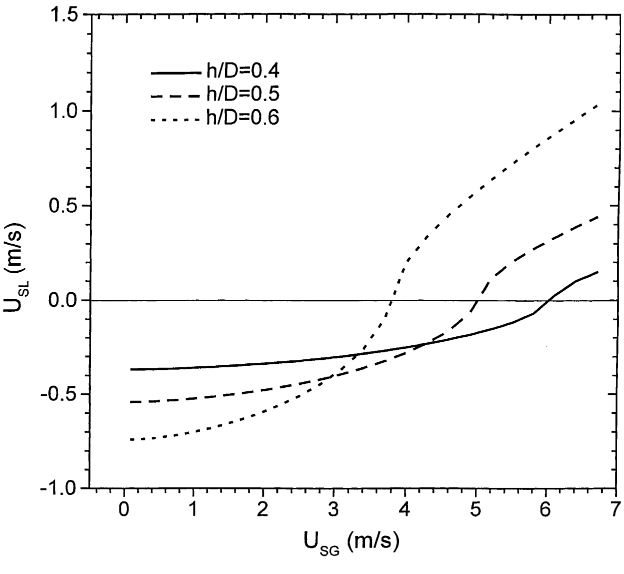

Fig. 2. Calculations of U_{SL} for flow in channel that is inclined upward by 0.4°.

large change of U_{SL} with gas flow in the neighbourhood of $\Gamma = 0$. This suggests that the gas velocity required to produce $\Gamma = 0$ is very close to the condition for which $\tau_{WL} = 0$. The velocity profile for $\tau_{WL} = 0$ is also shown in Fig. 1 as the solid line. As $\mathrm{d}u/\mathrm{d}y = 0$ at the wall, the slope is infinity at the wall.

In pipe co-ordinates, there is no satisfactory method for calculating turbulent velocity profiles. Therefore, the limiting condition of $\Gamma = 0$ is approximated by $\tau_{WL} = 0$. The momentum balances for flow in a pipe are

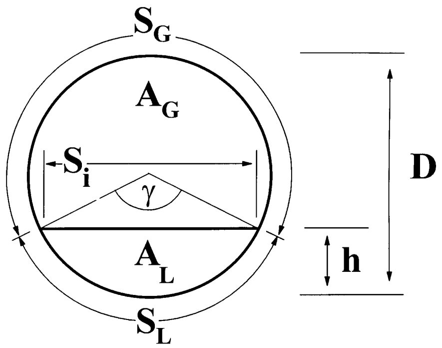

Fig. 3. Illustration of geometry of the idealized two-fluid model in a round pipe.

$$-A_G\left(\frac{dp}{dz}\right) - \tau_{WG}S_G - \tau_i S_i + \rho_G A_G g_x = 0, \tag{16}$$

$$-A_L\left(\frac{dp}{dz}\right) - \tau_{WL}S_L + \tau_i S_i + \rho_L A_L g_x = 0. \tag{17}$$

The geometrical parameters A_i and S_i are defined in Fig. 3. The gas phase wall shear stress, τ_{WG}, is calculated by using the Blasius equation for turbulent flow

$$\tau_{WG} = \frac{f_s \rho_G U^2}{2}, \quad f_s = 0.046\left[\frac{\rho_G U D_{HG}}{\eta_G}\right]^{-0.2}, \tag{18}$$

where D_{HG} is the hydraulic diameter of the gas,

$$D_{HG} = 4\frac{A_G}{S_G + S_i}. \tag{19}$$

A critical gas velocity can be calculated with (16) and (17) by the setting of $\tau_{WL} = 0$. A knowledge of f_i is needed since

$$\tau_i = \frac{f_i \rho_G U^2}{2}. \tag{20}$$

2.3. Stability of a slug

Fig. 4 gives a pictorial representation of a slug moving over a stratified liquid layer of area A_{L1} and velocity u_1, which is assumed to contain no air bubbles. Liquid is incorporated into the slug at a rate given by $(C_F - u_1)A_{L1}$, where C_F is the velocity of the front of the slug. Liquid is shed from the tail at a rate Q_L so a necessary condition for a stable or growing slug is

$$(C_F - u_1)A_{L1} \geqslant Q_L. \tag{21}$$

Ruder et al. (1988) used (21) to define a critical height, h_0 (obtained from A_{L1}), by calculating Q_L with the equation for a bubble displacing liquid in a horizontal tube (Benjamin, 1968). For a stationary condition, $C_F = C_B$, they obtained

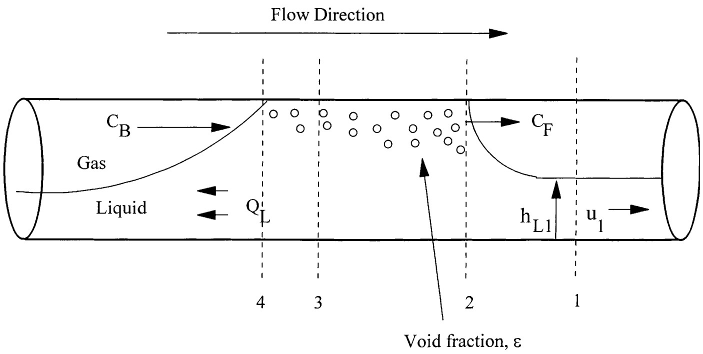

Fig. 4. Pictorial representation of a slug.

$$\frac{A_{L1}}{A} = \frac{0.542\sqrt{gD}}{C_B - u_1}, \tag{22}$$

where D is the pipe diameter. Eq. (22) defines a necessary condition for slug stability.

