

Cleveland, Ohio, June 1996

MULTIPHASE FLOW: THE GRAVITY OF THE SITUATION

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SI-34
1996

ABSTRACT

A brief survey is presented of flow patterns in two-phase, gas-liquid flows at normal and microgravity, the differences between them being explored. It seems that the flow patterns in zero gravity are in general much simpler than those in normal gravity with only three main regimes (namely bubbly, slug and annular flows) being observed. Each of these three regimes is then reviewed, with particular reference to identification of areas of study where investigation of flows at microgravity might not only be interesting in themselves, but also throw light on mechanisms at normal earth gravity. In bubbly flow, the main area of interest seems to be that of bubble coalescence. In slug flow, the extension of simple displacement experiments to the zero gravity case would appear to be a useful option, supplemented by computational fluid dynamics (CFD) studies. For annular flow, the most interesting area appears to be the study of the mechanisms of disturbance waves; it should be possible to extend the region of investigation of the onset and behaviour of these waves to much low gas velocities where measurements are clearly much easier.

1. INTRODUCTION

Two-phase gas-liquid flow is important in a whole range of applications under earth gravity conditions; these include pipeline transport of oil/natural gas mixtures, flows in nuclear reactor systems under accident conditions, evaporation and condensation systems in power and process plant, geothermal energy systems etc. Such flows are also important in space applications where, of course, microgravity conditions apply. These space applications include transfer line flows of cryogenic fluids, heat transfer associated with space power systems, design and operation of the thermal bus which operates as a heat-sink etc. At normal gravity conditions, the existence of a gravitation force has a profound effect on the nature of the flows, due to the large density differences which normally exist between gas and liquid phases. Thus, in vertical flows, gravitation forces give rise to local slip between phase elements (drops or bubbles) and can cause periodic flow reversals (for instance in slug or churn flows). In horizontal flows, the effect of gravity is to cause asymmetry of the flow, the extreme case being that of a fully stratified flow with the liquid flowing at the bottom of the channel and the gas at the top. Thus, in micro gravity situations, one would expect major differences in flow behaviour and such differences are indeed observed. However, as we shall see, gravity is a *complicating factor* and flows at microgravity are essentially much simpler.

In what follows, Section 2 discusses flow regimes and the specific regimes of bubbly flow, slug flow and annular flow are discussed in Sections 3, 4 and 5 respectively.

2. FLOW REGIMES

A wide variety of descriptors has been given to flow regimes in gas-liquid flow; sketches of the more commonly accepted regimes for vertical and horizontal flows are given in Figures 1 and 2 respectively.

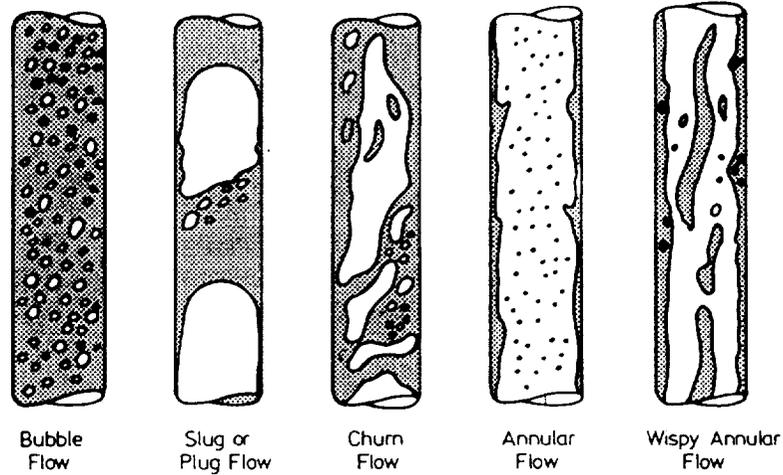


Figure 1: Flow regimes in gas-liquid flow in a vertical tube at normal gravity

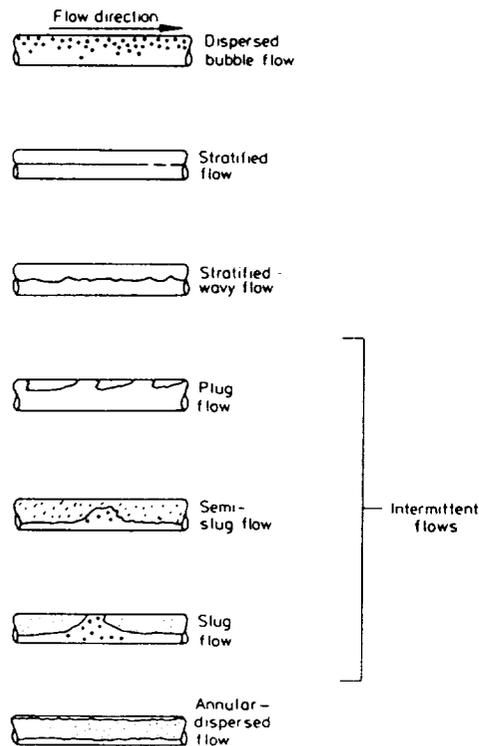


Figure 2: Flow regimes in gas-liquid flow in a horizontal tube at normal gravity

For flows at zero gravity, the regimes observed are bubbly flow, slug flow and annular flow and sketches of these regimes, taken from the paper of Dukler et al (1988) are shown in Figure 3.

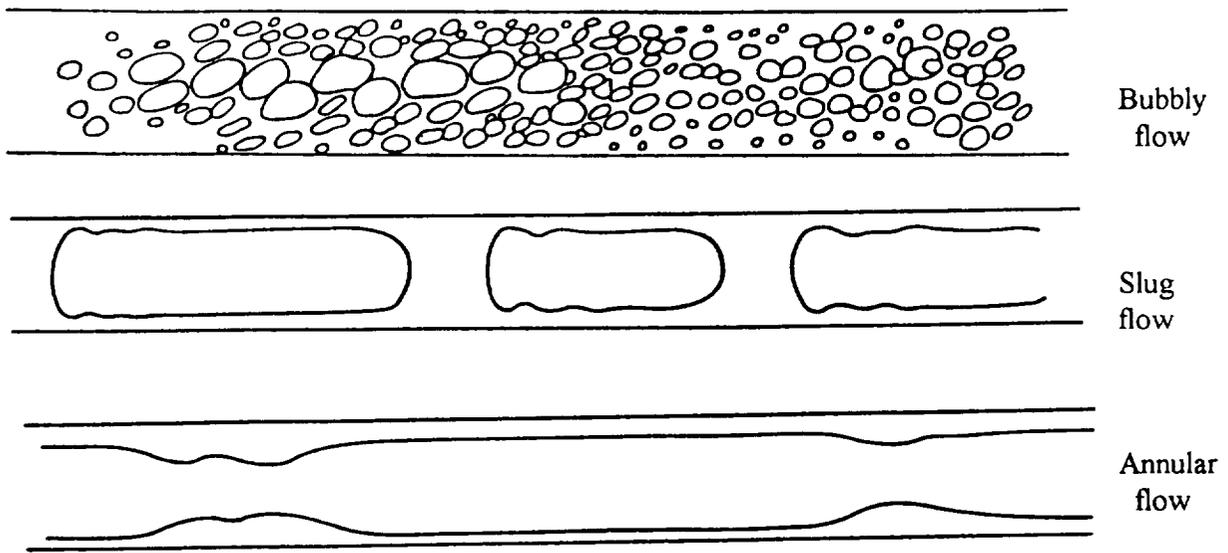


Figure 3: Sketches of flow regimes in gas-liquid (air-water) flow under microgravity conditions (Dukler et al, 1988)

A very large number of methods (ranging from purely empirical to semi-theoretical) have been developed for the prediction of flow pattern in normal gravity flows. The mechanistic models often take account of gravity as a parameter and a natural question is whether such models can be applied to the microgravity case. This approach was followed by Reddy Karri and Mathur (1988) who made predictions for a 2.54 cm internal diameter pipe using the mechanistic models of Taitel and Dukler (1976) and Weisman et al (1979) models. The results are shown in Figure 4 for the case of the horizontal flow models; though the two approaches give reasonable agreement at normal gravity (Figure 4a) they differ greatly at microgravity (Figure 4b).

