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TWO-PHASE FLOW SPLIT AT T JUNCTIONS: EFFECT OF SIDE ARM ORIENTATION AND DOWNSTREAM GEOMETRY

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Abstract—The effect of flow pattern and geometry on the phase split of gas/liquid flows at T junctions has been examined for a horizontal main tube and horizontal and vertically upwards side arms. Important phenomena which control this split in annular and wavy stratified flow have been identified. The capability of current models to predict the split are discussed. In particular, the effect of geometry in the downstream leg of the main pipe was studied. The configurations studied had no effect in annular flow but influenced the amount of liquid taken off at high take off when stratified flow approached the junction.

Key Words: junctions, flow split, data, gas/liquid

1. INTRODUCTION

The division of two-phase flow at junctions, with its almost inevitable maldistribution of the phases between the outlets, can constitute a major problem when it occurs in chemical process and oil refinery plant and in gas oil production equipment. This maldistribution can have significant effect on the behaviour of equipment downstream of the junction. For example, when steam injection is being used to effect enhanced recovery of viscous oils, the steam is usually generated at a central point and distributed to a number of wells. This can involve several junctions. In this process it is important to know where the water (either that coming from the boiler because of incomplete evaporation or that due to condensation of steam along the transmission lines) goes to, as water having a much lower enthalpy than steam is much less effective at lowering the viscosity of the oil.

The phase split at T junctions is also important in the design of multi-pipe (multi-bottle) slug catchers used in oil and gas production. In these, the flow is slowed down by being divided into a number of parallel flow paths through a series of T junctions. The large-diameter pipes that form the slug catcher are set at a small downward inclination and have a side arm emerging from the top of the main pipe. Under normal operation, gas emerges from these side arms while the liquid exits from the bottom end of the main pipe. All gas outlets are linked together to lead to the gas processing equipment, there is a similar arrangement for the liquid. Obviously, correct operation of the equipment relies on complete phase separation at the vertical side arm Ts. To date there has been limited work on vertical side arm T junctions. Bos & du Chatinier (1985) and Johnston (1988a,b) have published research on this type of separator, with the former workers indicating that complete phase separation at the junction was not easy to achieve. Reimann (1987) has suggested a separator using a vertical side arm junction. However, as he was aware that complete phase separation was unlikely, his design included an arrangement for the subsequent separation and reintroduction of liquid emerging through the side arm.

Oranje (1973) and Hong (1978) published early papers which illustrated the phase separation which can occur at T junctions for two-phase flows with very low liquid content. In particular, they observed that a small increase in the gas take off can divert the liquid from the main tube to the side arm. Shoham *et al.* (1987), who studied horizontal annular and stratified flows with low liquid flow rates, put forward a model in which the phase maldistribution was the result of centrifugal separation of the phases produced by the fluids following a circular path into the side arm. It gives reasonable predictions of data. Hwang *et al.* (1988; Hwang 1986) model the phase separation by assuming that there is a zone of influence for each of the two phases from which the fluid is taken off. This is bounded by the channel wall and an appropriate dividing streamline, the position of which are determined from a balance between the dominant forces acting on each phase. A significant experimental study has been published recently by Reimann *et al.* (1988), it contains much useful information but has not yet been analysed fully.

Sliwicki & Mikieliwicz (1988) analyse the diversion of the liquid film in vertical annular flow by considering the local forces at the front corner of the junction. They also calculate the fraction of drops diverted into the side arm. Constants in their equations have been optimized using the data of Azzopardi & Whalley (1982). Lately, Hart *et al.* (1991) have developed a model for gas flow with small liquid content. This was based on Bernoulli equations for each phase along the main pipe and from the main pipe to the side arm. They assume no interaction between the phases.