Woods and Hanratty (1996) made direct measurements of Q_L for air and water flowing in a horizontal pipe with a diameter of 0.0953 m. Eq. (22) was found to define h_0 only in the limit of small gas velocities, for which the slug body is unaerated. They showed that at low U_{SG} the critical height predicted by linear stability theory is greater than the height required for slug stability. At high U_{SG}, this is not the case so linear stability theory does not predict the liquid height at which slugs appear (Lin and Hanratty, 1986; Fan et al., 1993); the transition is determined by (21).

3. Experiments

The flow facility used in this study was operated at atmospheric conditions. The liquid and gas were combined at the beginning of the pipeline in a specially designed tee section which contained an insert to separate the two phases before the first pipe section at $L/D = 0$. Several tees with different h_{insert} were used to introduce the liquid at a height close to the equilibrium value. A critical orifice plate was installed just upstream of the inlet to prevent the slugs from causing large pressure fluctuations in the air supply.

Conductance probes were located at L/D of 2.3, 80, 155, 195 and 210. The transition to slug flow was determined by increasing liquid flow at a constant gas flow. At low gas flows and higher angles, the transition was determined by decreasing gas flow at a constant liquid flow. In all case, observations of the condition of the gas–liquid interface and the location for slug initiation were recorded.

The pressure gradient was obtained close to the transition to slug flow by measuring the pressure drop in the gas–phase of the stratified flow. Two capacitive differential pressure transducers with pressure ranges of 25 and 625 N/m^2 were used.

The pipeline was inclined by using the tilting mechanism designed by Williams (1990). The pipe racks holding the pipeline are mounted on a 27 m beam which is supported by a series of five lifting stations and a stationary pivot point at one end of the beam. Each lifting station is comprised of a support bed, a pair of screw jacks and a pair of rollers. The rollers allow the point of contact between the bed and the beam to charge and each lifting station is synchronized by a gearing system so that the beam remains straight as it is inclined. The mechanism, which is driven by a single 0.25 HP AC motor, can tilt the pipeline between $-2°$ and $+2°$. An electronic revolution counter was used to determine the inclination of the beam from the horizontal position. Each degree of inclination corresponds to 3435 revolutions of the main drive shaft. The angle of inclination can therefore be obtained with a high degree of accuracy.

A careful alignment of the pipeline was imperative, as the transition to slug flow is highly sensitive to small changes in inclination. This was accomplished by adjusting the pipe racks until the pipe was the same distance from the beam at all points. The alignment was then improved further by introducing a wavy stratified flow into the pipe. The pipe racks were then adjusted until no hydraulic gradients were present. The levelling of the entire beam was verified by use of a 10 m long U-tube partly filled with water.

4. Results

4.1. Transition from stratified to slug flow

The effect of inclination on the stratified–slug transition for upflows is shown as a plot of U_{SG} versus U_{SL} in Fig. 5. The liquid flow rates required to initiate slugging decrease with increasing angles of inclination. At inclinations of 0° and 0.05° slugs were observed to be initiated towards the end of the pipe. For $U_{SG} < 5$ m/s, large amplitude waves, with typical wavelengths of 10–20 cm and amplitudes ranging from 1 to 3 cm, were found to grow (and sometimes bifurcate) until

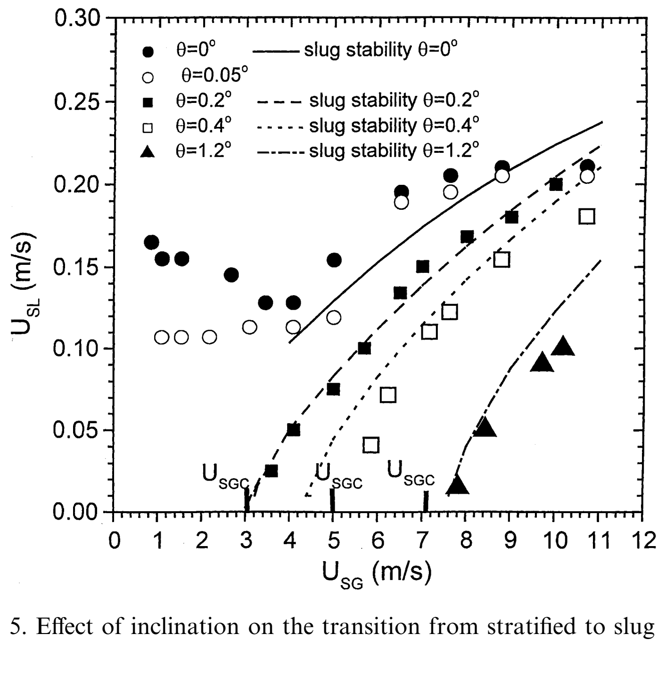

Fig. 5. Effect of inclination on the transition from stratified to slug flow.