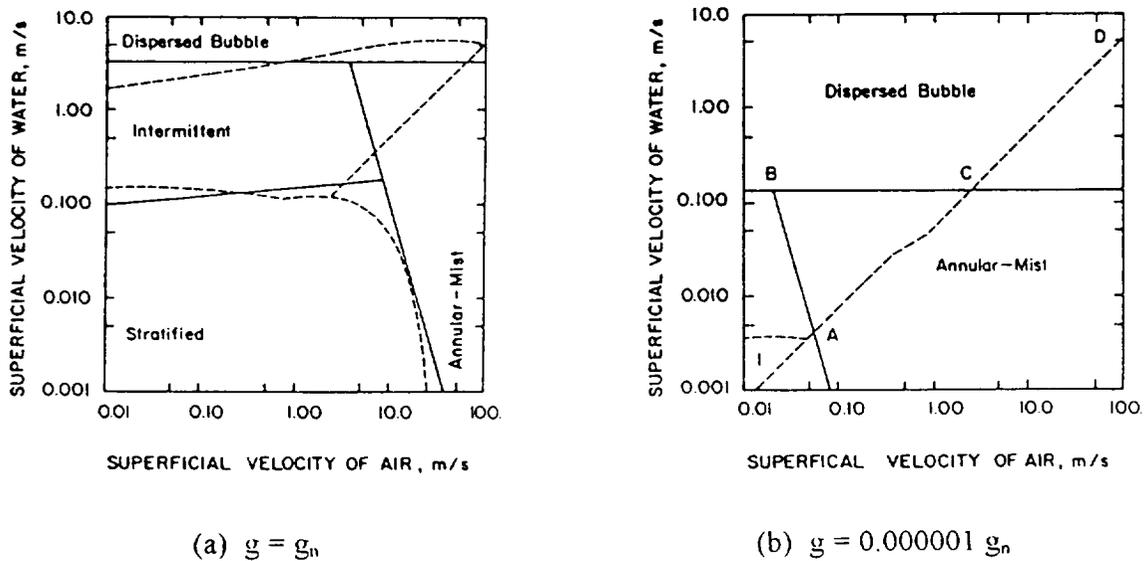


Figure 4: Predictions of flow patterns in normal and microgravity using mechanistic models proposed for normal gravity conditions (Reddy Kari and Mathur, 1988)
 - - - Taitel Dukler model — Weisman et al model

It is an unfortunate fact that most models for two-phase flow patterns are developed using air-water data at near atmospheric pressure. It is not necessary to go to microgravity conditions to show the deficiencies of these models. To illustrate this point, two examples may be cited:

- (1) Reiman et al (1982) compared a variety of models for the transition from slug to annular flow in horizontal pipes. Their results are shown in Figure 5. The predictions vary by an order of magnitude and, more worryingly, the trends of variation of the position of the transition with fluid velocities can be in opposite directions depending on the model.
- (2) System pressure is a very important variable in multiphase flow but most experiments (and their associated models) are carried out at near atmospheric pressure. Recent work at Imperial College on the stratified-slug transition in horizontal flows (Manolis, 1995) shows that the transition moves to higher liquid superficial velocities as the pressure increases (Figure 6) whereas the trends predicted from the Taitel-Dukler (1976) model are in entirely the opposite direction (Figure 7).

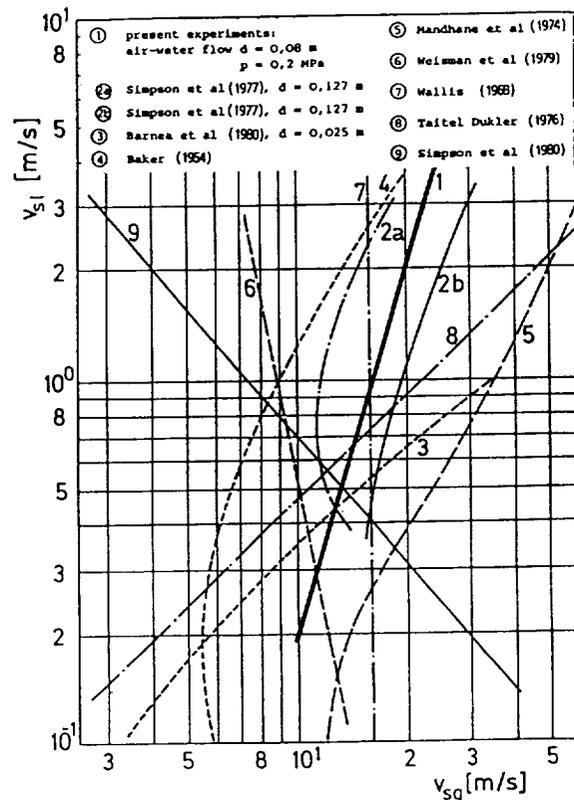


Figure 5: Slug-annular transition in horizontal flow at normal gravity: Comparison of models (Reiman et al, 1982)

The inadequacies of flow pattern prediction methods provide a serious barrier to the development of improved modeling methods for multiphase flows at normal gravity. A particularly difficult area is that of the transition from slug to churn flow and from churn flow to annular flow in vertical tubes. Some authors consider the churn flow regime to be merely a manifestation of a developing form of slug flow (see for instance Mao and Dukler, 1993) whereas an alternative view is to draw an analogy with flooding in counter-current flow of a falling liquid film and a rising gas stream; flooding appears to occur as a result of the formation of large waves ("flooding waves") which are swept up the channel by the gas stream, leading to transport of liquid above the injection point. It has been hypothesized that the transition from slug flow to churn flow occurs when such flooding waves are

formed in the large Taylor bubble (where there exists a falling liquid film around the periphery with upward gas flow in the centre of the pipe).

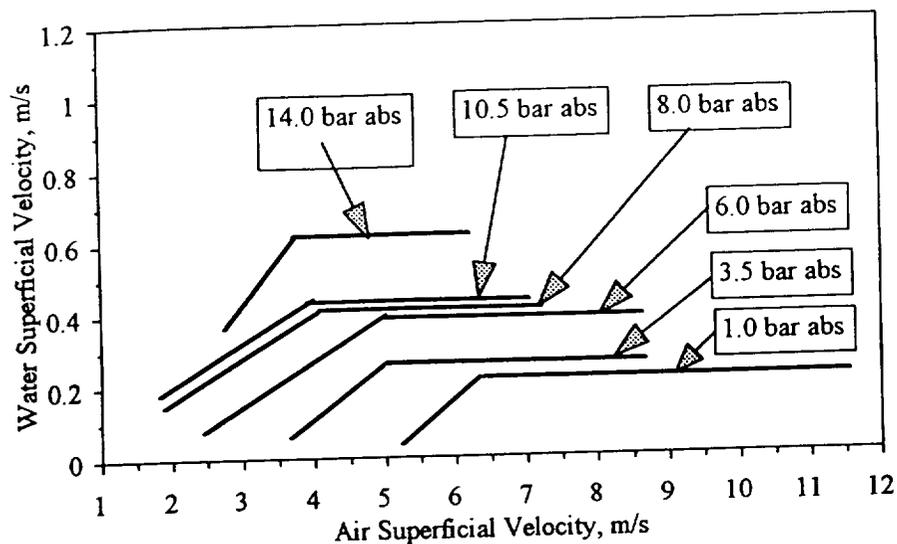


Figure 6: Effect of pressure on stratified-slug transition in horizontal flow (Manolis, 1995)

