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BRIEF COMMUNICATION

THE INFLUENCE OF RETURN BENDS ON VELOCITY RATIO IN GAS–LIQUID PIPE FLOW

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1. EXPERIMENTAL INVESTIGATION OF FLOW

The objective of the present work is to investigate the ratio of velocity between phases in the vicinity of a bend under conditions of bubbly flow at inlet. This aspect of the flow, which influences the mixture momentum balance, has not been considered in detail by other investigators (e.g. Golan & Stenning 1970, Traviss & Rohsenow 1973 or Gardner & Neller 1969).

Three types of mixer (Herringe & Davis 1976) were employed to create turbulence and mix the phases as they entered the pipe (diameter 5.08 cm, length 101.6 cm) leading vertically to the return bends ($R_c/r_o = 2$ and 3, r_o being the pipe radius and R_c the radius of the centre line curvature). The mixture discharged downwards from an outlet pipe 122.9 cm long. Resistivity probe techniques were used as described by Herringe & Davis (1974, 1976). These allow measurement of void fraction and flow speed to within 2 per cent.

A high speed film (at 2000 frames/s) showed the upstream flow at Fr = 23.7 (where Froude number is defined as $U_m^2/(gd)$ and d is pipe diameter) to contain an homogeneous bubble distribution with the appearance occasionally of large bubbles, whilst at Fr = 60.3 and 160.0 more homogeneous and finer bubble distributions existed upstream. Separation of phases occurred in the bend, commencing at about 5° from the inlet, more air being observed at the inner wall of the bend at the higher velocities. A very high percentage of water was observed at the outer wall of the bend. Downstream, oscillatory flow was always observed, slugs of air periodically occurring with a higher percentage of air close to the inner wall. At higher Froude number the two phases re-mixed more rapidly.

1.1 *Void profiles*

Selected void profiles in figure 1 (Fr = 60.3) show results obtained from mixers which gave the most widely differing inlet flow structures. At Fr = 23.7 a peaked void fraction profile was found whatever the type of mixer used. For Fr = 60.3 (figure 1) a fairly uniform air concentration over the pipe diameter was found with the nozzle mixer, whilst the cylindrical mixer produced a centrally peaked void profile due to the difference in the size of the bubbles from the different mixing techniques (see Herringe & Davis 1976). At Fr = 160.0, similar void profiles were recorded at the − 1.5 d inlet section of the flow rig for all mixers with uniform voidage over the central 30 per cent of the diameter.

At the bend exit (figure 1b) similar void fraction distributions were found for all types of mixers irrespective of inlet distributions. This is because of the high degree of turbulence and losses in the bend which dominate over inlet flow effects and completely reorganise the flow structure. At higher flow velocities, the gas concentrated more strongly towards the inner wall of the bend. Table 1 summarizes the separation effects in terms of the centroid positions of the gas phase on the pipe cross section.

The approximate equality of turbulent kinetic-energy of the mixture and the difference in potential energy across the pipe diameter can be used to indicate the onset of separation. Where