they touched the top of the pipeline to form a slug. For $U_{SG} > 5$ m/s, small wavelength waves generated by a Kelvin–Helmholtz mechanism dominate the interface. These were observed to break and form roll waves that can coalesce to form slugs.

For angles of inclination at or above 0.2°, slugging was always observed to occur below a limiting or critical gas velocity, U_{SGC}. This was determined by decreasing U_{SG}, at several low liquid flow rates, until slugs were formed. The curve representing these transitions was then extrapolated to $U_{SL} = 0$. The values of U_{SGC} estimates in this way, are shown by the short, thick vertical lines on the abscissa of Fig. 5. The effect of inclination upon the dimensionless critical equilibrium height of a stratified flow is shown in Fig. 6 for $U_{SG} > U_{SGC}$. At these velocities hydraulic gradients exist only near the inlet where wave were developing; the h/D in Fig. 6 represent what would be observed for a fully developed region. At high gas velocities, it appears that the critical h/D decreases only slightly with increasing inclination. The calculations of the critical height required for slug stability, presented in Fig. 6, suggest that this criterion provides an approximate interpretation for the data above $U_{SG} \cong 5$ m/s. The long wavelength viscous stability analysis of a stratified flow are compared with the data for $\theta = 0°$ and $\theta = 0.2°$ in Fig. 7. Good agreement is noted for $U_{SG} < 5$ m/s, for which slugs form from growing large amplitude waves. The analysis of Taitel and Dukler (1976) overpredicts these data. The analysis of Lin and Hanratty (1986), which allows for the effects of interfacial roughness and the destabilizing effects of liquid inertia, gives better results.

Interfacial friction factors, used in the calculations presented in this paper, were obtained from measurements of pressure gradients at transition in a region of the pipe where the flow is fully developed and hydraulic gradients did not exist. These are plotted in Fig. 8 for wavy stratified flows (above U_{SGC}) as close as possible to transition. For horizontal flows, f_i/f_s is seen to increase with increasing U_{SG} in the range $U_{SG} = 1$–3 m/s and, then, rapidly decrease to a minimum at $U_{SG} = 5$ m/s. At higher gas velocities it increases again, reaching a value of 8.5 at $U_{SG} = 10$ m/s.

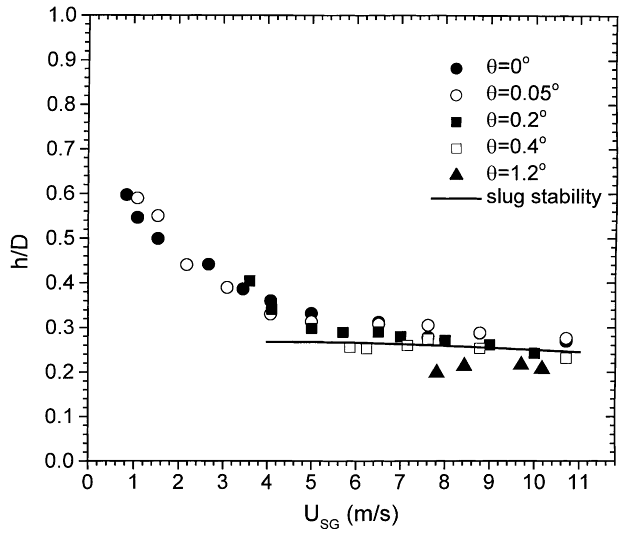

Fig. 6. Critical liquid height for an equilibrium stratified flows at $U_{SG} > U_{SGC}$.

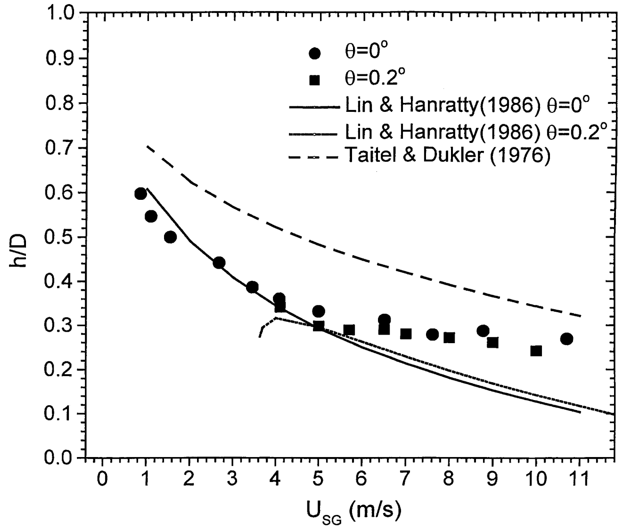

Fig. 7. Comparison of the critical height with calculations based on the linear stability analysis of Lin and Hanratty (1987) and the correlation of Taitel and Dukler (1976).