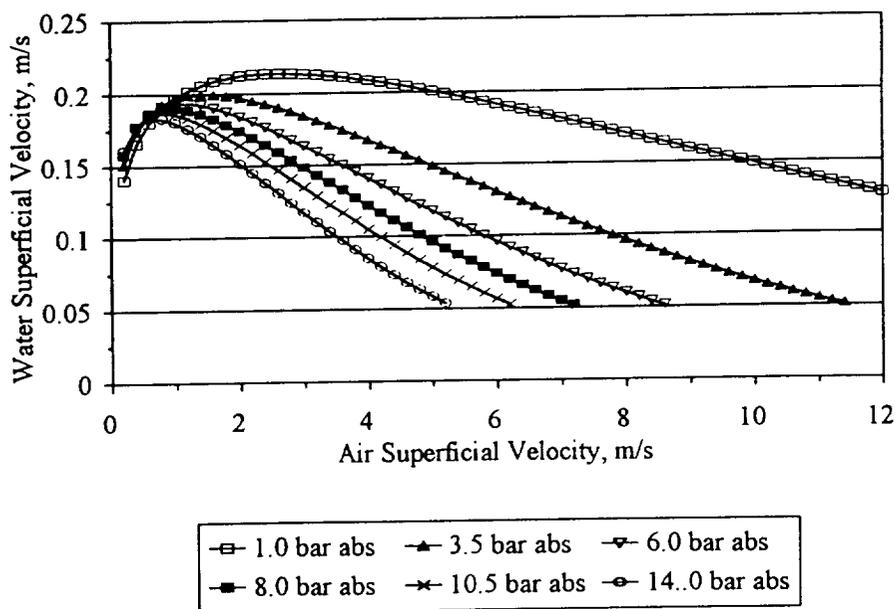


Figure 7: Effect of pressure on transition from stratified to slug flow as predicted from the Taitel-Dukler (1976) model (Manolis, 1995)

This explanation is consistent with experimental data, as is shown by Jayanti and Hewitt (1992). Hewitt and Jayanti (1993) show the observations by Mao and Dukler (1993) are also not inconsistent with the flooding hypothesis, though there is clearly a great deal of work to be done in the area since tube diameter has a crucial effect on flooding transitions (Jayanti et al, 1996).

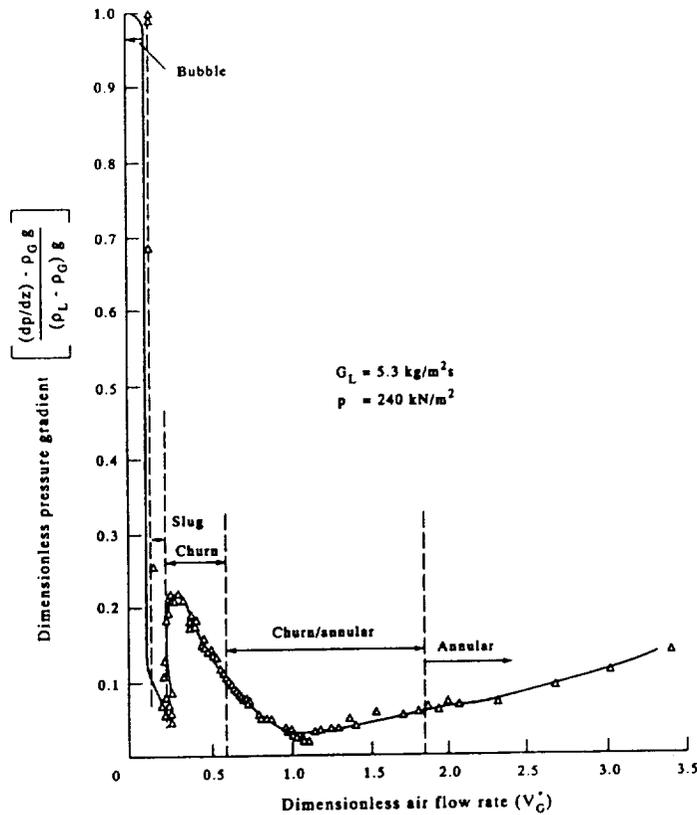


Figure 8: Data for pressure gradient as a function of dimensionless gas velocity (Owen, 1986). Liquid flow rate constant.

Figure 8 shows how the pressure gradient varies in vertical flow as a function of dimensionless gas flow rate, V_G^* which is defined as follows:

$$V_G^* = U_G \rho_G^{-1/2} [gD(\rho_L - \rho_G)]^{-1/2} \quad (1)$$

where U_G is the superficial velocity of the gas phase, ρ_G and ρ_L are the gas and liquid phase densities, g is the acceleration due to gravity and D is the tube diameter. As will be seen, the pressure gradient at a fixed liquid flow rate decreases very rapidly with increasing gas flow rate in the bubbly flow and slug flow regions due to the decrease in the gravitational component of the pressure gradient as the void fraction increases. However, when the slug flow region breaks down due to the onset of flooding within the Taylor bubbles, a very rapid increase in pressure gradient occurs as the churn flow regime is entered. In churn flow, large flooding waves are formed periodically and traverse up the channel. As can be seen from observations using photochromic dye-tracing (Hewitt et al, 1985), the flow reverses between the large waves, with the liquid film on the tube wall beginning to descend and to fall into the subsequent wave. Eventually, the shear stress between the gas phase and the intervening film is sufficient to carry the film upwards and the flooding waves disappear since there is no replenishment mechanism for them. The region in which flow reversals occur is that to the left of the minimum in pressure gradient in the churn-annular region as is illustrated in Figure 9

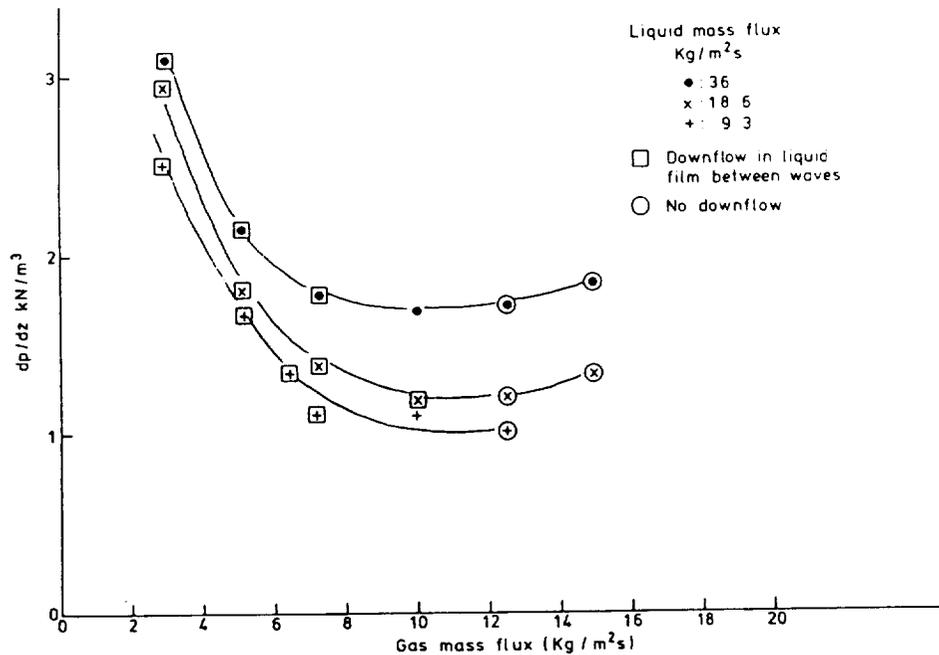


Figure 9: Existence of regions of periodic downflow in the churn-annular transition region (Hewitt et al, 1985)

The interesting features of microgravity flows which make them substantially different to those at normal gravity are, therefore:

- (1) The flows are essentially axisymmetric.
- (2) Though local variations in void fraction do occur, the flow velocity in a channel of constant cross section does not show the characteristic periodic reversals which occur in some regions of flow at normal gravity.