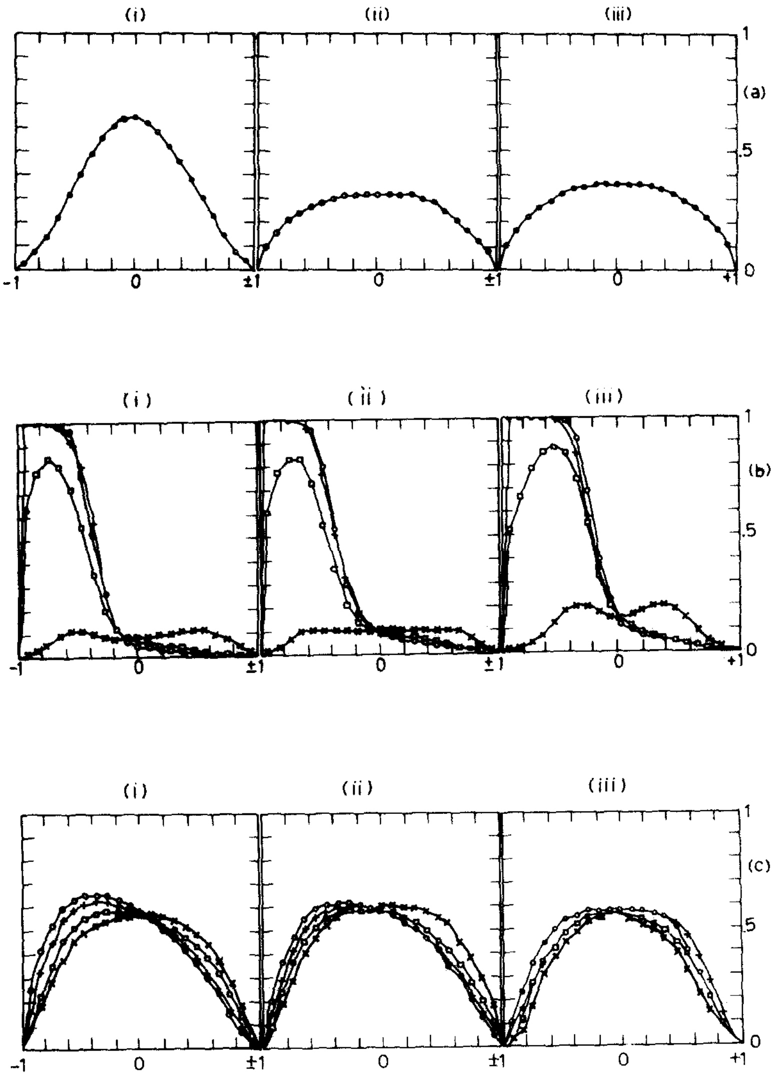

Figure 1. Voidage distributions around the bend at intermediate velocity (Fr = 60.3). (i) $R_c/r_o = 3$, mixer : cylindrical (no screen); (ii) $R_c/r_o = 3$, mixer : nozzle; (iii) $R_c/r_o = 2$, mixer : nozzle. (a) At inlet section ($x = -1.5d$); (b) At outlet section ($\theta = 180°$); (c) At downstream ($x = +9d$). ○ .... traverse $\phi = 0°$; + ... traverse $\phi = 30°$; □ ... traverse $\phi = 60°$; × ... traverse $\phi = 90°$. Horizontal scaler: radical position $\bar{r}/r_o$; Verticle scales: void fraction α.

Table 1. Radial positions of the centroid of gas phase (Mixer : Nozzle)

Bend $\frac{R_c}{r_o}$	Section	Dimensionless co-ordinates of centroids $\bar{r}/r_o$		
		Flow 2 (Fr = 23.7) $\beta = 0.30$	Flow 6 (Fr = 60.3) $\beta = 0.22$	Flow 7 (Fr = 160.0) $\beta = 0.42$
2	Exit	−0.372	−0.394	−0.384
	Exit + 9d	−0.036	−0.026	−0.001
3	Exit	−0.415	−0.428	−0.396
	Exit + 9d	−0.074	−0.047	−0.031

the turbulent kinetic-energy exceeds the potential energy difference across the pipe radius it is expected that separation does not occur, and vice versa. If $c = U'^2/U^2$ is the ratio of turbulent to mean kinetic-energy, the condition for the separation is:

$$c\rho_m \frac{U^2}{2} \leq \rho_m \frac{U^2}{R_c} d \qquad [1a]$$

which simplifies to:

$$\frac{d}{R_c} \geq \frac{c}{2} \qquad [1b]$$

where ρ_m is the mixture density (Hoang 1976).

In most turbulent flows the value of c is about 0.04. In this work, the ratio d/R_c ranged from 0.67 to 1.0. Thus condition [1b] is always expected to be satisfied and as observed the separation of phases in the flow under this test always occur. An alternative estimation of the separation tendency may be made on the basis of flow regime maps for horizontal flow. The gravitational acceleration g for flow in a horizontal pipe is replaced by a centripetal acceleration U_m^2/R_c in the curved duct flow. Kosterin (1949) discussed the dependence of horizontal flow patterns on the Froude number of the mixture and Weber number ($\mathrm{We} = L\rho U_m^2/\sigma$ where L is a characteristic length associated not with the tube diameter but with bubble size). The present work lies in the region defined as plug flow on Kosterin's regime map for which slugs are present divided by regions of froth and for which stratification is evident. This is in accord with the observations of the flow leaving the bend. Another widely used flow map for adiabatic horizontal two-phase flow is that due to Baker (1954). The values of maximum Froude number $(U_m^2/gd)_{\mathrm{Baker}}$ on the stratified flow boundary on the Baker map which correspond to the volumetric flow ratio β of this work may be estimated. The occurrence of stratification can be explained in this work under centripetal action, and we may determine an equivalent Froude number for the curved flow as:

$$\left[\frac{U_m^2}{\left(\frac{U_m^2}{R_c}\right)d}\right]_{\text{curved flow}} = \left(\frac{R_c}{d}\right) = 1.0 \text{ and } 1.5 \text{ (in present work).}$$

This shows that the effective transverse Froude number in the present work lies close to the Froude number at which Baker usually observed stratification to begin.

Downstream of the bend (+9 diameters from exit) the effects of the flow velocity on re-mixing the stratified flow are seen. At Fr = 23.7 the air concentration at the inner wall remains high for the larger radius bend and the void profiles at traverses 0, 30 and 60° continue to be asymmetrical. Similar profiles were found at Fr = 60.3 (figure 1) with an intermediate flow rate of liquid. However, following the smaller bend ($R_c/r_o = 2$) and at Fr = 160.0 for both bend sizes the high degree of turbulence due to bend losses causes the void profiles to return to the symmetrical shape within the 9 diameter length.