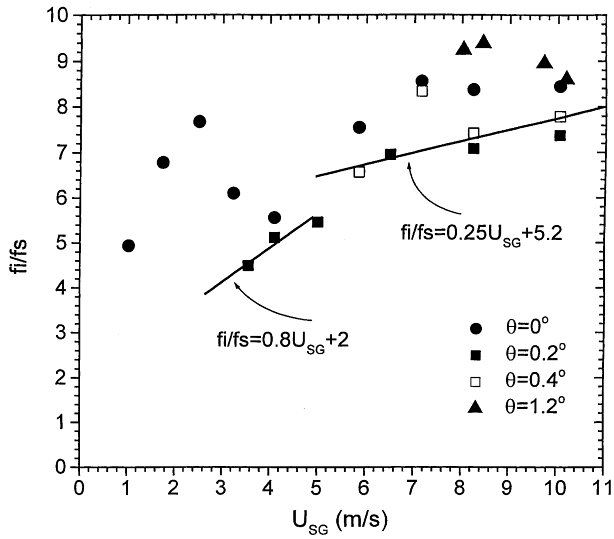

Fig. 8. Measurements of f_i/f_s at the transition from stratified to slug flow.

The decrease in f_i/f_s observed for horizontal flows seems to correspond with the transition from large amplitude interfacial waves to roll waves. Large amplitude waves have a large frontal area perpendicular to the direction of the air flow and travel more slowly. They would, thus, be expected to present more resistance to the air flow than roll waves. For inclinations of 0.2° and 0.4°, f_i/f_s increases with increasing gas velocity. For all inclinations, the values of f_i/f_s at transitions are in the range 7.5–9 at high gas velocities. This would be expected since critical values of h/D are very close to one another for large U_{SG} for all of the inclinations that were examined. For convenience, we chose to represent f_i/f_s by the linear relations indicated in Fig. 8.

From the momentum balance for a fully developed stratified flow, Eq. (17), the height of the liquid is determined by a balance among forces due to the interfacial drag, the pressure gradient, gravity and the resistance at the wall. The transition data in Fig. 5 for $\theta = 0.2°$, $0.4°$ and $1.2°$ represent the U_{SL} and U_{SG} needed to produce an unstable h/D. The increase in the critical U_{SG} with increasing U_{SL} reflects the need to increase the interfacial drag to counterbalance the increased wall resistance, in order to have a stratified flow with a critical height. The decrease in critical gas velocity with decreasing θ results from a decrease in the gravitational force and, therefore, a decrease in the interfacial stress needed to produce an unstable height. In the limit of small U_{SL}, the wall resistance is negligible and the critical gas velocity is needed to produce interfacial stresses and pressure gradients that just balance the gravitational forces. It is clear, therefore, that the calculation of U_{SGC} needs accurate estimates of f_i/f_s.

For a horizontal flow ($\theta = 0°$), the transitional relation between U_{SG} and U_{SL} at large U_{SG} is similar to what is found for $\theta = 0.2°$, $0.4°$, and $1.2°$. In this case, the U_{SG} produces an interfacial stress and a pressure gradient that balance the wall shear stress, which increases with increasing U_{SL}. At small U_{SG}, the critical height increases with decreasing U_{SG}, so the critical U_{SL} also needs to increase. This accounts for the minimum that is observed in Fig. 5.

The behaviour in Fig. 5 for $\theta = 0.05°$ is different, at low gas velocities, from what was observed for larger inclinations. A critical superficial gas velocity cannot be determined. However, different results might have been obtained if the pipe were longer. The liquid phase finds its own level in the pipeline when the gas drag is unable to counteract gravitational effects. If the angle is very low, then pooling could extend over the whole pipeline, and large changes in the height of the stratified layer would occur. These hydraulic gradients cause the liquid to flow out of the pipeline. This behaviour will be avoided if the pipe is long enough that the outlet is completely above the pipe inlet. This can be realized for

$$\sin\theta = D/L \tag{23}$$

or an angle of 0.19° for the system studied in this research. Below this angle, measurements would not correspond to what would be observed in an infinitely long pipe.

4.2. Formation of slugs, at $U_{SG} < U_{SGC}$ by a pooling at the inlet

As has been shown in Section 2.2, U_{SGC} is very close to the value of U_{SG} below which a stratified flow would reverse direction. Because of this, there is a large region below U_{SGC} where slugs must carry the fluid out of the pipe so as to allow for a net positive U_{SL}. These evolve by an interesting process. Liquid at the inlet forms a pool whose height changes with time. Slugs appear very rapidly when a critical height is exceeded, thus suggesting a Kelvin–Helmholtz mechanism. The height, then, suddenly decreases and another slug is formed when the liquid again builds up at the inlet to reach a critical condition.