Feature (1) is, of course, shared with vertical flows though vertical flows are demonstrably subject to periodic flow reversals (feature (2)) which would not occur at zero gravity. One must conclude, therefore, that *flow patterns at zero gravity are much simpler than those found at normal gravity*. There is little point in attempting to use normal gravity methodologies to predict microgravity flows. Rather, a new approach to flow pattern transition needs to be adopted. Two interesting approaches have been followed in the literature on microgravity flows:

- (1) Zhao and Rezkallah (1993) argue that the interaction forces governing flow patterns are different under microgravity conditions and that the Weber numbers for the respective phases are the important determinants. The Weber numbers are defined as:

$$We_{SG} = \frac{U_G^2 \rho_G D}{\sigma} \quad (2)$$

$$We_{SL} = \frac{U_L^2 \rho_L D}{\sigma} \quad (3)$$

where U_L is the liquid superficial velocity and σ is the surface tension. A plot of Zhao and Rezkallah's own and literature data in terms of these two Weber numbers is shown in Figure 10.

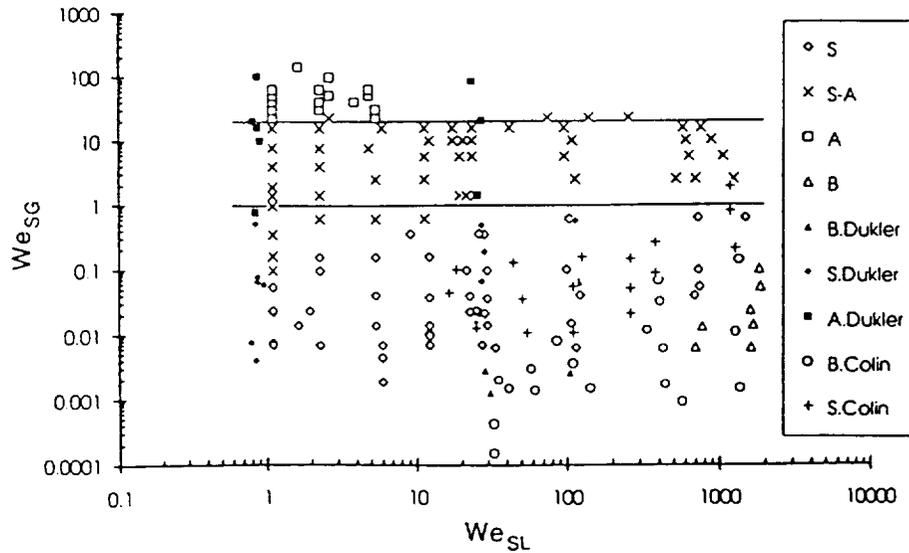


Figure 10: Microgravity of flow patterns plotted in term of We_{SG} and We_{SL} (Zhao and Rezkallah, 1993) (B = bubbly flow, A = annular flow, S = slug flow, S-A = frothy slug annular flow)

Zhao and Rezkallah suggest that, at high values of We_{SG} , the system is inertial controlled and annular flow would occur. At low values of We_{SG} , they suggest that the system is surface tension controlled, giving rise to bubble or slug flow. There is also an intermediate region in which frothy slug-annular flow occurs.

- (2) Dukler et al (1988) predicted the bubble-slug and slug-annular transitions on the basis of void fractions. The bubble-slug transition was hypothesized to occur at a void fraction (ϵ_G) of 0.45 and the slug-annular transition was hypothesized to occur when the void fraction predicted for annular flow equaled that predicted for slug flow. This predicts the transitions quite well as is illustrated in Figure 11.

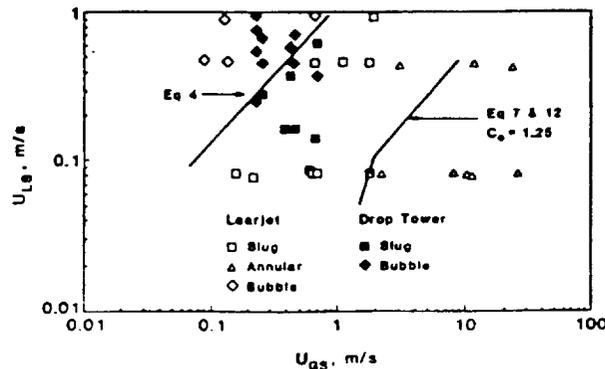


Figure 11: Predictions of microgravity flow patterns by the method of Dukler et al (1988) compared with experimental data

On the whole, a more phenomenological approach to flow pattern prediction is clearly preferable and the approach suggested by Dukler et al is a promising one. However, topics for further study might include:

- (1) The development of more mechanistic models for the bubble-slug transition. There is a growing consensus that this transition at normal gravity follows from the formation of void waves and not, as had once been believed, from progressive coalescence of the bubbles. However, in microgravity, the coalescence behaviour is very different (see Section 3 below) and this may have a significant effect on the regime transition behaviour.
- (2) The model used by Dukler et al (1988) for calculating void fraction in an annular flow included the calculation of interfacial friction factor based on normal gravity measurements. It is not clear whether it is appropriate to extrapolate such measurements into the microgravity transition region bearing in mind the non-existence of flow reversals and churn flow as discussed above.
- (3) In the absence of gravitational forces, surface tension must assume a more significant role, particularly in small diameter tubes. This aspect needs to be further investigated.

Although there is much work still to be done it is, however, clear that the transitions are fundamentally simpler than those in normal gravity and one might expect a better chance of success in prediction methodologies.

3. BUBBLY FLOW

A study of gas-liquid bubbly flow at microgravity conditions is reported by Colin et al (1991). Measurements of void fraction were made for both vertical normal gravity flows and microgravity flows and the results were plotted in terms of gas velocity $u_G (= U_G/\epsilon_G)$ against U , the total superficial velocity. The results are illustrated in Figure 12.

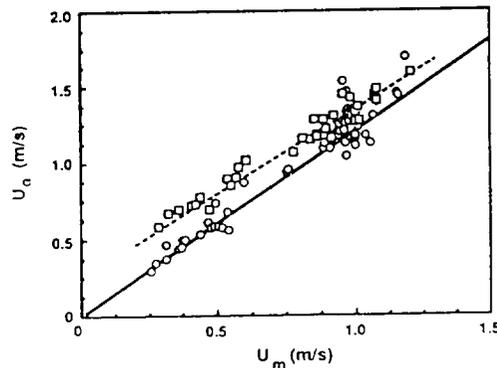


Figure 12: Actual gas velocity as a function of total superficial velocity for normal gravity vertical bubbly flows (□) and microgravity bubbly flows (○). - - Zuber & Findlay (1965) relationship with u_w from Equation 5, $C_0 = 1.1$. — Zuber & Findlay relationship with $C_0 = 12.$, $u_w = 0$ (Colin et al, 1991)

Colin et al followed the “drift-flux” approach of Zuber and Findlay (1965) fitting their data with an equation of the form:

$$u_G = C_0 U + u_w \quad (4)$$

where u_r is the average local drift velocity and C_o is a constant which takes account of the differences between the profiles of velocity and void fraction. For normal-gravity vertical flows, the data were quite well fitted by setting $C_o = 1.1$ and calculating u_r from the expression:

$$u_r = 1.53 \left[\frac{(\rho_L - \rho_G) g \sigma}{\rho_L^2} \right]^{0.25} \quad (5)$$

The zero gravity flow was fitted best by setting $C_o = 1.2$ and $u_r = 0$.

Perhaps the most interesting finding with respect to microgravity bubbly flows relates to bubble coalescence. Colin et al (1991) measured bubble size distributions at the inlet and outlet of a channel in normal and zero gravity respectively. The results are shown in Figure 13; as will be seen, the normal gravity vertical flow case shows little change of bubble size indicating minimal coalescence from the inlet to the outlet of the channel. This is in agreement with many other observations in normal gravity flow. However, at microgravity, the bubble size distribution changes dramatically, indicating extensive coalescence.