If radial motion of bubbles under the action of the radial pressure gradient is resisted by a force depending upon the square of the radial velocity, the radial separation velocity varies with the square root of the radial pressure gradient. For a given size of bubble and axial speed, this pressure gradient itself varies with the inverse of the radius of curvature. Further, the radial displacement of a bubble is expected to increase with the time of passage through the bend, which increases in proportion to the bend radius. Combination of these factors suggests that the net displacements of the gas phase increase with the (bend radius)$^{1/2}$. Whilst only small displacement variations have been observed here, the increase of centroid displacement at exit with bend radius appears consistent with this argument.

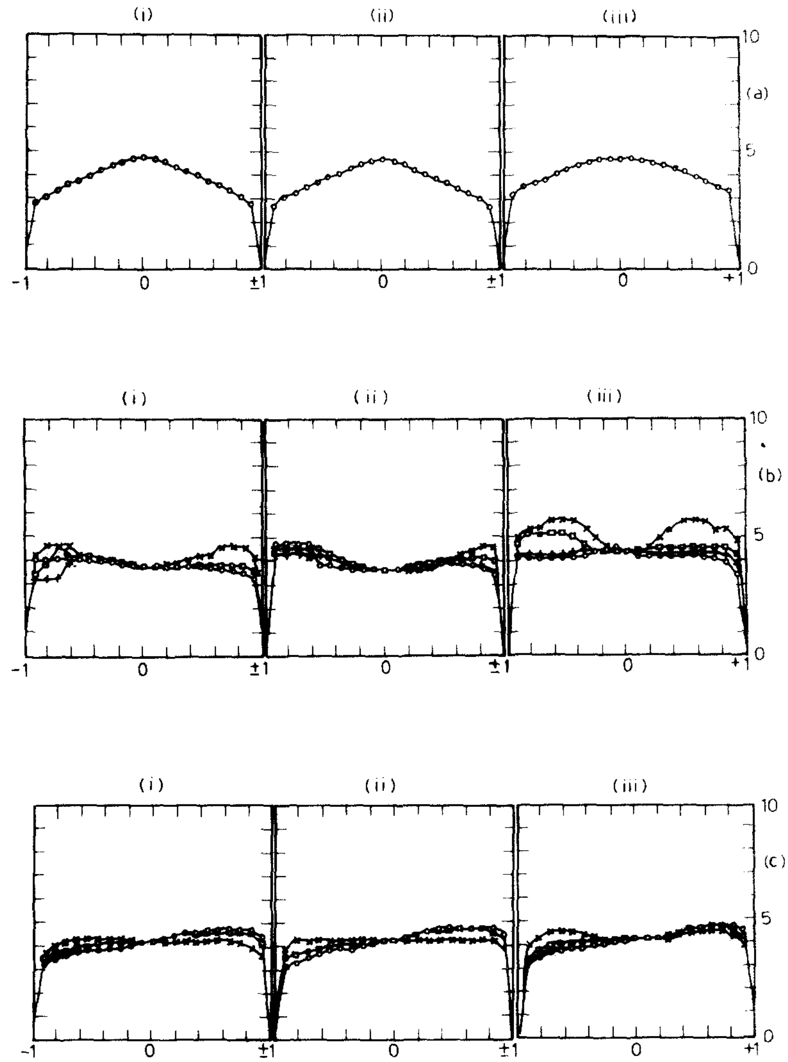

Figure 2. Gas velocity distributions around the bend at low velocity (Fr = 23.7). Legend as figure 1. Horizontal scales: radical position r/r_o. Vertical scales: gas velocity U_G (m/s).

1.2 *Gas velocity*

Typical velocity profiles are shown in figure 2, and show that the effect of the bend at the upstream section can be neglected. The effect of mixing method on the velocity profiles is not strong although the velocity profiles from the nozzle mixer were generally flatter due to its strong mixing action. At Fr = 23.7 the velocity profiles (figure 2) were markedly peaked at the pipe centre, whilst at Fr = 60.3 and 160.0 a much more uniform velocity distribution was found. Within the bend, strong separation of phases gives rise to the transmission of a nearly constant pressure around the inner wall of the bend through the gas phase approximately equal to the exit pressure. Pressures were observed experimentally using drilled wall tappings containing air (purged before taking pressure readings). The pressure at the outer wall drops steadily towards this exit value. Thus the maximum velocity moves from the inner to the outer wall of the bend. This is clearly shown at the bend exit section (figure 2). It may be seen that the smaller radius bend produces stronger maxima in the velocity profiles towards the wall. The regions of high velocity towards the wall on the $\phi = 90°$ plane (ϕ being probe traverse angle, measured from the plane of the bend) appear to correspond to higher conditions of local void fraction.