The formation of slugs from the pooling of liquid at the inlet of the pipe is shown by traces from the conductance probes in Fig. 9. At $L/D = 4$, the liquid is seen to build up until a critical dimensionless height of $h/D = 0.68$ is reached. A slug forms almost instantaneously and the level of the liquid behind the slug drops to $h/D \cong 0.24$. The liquid at the inlet then rebuilds until a

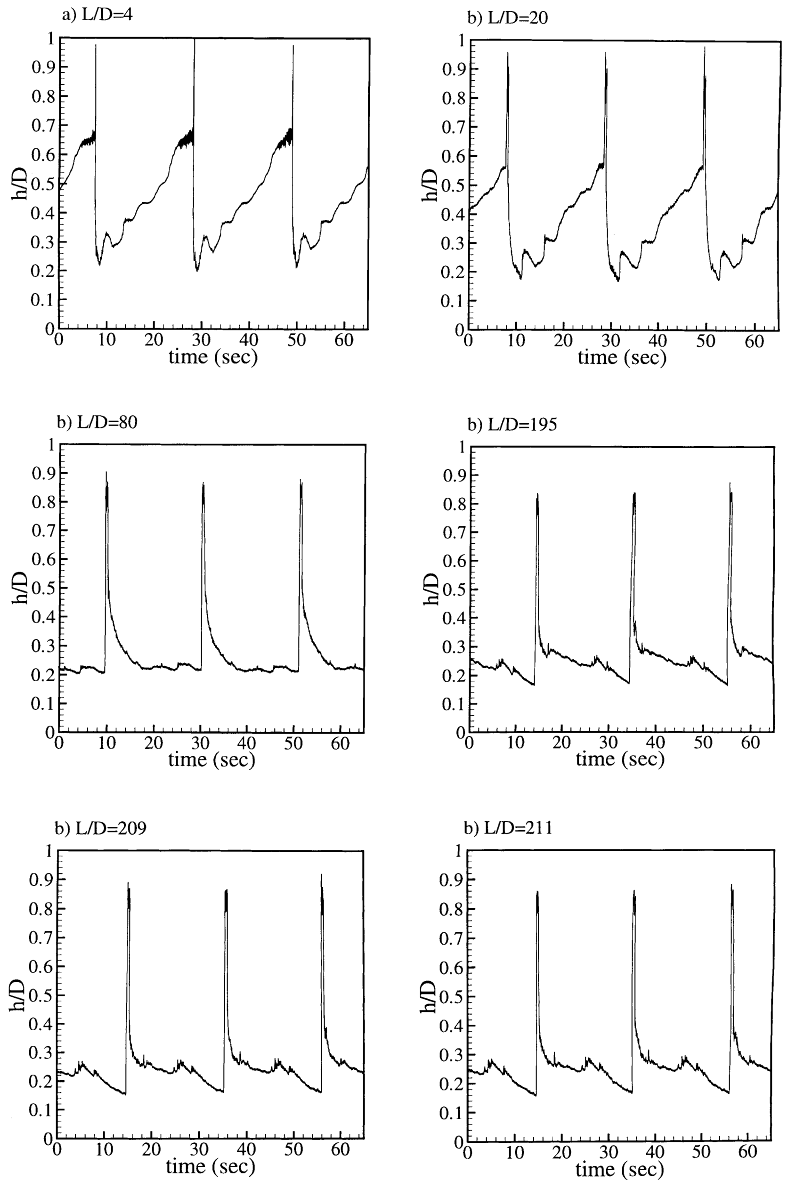

Fig. 9. Conductance probe traces down pipe for 0.4° upflow $U_{SG} = 1.54$ m/s, $U_{SL} = 0.064$ m/s.

height is reached that is large enough to cause another slug to form. The situation shown in Fig. 9 is one for which one or no slugs appear in the pipe at any time. Liquid is moved along the pipe by the slugs. The liquid in the stratified flows, shown in Fig. 9, moves backward toward the inlet and contributes to the pooling at the inlet. Liquid slugs or pseudoslugs (that result from decayed slugs) carry the liquid out of the pipe.

A decrease in U_{SG} at constant U_{SL} causes an increase in the frequency of slugging, as shown in Fig. 10. This displays a situation in which several slugs were in the pipe at a given time. The