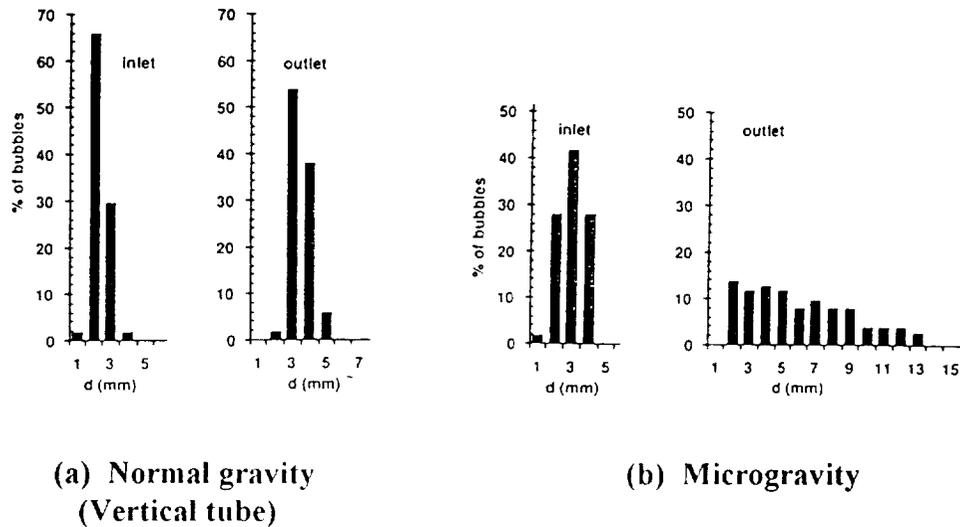


Figure 13: Bubble-size distribution in air-water bubbly flow in a 3 m long 4 cm diameter tube (Colin et al, 1991)

It is interesting to speculate on the causes of the differences between bubble coalescence behaviour at micro and normal gravity. The time required for coalescence is a strong function of the velocity of approach of the bubble to the interface at which it coalesces. This was demonstrated by some experiments by Kirkpatrick and Lockett (1974); they released bubbles below a flat interface and determined the coalescence time as a function of the distance (x) at which they were released relative to the interface. Clearly, the bubble accelerates as it moves towards the interface and the effect is one of velocity. Their results are illustrated in Figure 14. When the bubbles are released close to the interface, the velocity of approach is small and the coalescence time is of the order of a few milliseconds. However, when the initial separation distance reaches about 0.6 cm, the coalescence time rises dramatically to around 140 milliseconds, thereafter increasing only slightly with separation distance. If we consider a bubbly flow, the velocity of approach of bubble will depend on the turbulence and on the interactions with bubble wakes. A bubble trapped in the wake of a bubble ahead of it will rise more rapidly towards the preceding bubble and its coalescence time will be extended. Turbulent fluctuations within the flow would lead to separation before coalescence could take place. In a further set of experiments, Lockett and Kirkpatrick (1975) trapped a bed of bubble

in a counter-current flow of liquid through a diverging duct (in fact, a rotameter tube) as illustrated in Figure 15. They observed that, over very extended periods, no discernible coalescence occurred in the bubble bed. This is consistent with the observations of Colin et al (1991) as illustrated in Figure 13a. One may hypothesize that the approach velocities for bubbles in microgravity (where there would be no wake formation due to local relative velocity of the bubble in the surrounding liquid) are much lower and that the probability of success of coalescence is much higher.

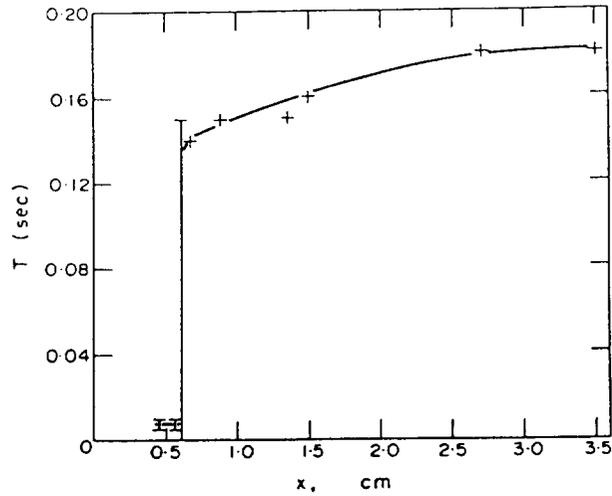


Figure 14: Coalescence time as a function of release distance for a bubble approaching a flat interface (Kirkpatrick and Lockett, 1974)

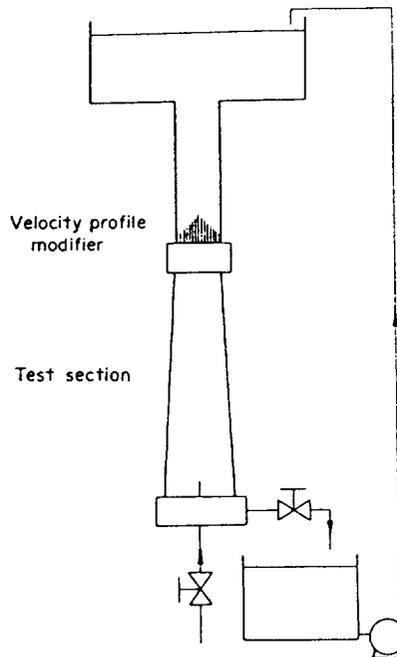


Figure 15: Diverging duct apparatus used for the study of bubble beds (Kirkpatrick and Lockett, 1974, Lockett and Kirkpatrick, 1975)

For bubbly flow, therefore, the coalescence phenomenon appears to represent a very interesting challenge. Possible areas for further work might include:

- (1) Simple experiments on bubble-bubble coalescence using two bubbles. These could include studies of the interaction of two bubbles growing from fixed locations at a controlled rate or experiments on controlled arrays of bubbles.
- (2) The role of system turbulence is crucial and one might suggest a whole range of experiments with controlled (grid generated) turbulence to investigate the turbulence of the continuous (liquid) phase in the absence of wake effects.

4. SLUG FLOW

Colin et al (1991) report measurements of void fraction in slug flow for both normal gravity (vertical tube) and microgravity; the results were again plotted in terms of u_G as function of mixture velocity U and the data are shown in Figure 16.

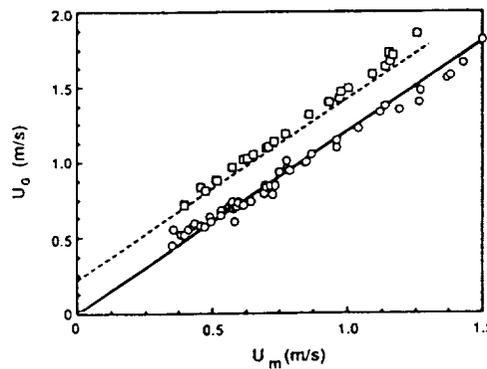


Figure 16: Actual gas velocity as a function of total superficial velocity for normal gravity vertical slug flows (\square) and microgravity slug flows (\circ). Zuber & Findlay (1965) relationship with u_∞ from Equation 6, $C_o = 1.2$. Zuber & Findlay relationship with $C_o = 1.2$, $u_\infty = 0$

The normal gravity data well fitted by Equation 4 with $C_o = 1.2$ and u_∞ given by the classical expression for the rise of a single Taylor bubble:

$$u_\infty = 0.35 \sqrt{\frac{(\rho_L - \rho_G)gD}{\rho_L}} \quad (6)$$

The microgravity data was fitted with $C_o = 1.2$ and $u_\infty = 0$.