Downstream of the bend the high velocity region of the flow is close to the outer wall for all flow conditions. The local velocity maxima towards the walls along the $\phi = 90°$ diameter persist in the flow from the smaller bend but are not evident at all in the flow from the larger bend as a result of the stronger non-uniformity developed on the $\phi = 90°$ diameter at exit. Also the velocity increases from inner wall to outer wall more strongly in the flow from the smaller bend. This is consistent with the observations at exit, where the smaller bend appeared to have imparted a greater rotational motion to the flow. The most uniform velocity distribution appeared following the larger bend under the conditions of Fr = 160.0, as the larger bend established a weaker initial rotation at exit, whilst the larger mean flow velocity promotes most rapid re-mixing of the flow and this dampens any imparted rotation downstream of the bend more quickly.

1.3 *Velocity ratio*

In a gas–liquid flow system the velocity ratio is related to the mean void fraction α and mean volumetric flow ratio β by:

$$S = \frac{U_G}{U_L} = \frac{1/\alpha - 1}{1/\beta - 1} \quad [2]$$

where U_G and U_L are mean gas velocity and mean liquid velocity respectively. α can be obtained by numerical integration of the measured void profiles.

Corrections to measured local voidage of 7 per cent on average were made to match the overall mass flow rates, measured voidages being slightly low due to bubble deflection from the needles.

Figure 3 shows the variation of velocity ratio which resulted. At Fr = 23.7 the velocity ratio increases substantially within the bend in all cases and subsequently shows a slight reduction in the outlet pipe. At Fr = 60.3 the flow in the sharper bend ($R_c/r_o = 2$) shows a rather similar behaviour, whilst in the larger bend all flows show a reduction in the velocity ratio as the flow enters the bend. From the void profiles, it may thus be seen that the cases where the velocity ratio is increased within the bend correspond to cases where a rather larger separated region of high gas content is formed. At Fr = 160.0 a reduction in velocity within the bend was observed under all conditions, whilst appreciably greater increases in velocity ratio then occurred in the downstream passage, a maximum of $S = 1.56$ being observed in the passage downstream of the smaller bend.

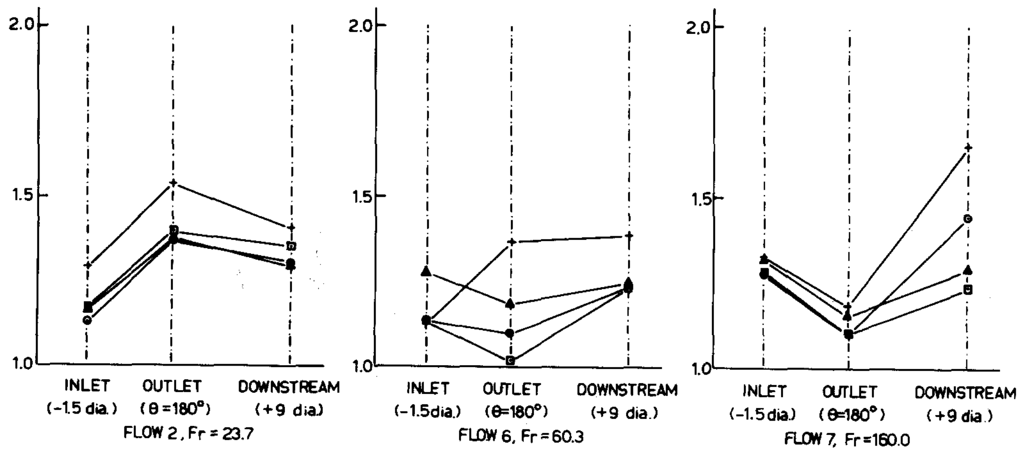

Figure 3. Variation of velocity ratio through bend: ○ ... $R_c/r_o = 3$, mixer : nozzle; △ ... $R_c/r_o = 3$, mixer : cylindrical (no screen); □ ... $R_c/r_o = 3$, mixer : cylindrical (two screens); + ... $R_c/r_o = 2$, mixer : nozzle. Vertical scales: velocity ratio S.

2. CONCLUSIONS

At the lowest test Froude number velocity ratio reduced within the bend and increased in the downstream duct. At the highest Froude number the velocity ratio increased strongly within the bend and reduced only slightly in the downstream duct. These velocity variations depend upon both velocity and void distributions and thus depend upon several mechanisms present in the bend flow, namely the rotation established in the flow, separation of phases and the high velocity of regions of high gas content. The velocity ratio between 1.02 and 1.56 over the range of observations made. It appears that stratification should be related to the bend radius of curvature in terms of centrifugal accelerations, rather than the diameter and gravity based Froude number used by Gardner & Neller (1969) at much lower Froude numbers.

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