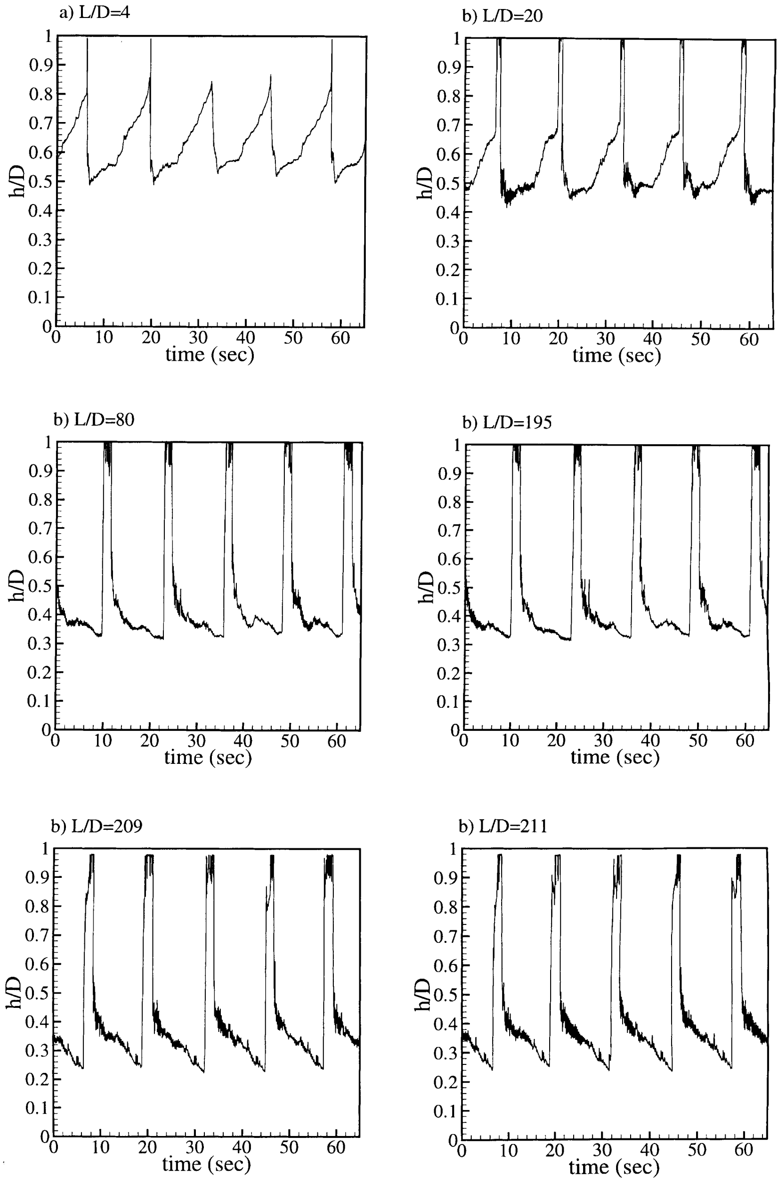

Fig. 10. Conductance probe traces down pipe for 0.4° upflow $U_{SG} = 0.54$ m/s, $U_{SL} = 0.078$ m/s.

slugs formed at a critical h/D of 0.8, but the liquid level behind the slugs only dropped to a value of 0.5 at the entry. The time to refill the pipe to the critical height was, therefore, smaller, so the frequency of slugging increases. An almost periodic pattern is observed downstream at $L/D = 209$. The highest level in the stratified flow occurs when a slug passes a given location. As the fluid drains backward from this location the level drops until another slug arrives.

At very high U_{SL} pooling was not observed. As discussed later, this represents a region in which reversed flows cannot occur. Slugs formed farther downstream than was observed for smaller liquid flows.

5. Interpretation of results

For inclinations of 0.2° and 0.4°, at low liquid flow rates, heights of liquid required to trigger a slug were recorded using the conductance probes. These heights are approximate because large gradients in the pipeline made it difficult to determine the h/D at the location where slugs are formed. Because of this problem, measurements were not attempted at the inlet for an inclination of 1.2°. The critical heights, plotted in Fig. 11, agree reasonably well with the height required to produce a Kelvin–Helmholtz instability, defined by (4) and (6). However, the measured heights are consistently lower than predicted for the case of a 0.2° upflow. This may be explained because of the presence of waves on the liquid surface. These waves cause a local acceleration of the gas at the wave crest; hence, the instability is initiated at a slightly lower height.

The prediction of flow reversal in the liquid layer of a stratified flow was done by solving the momentum balances for a round geometry at the condition $\tau_{WL} = 0$. The results are shown in Fig. 12 as curves with thin dashed lines. They represent an approximation of the conditions for which $U_{SL} = 0$. The mean flow is predicted to reverse direction for conditions to the left of these curves. In this region, slugging would be expected to occur from liquid pooling until a critical h/D is reached, at which a Kelvin–Helmholtz instability occurs. The critical velocities for the existence of stratified flows, determined in Fig. 5, are indicated by the thick solid lines on the bottom of