The experiments by Colin et al (1991) were for air-water mixtures in a relatively large bore tube (4 cms). It would be advantageous to have a methodology for predicting the effects of parameters such as viscosity and surface tension on gas velocity (i.e., slug propagation velocity). The prediction of slug propagation at normal gravity is a matter of some interest and controversy. Specifically, there is a question about whether, in horizontal tubes, the term u_∞ is significant. Clearly, if a horizontal tube full of a stationary liquid is emptied from one end, then the gas would penetrate into the tube, with the liquid falling out of the end. The gas bubble penetrates at the classical Benjamin bubble velocity given by:

$$u_\infty = 0.54 \sqrt{gD} \quad (7)$$

and this clearly represents a limiting case for slug propagation at the lowest velocities. However, at higher velocities, the bubble is known to become more symmetric (the nose moving down towards the centre of the tube) and Equation 7 may not apply. In order to investigate this question in more detail, two approaches have been followed in work at Imperial College:

- (1) The rate of bubble front propagation has been measured in experiments in which the liquid in a liquid-filled tube is pushed out by a known volumetric flowrate (\dot{V}_G) of gas (the gas being fed through a critical flow valve to ensure constancy of mass flow, corrections being made to allow for compressibility in the inlet system). The gas velocity in the system is equal to the bubble propagation velocity u_b (which is measured using a series of conductance probes along the channel) and we may write:

$$u_G / U = Au_b / \dot{V}_G = 1 + C = C_o + u_\infty / U \quad (8)$$

where A is the cross sectional area of the channel and C is a parameter defined by Hubbard and Dukler (1966) according to Equation 8. Thus, the “push-out” experiment can allow precise measurements of u_G/U which can be compared with various analytical predictions. Data generated by this methodology are reported by Davies (1992) and Manolis (1995).

- (2) CFD calculations were carried out using the CFDS-CFX 4 code. The position of the interface was determined using the “homogeneous” (VOF) method and the methodology is illustrated in Figure 17.

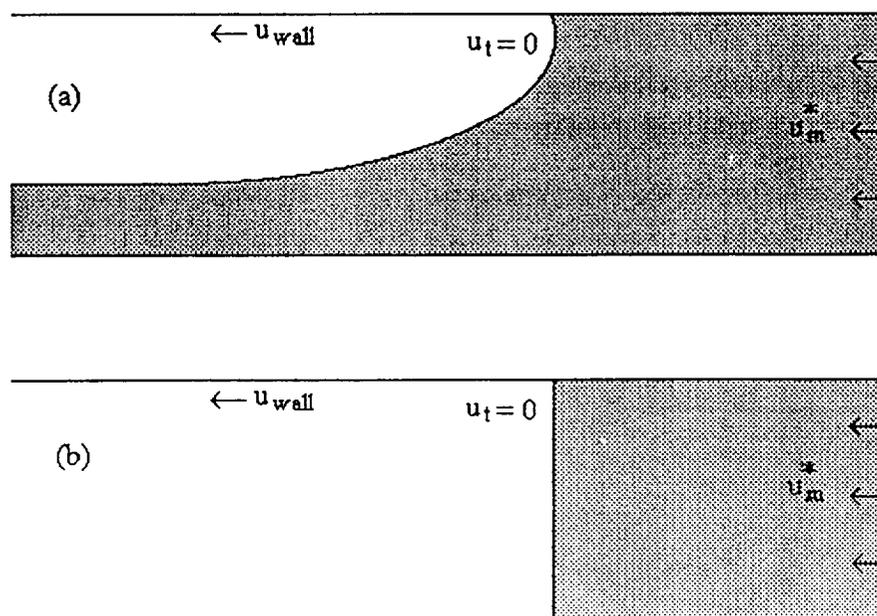


Figure 17: Calculation of slug tail propagation using CFDS-CFX4 (Pan, 1996)

In the steady-state, the interface remains stationary within the computational domain, with the wall of the channel moving and liquid being fed into the domain from the right hand side to maintain the interface in a constant position (Figure 17(a)). The computation is started at zero time with the liquid in the (circular) tube being separated from the gas by a vertical plane (Figure 17(b)). Further details of the calculation method are given by Pan (1996). Figure 18 shows results for the steady-state condition at a variety of mixture velocities, illustrating how the nose of the bubble moves towards the centre of the tube at higher velocities.

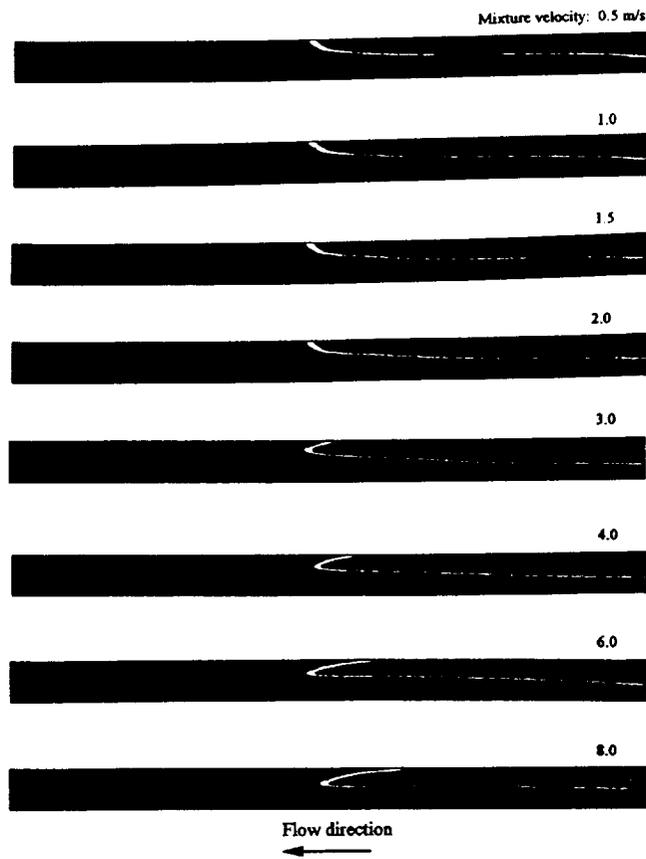


Figure 18: Prediction of slug tail propagation in a horizontal tube: interface shape as a function of mixture velocity (Pan, 1996)

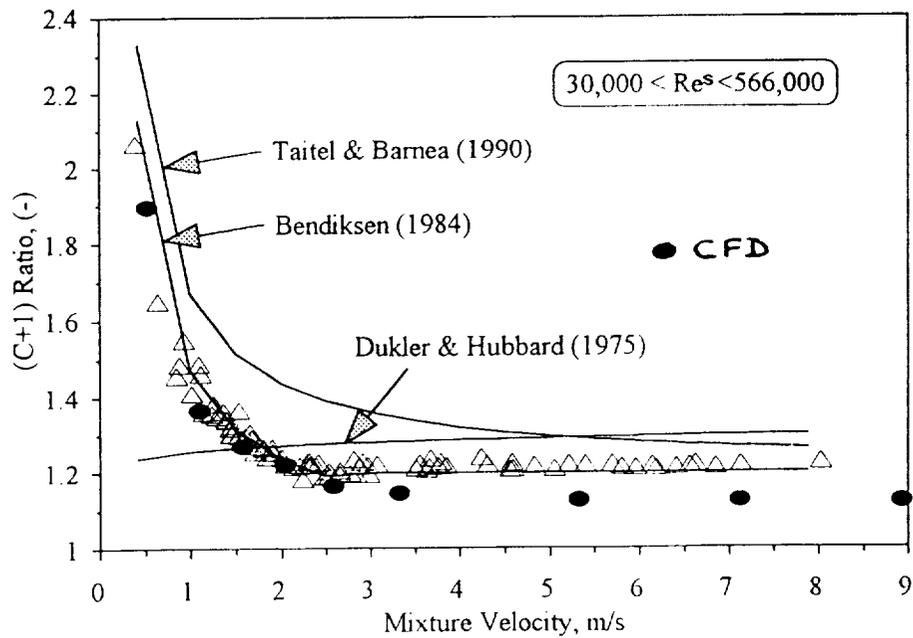


Figure 19: Comparisons of CFD calculation and data from the “push-out” experiments with various models for slug tail propagation

Figure 19 shows a comparison of the results from the push-out experiments (triangular symbols) and the CFD calculations with various models for slug propagation. The CFD calculations and the push-out experiments are in reasonable agreement and the data are consistent with the idea that the drift flux (u_{∞}) term disappears at higher mixture velocities giving a constant value of $(1+C) = C_o$ of around 1.2; this is consistent with the analysis of Bendicksen (1984).

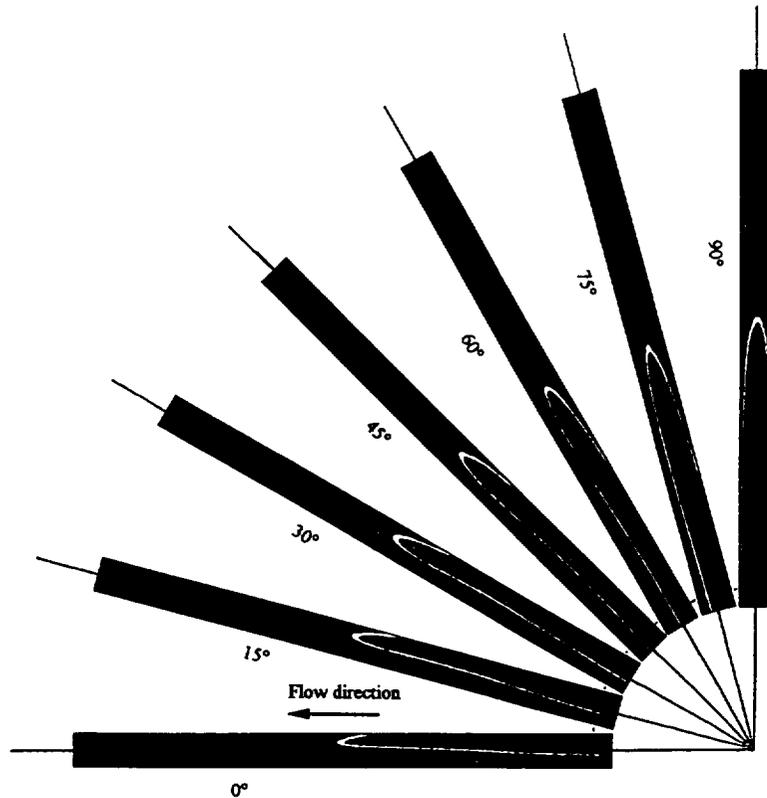


Figure 20: Effect of angles on interface shape in slug tail propagation (Mixture velocity 4 m/s) (Pan, 1996)

The CFD methodology can be applied to non-horizontal systems; Figure 20 shows predictions for a series of tube inclinations ranging from horizontal to vertical. Obviously, the axial symmetry of the flow increases progressively as the angle goes from 0 to 90°. The CFD methodology can also be applied to the zero gravity case and Figure 21 shows calculations of slug tail propagation at zero gravity. These calculations can be compared with calculations for vertical upwards flow and horizontal flow, and with the various models, and these comparisons are presented in Figure 22. As will be seen, C is constant independent of mixture velocity for zero gravity flows, the value being close to that for horizontal pipes at a higher velocities. For a given mixture velocity, it is possible also to calculate the translation velocity as a function of the fraction of normal gravity for horizontal and vertical flows respectively and calculations of this type are shown Figure 23. The vertical and horizontal flow cases converge at zero gravity, as expected.

Slug propagation under zero gravity conditions is thus an interesting limiting case for study and possible areas of work might include the following:

- (1) "Push-out" experiments at zero gravity. This experiment is a very simple method of investigating slug tail velocities and, by using parallel tubes, a whole range of tube diameters and fluids could be investigated simultaneously. The effects of viscosity and surface tension are particularly important.

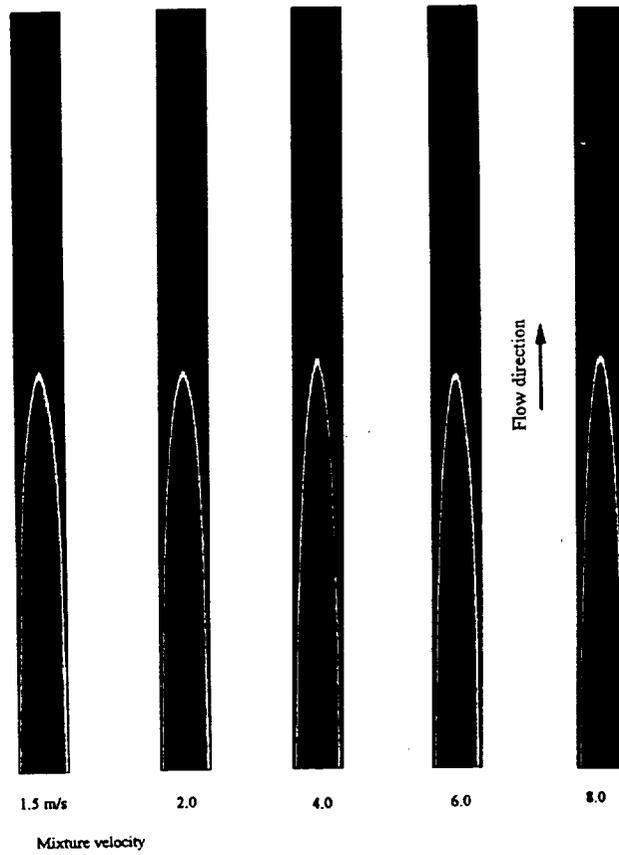


Figure 21: Interface shape of slug tail for zero gravity case (Tube diameter 77.92 mm, air water flows)