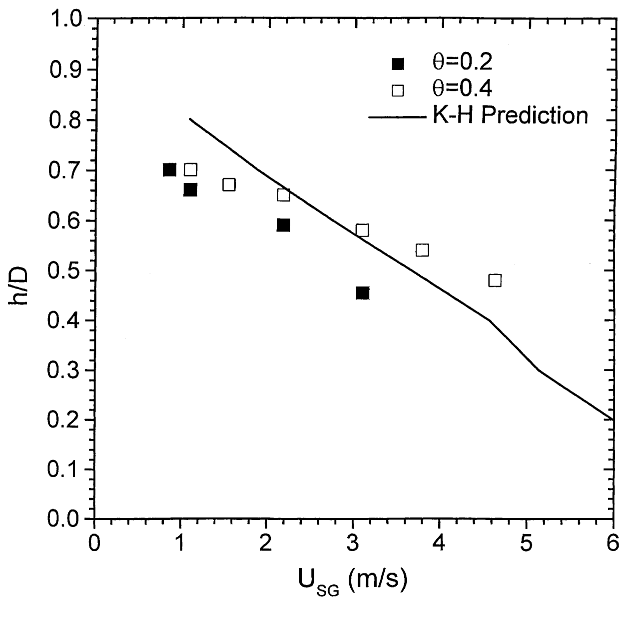

Fig. 11. Comparison of the critical height of the pooling liquid with prediction based on a Kelvin–Helmholtz instability.

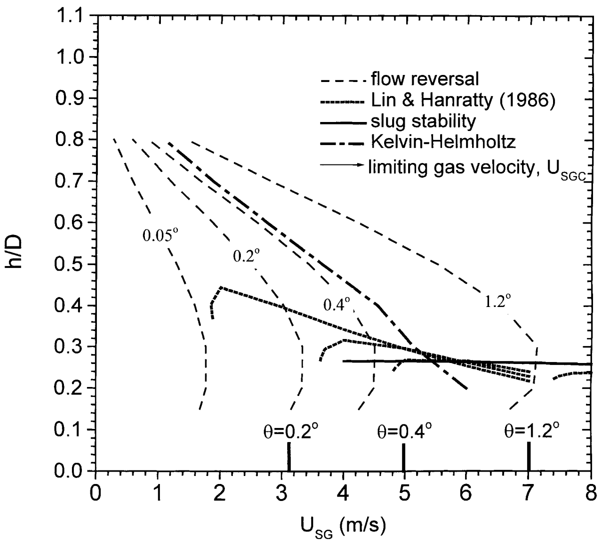

Fig. 12. Interpretation of observation of the transition from a stratified to a slug flow in upwardly inclined pipes.

Fig. 12. The good agreement of these experimentally determined U_{SGC} and the limiting value of U_{SG} determined by the calculated curves suggests that U_{SGC} corresponds to the occurrence of flow reversal. The linear estimates of f_i/f_s have a strong effect on the calculations, so slightly different relations may give better results. The calculations predict a value of U_{SGC} of 1.8 m/s for an inclination of 0.05°, but this was not observed because of effects of pipe length, already discussed.

The transition to slug flow outside the reversed flow region occurs on a stationary stratified flow by wave growth, defined by a long wavelength instability or by a Kelvin–Helmholtz instability. The conditions for the initiation of viscous long wavelength waves, calculated with the analysis of Lin and Hanratty (1986) are indicated by the thick dashed lines. The analysis of Andritsos et al. (1989) is used to calculate the height needed for the stratified flows to experience Kelvin–Helmholtz instabilities. These results are also plotted in Fig. 12. In order for these instabilities to lead to slugging, it is necessary that the height of the liquid in the stationary stratified flow be above that required for the existence of a stable slug. This condition is indicated by the thick solid line in Fig. 12.

The predictions from the long wavelength stability analysis are seen to depend on θ. As U_{SG} decreases, these solutions predict a limiting value, for a given θ, as $U_{SL} \to 0$. These limiting values are seen to be close to U_{SGC}, defined in Fig. 5. This coincidence is not understood.

For $\theta \geqslant 0.4°$ and large h/D, the conditions defining flow reversal is at or above the conditions for slugs to form on a steady stratified flow through a Kelvin–Helmholtz instability. One would, therefore, expect that outside the region of reversed flow K–H instabilities lead to slugging since the h/D is larger than the critical value needed for stable slugs to exist. For $\theta < 0.4°$ and $U_{SG} < U_{SGC}$ the flow reversal curve lies below the curve representing a K–H instability.

The boundaries for flow reversal suggest that, at very low h/D, forward moving flows can exist in a stratified pattern. It is noted that these have heights below that needed for a stable slug to exist. Consequently, a stable stratified flow would exist. This region was not studied, so its existence was neither proved nor disproved.

6. Concluding remarks

Slugs form in upward stratified flow at, almost, all U_{SL} when U_{SG} is less than a critical value, which corresponds to the maximum gas velocity at which reversed flows can be maintained. Within a region where reversed flows exist slugs are formed when the pooling of the liquid at the inlet caused the liquid level to rise to levels such that the gas velocity is large enough for a Kelvin–Helmholtz instability to occur. Slugs formed in this region carry all of the liquid out to the pipe. The stratified flows between slugs are carrying liquid backward, toward the inlet.