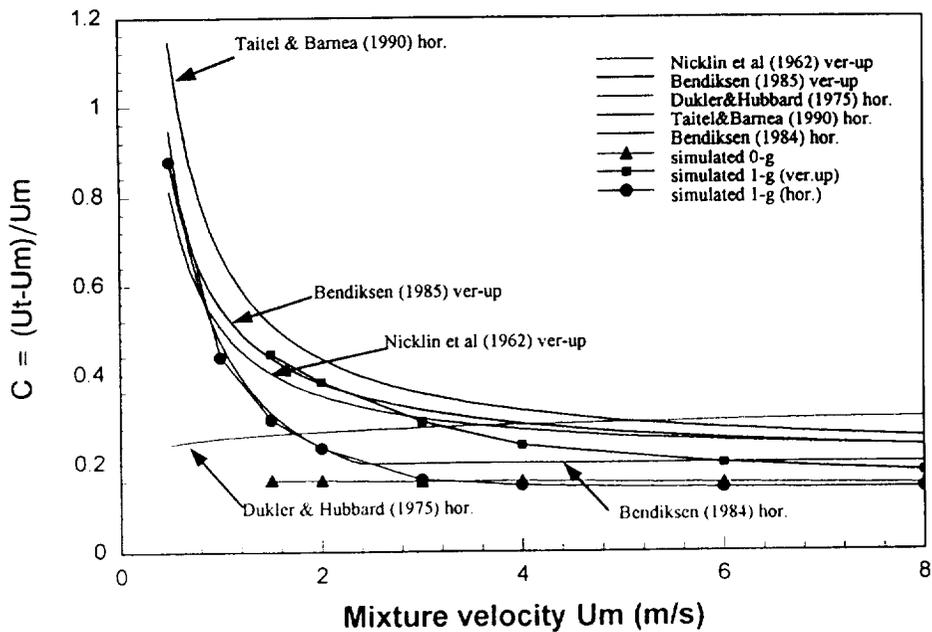


Figure 22: Comparison of C values obtained from models and from CFD calculations

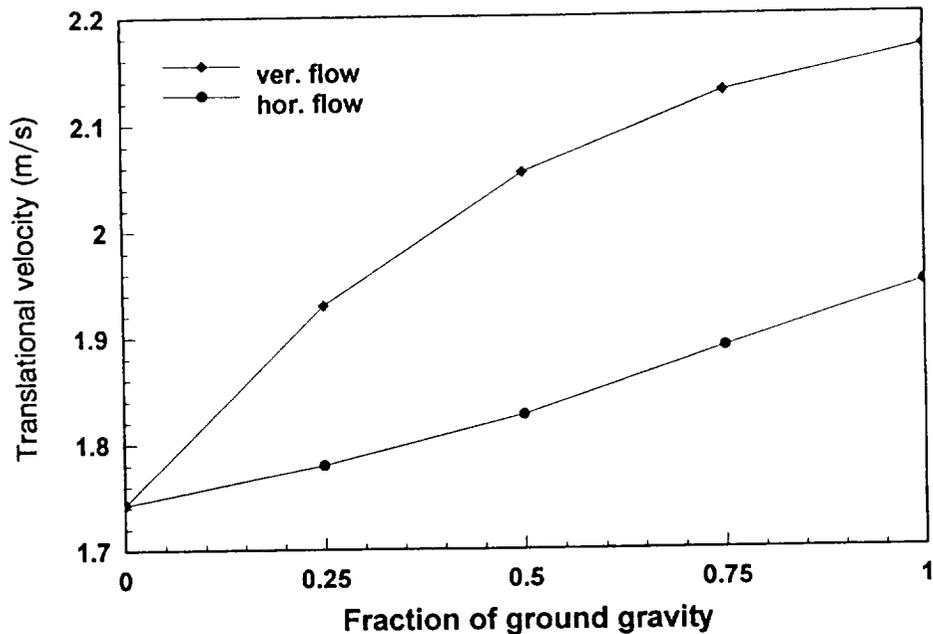


Figure 23: Slug tail translational velocity as a function of fractional gravity (Tube diameter 77.92 mm, mixture velocity, 1.5 m/s)

- (2) The preliminary work on CFD prediction of slug tail propagation at zero gravity could be extended to cover a much wider range of tube diameter, fluid viscosity and surface tension. The results can also be evaluated in more detail with respect to velocity profiles, wall shear stresses (related to pressure gradient) etc.
- (3) It should in principle be possible to extend the CFD studies to include studies of the motion of bubble within the liquid slugs. There is evidence that these bubbles are traveling at the same velocity as the Taylor bubbles which implies that they are not in the wall region where there is a difference in velocity.

5. ANNULAR FLOW

In high velocity vertical annular flows, the most important characteristic feature is the existence of *disturbance waves*. The main features of these waves are as follows:

- (1) They do not occur at very low liquid rates, the transition being at film Reynolds numbers of around 250.
- (2) The waves are formed near the channel entrance at a frequency which may be related to turbulent burst frequencies. The frequency then falls with distance due to wave coalescence, reaching an asymptotic value at large distance. The spacing between the waves is random.
- (3) The waves have velocities typically in the range 3-10 m/s, namely much higher than the average velocity in the liquid film but much lower than the gas velocity in the core.
- (4) The waves are seen as “squally” regions in the flow which are typically 1-2 diameters in extent.

- (5) The wall shear stress in the wave region rises rapidly to a peak which is several times that in the intervening substrate film.
- (6) Disturbance waves are a necessary condition for droplet entrainment, the entrainment arising due to breakup of the wave tip. Such droplet entrainment is therefore the rule rather than the exception in annular flow.

Recent work at Harwell and Imperial College on annular flow is summarised, for instance, by Hewitt and Govan (1990) and by Wolf (1995). Recently, attempts have been made to model the flows in disturbance waves using CFD techniques. In order to achieve this, it is necessary to have a prescription for the interfacial shear stress. This is calculated assuming that the interfacial roughness is equal to five times the local film thickness in the wave region (this is consistent with experimental data) and using the expression of Shearer and Nedderman (1965) (who correlated interfacial friction for sub-critical films without disturbance waves) for the substrate region. Details of the calculations are given by Jayanti and Hewitt (1994) and some sample results are given in Figures 24 and 25; in these Figures, the vertical scale is exaggerated by a factor of 10 in the interests of clarity

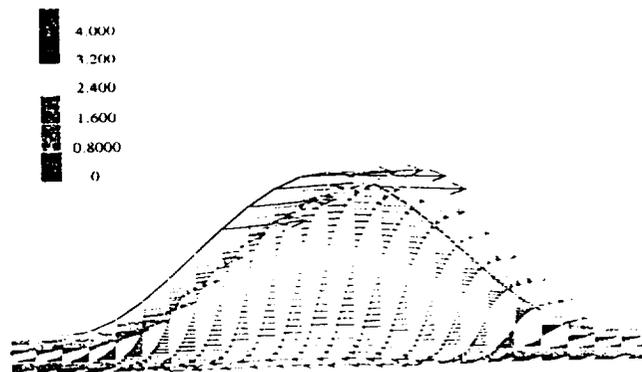


Figure 24: Velocity vectors in a disturbance wave in annular flow (Jayanti and Hewitt, 1994)

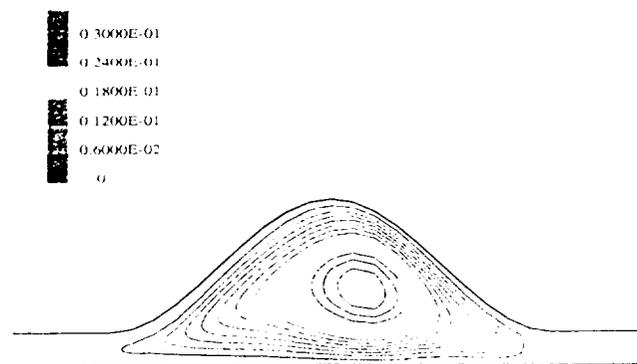


Figure 25: Turbulent viscosity distribution in disturbance wave (Jayanti and Hewitt, 1994)

The calculations shown in Figures 24 and 25 were carried out using the low Reynolds number $k-\epsilon$ model.

Figure 24 shows velocity vectors within the wave indicating intense recirculation and Figure 25 shows the distribution of turbulent viscosity. Using the low Reynolds number $k-\epsilon$ model, the turbulent viscosity in the substrate region is predicted to be zero. Clearly, there is a sensitivity to prediction models and it is extremely difficult to establish the local nature of the flows within these flows experimentally. In normal gravity vertical flows, slug flow breaks down into churn flow in which, in addition to normal disturbance waves, there are large waves of the flooding type (see discussion above) and it is not until large gas velocities are reached that the characteristic disturbance wave region is firmly identified without the ambiguities associated with the occurrence of churn flow. In the zero gravity case, however, there is a direct transition from slug flow to annular flow and, thus, the flows can be studied without the complications of flow reversals and flooding waves. At the high gas velocities necessary to have an ambiguous disturbance wave under normal gravity, the liquid films are very thin and details of the flow within them cannot easily be measured. However, with zero gravity flows, the disturbance wave region could be investigated at much lower gas velocities and much more intensive measurements made.

Work on annular flow under zero gravity conditions might include the following:

- (1) The establishment of the regions of interface behaviour at zero gravity. Would the transition to disturbance waves at a constant liquid film Reynolds number extend through to the transition to slug flow?
- (2) Studies of the onset and behaviour of disturbance waves over the full range of flow from the transition from slug flow, and in particular measurements of flow characteristics within the liquid film (here, techniques such as photochromic dye-tracing may be used).
- (3) Studies of droplet generation and behaviour at zero gravity. Of particular interest here is the formation of holdup waves within the gas core which is believed to lead to the occurrence of wispy annular flow.

6. CONCLUSION

To conclude, it may be said that zero gravity two-phase flows are not only interesting in themselves (in the context of their many applications in space technology) but also in the context of investigating mechanisms of gas-liquid flows without the complicating effect of the gravitational field. Many possibilities exist for further work in this area, ranging from studies of bubble coalescence and slug tail propagation to studies of disturbance wave behaviour and droplet formation and deposition phenomena in annular flow.

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