Outside the region of reversed flow (at $U_{SG} < U_{SGC}$) pooling does not occur and slugs form on a steady stratified flow downstream of the inlet. For $\theta \geqslant 0.4°$, the slugs evolve from Kelvin–Helmholtz waves, as described by Andritsos et al. (1989). At $\theta < 0.4°$ slugging occurs either by the wave growth mechanism described by Fan et al. (1993) or (at large U_{SL}) by the K–H mechanism. At extremely small U_{SL}, a stable stratified flow seems possible.

For $U_{SG} > U_{SGC}$, slugs form downstream by processes similar to those that prevail in horizontal flows. The dominant mechanism for the conditions studied in this research is slug stability. Thus, as shown in Fig. 5, a good approximation of the transition from stratified to slug flow can be constructed from a prediction of the maximum velocity at which reversed flow can exist and from a consideration of the stability of slugs.

In the reversed flow region, slugs are formed by a deterministic process. Therefore, it should be possible to develop a relation for slug frequency by using the physical ideas that emerge from this study. However, some consideration needs to be given to the fact that the slug flow regime in upwardly inclined pipes differs from what is found in horizontal pipes (Woods and Hanratty, 1996; Woods et al., 2000; Fan et al., 1993), in that the stratified flow behind the slug is moving in the opposite direction than the slug.

Acknowledgements

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References

Andritsos, N., 1986, Effect of pipe diameter and liquid viscosity on horizontal stratified flow, Ph.D. Thesis, University of Illinois.

Andritsos, N., Hanratty, T.J., 1987. Influence of interfacial waves in stratified gas–liquid flows. AIChE J. 33, 444–454.

Andritsos, N., Williams, L., Hanratty, T.J., 1989. Effect of liquid viscosity on the stratified–slug transition in horizontal pipe flow. Int. J. Multiphase Flow 15, 877–892.

Barnea, D., Shoham, O., Tatitel, Y., Dukler, A.E., 1980. Flow pattern transition for gas liquid flow in horizontal and inclined pipes. Int. J. Mulitphase Flow 6, 217–225.

Benjamin, T.B., 1968. Gravity currents and related phenomena. J. Fluid Mech. 31, 209–248.

Chen, J.J.J., 1984. A simple explicit formula for the estimation of pipe friction factor. Proceedings of the Institute of Civil Engineering Part 2, Technical Note 400, 77, 49–55.

Fan, Z., Lusseyran, F., Hanratty, T.J., 1993. Initiation of slugs in horizontal gas–liquid flows. AIChE J. 39, 1741–1753.

Grolman, E., Commandeur, N., de Batt, E., Fortuin, J., 1996. Wavy-to-slug flow transition in slightly inclined gas–liquid pipe flow. AIChE J. 42, 901–907.

Henstock, W.H., Hanratty, T.J., 1976. The interfacial drag and height of the wall layer in annular flows. AIChE J. 22 (6), 990–1000.

Kokal, S., Stanislav, J.F., 1989. An experimental study of two-phase flow in inclined pipes – I: flow patterns. Chem. Engrg. Sci. 44 (3), 665–679.

Kordyban, E.S., Ranov, T., 1970. Mechanism of slug formation in horizontal two-phase flow. J. Basic Eng. 92, 857–864.

Lin, P.Y., Hanratty, T.J., 1986. Prediction of the initiation of slugs with linear stability theory. Int. J. Multiphase Flow 12, 79–98.

Lin, P.Y., Hanratty, T.J., 1987. Effect of pipe diameter on flow patterns for air–water flow in horizontal pipes. Int. J. Multiphase Flow 13, 549–563.

Milne-Thomson, L.M., 1968. Theoretical Hydrodynamics, fifth ed. MacMillan, London.

Ruder, Z., Hanratty, P.J., Hanratty, T.J., 1988. Necessary conditions for the existence of stable slugs. Int. J. Multiphase Flow 15, 209–226.

Taitel, Y., Dukler, A.E., 1976. A model for prediction flow regime transitions in horizontal and near horizontal gas–liquid flow. AIChE J. 22, 47–55.

Wallis, G.B., Dobson, J.E., 1973. The onset of slugging in horizontal stratified air–water flow. Int. J. Multiphase Flow 1, 173–193.

Williams, L.R., 1990. Effect of pipe diameter on horizontal annular two-phase flow. Ph.D. thesis, University of Illinois, Urbana.

Woods, B.D., Hanratty, T.J., 1996. Relation of slug stability to shedding rate. Int. J. Multiphase Flow 22, 809–828.

Woods, B.D., Hurlburt, E.T., Hanratty, T.J., 2000. Mechanisms of slug formation in downwardly inclined pipes. Int. J. Multiphase Flow 26, 977–998.

Wu, H.L., Pots, B.F.M., Hollenburg, J.F., Merhoff, R., 1987. Flow pattern transitions in two-phase gas/condensate flow at high pressure in an 8-inch horizontal pipe. In: Proceedings of the BHRA Conference, The Hague, The Netherlands, pp. 13–21.