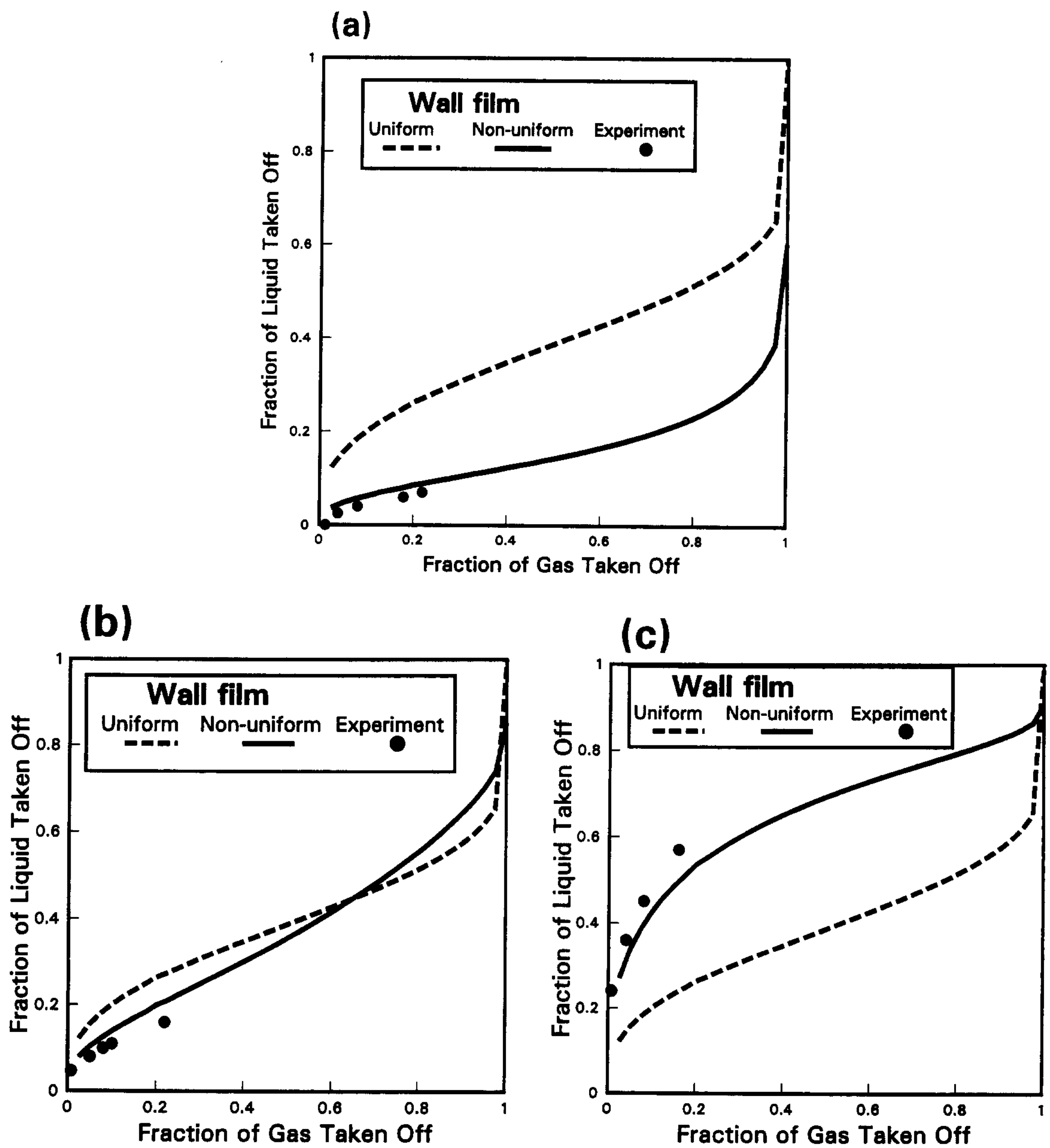

Figure 1. Effect of side arm orientation on the two-phase flow split at T junctions—comparison of the model of Azzopardi & Whalley (1982) with air/water experimental data. Main tube dia = 0.032 m, side arm dia = 0.0126 m; gas superficial velocity = 21 m/s, liquid superficial velocity = 0.08 m/s; pressure = 2.5 bar.

Loss coefficients are described by single-phase correlations. Manipulation of the equations results in a relationship between the fraction of liquid taken off through the side arm and the fraction of gas taken off.

Annular flow approaching the junction in a vertical main tube with a horizontal side arm has been studied by Azzopardi & Whalley (1982), Azzopardi (1984, 1988, 1989). They observed that initially the fraction of liquid taken off was greater than the gas fraction but that this was reversed at higher take off. The fraction of liquid taken off decreased with increasing inlet gas and liquid flow rates. At higher gas take off the amount of liquid extracted increased suddenly for a small increase in gas take off. An exception to the above behaviour occurred at low liquid inlet conditions when liquid was preferentially extracted. Azzopardi (1989) postulated a model which involved up to three phenomena. The first of these depended on the fact that the momentum of the film (defined as $\rho_L u_{LF}^2$) was similar to that of the gas ($\rho_G u_G^2$) and both were much less than that of the drops ($\rho_L u_{LD}^2$), measurements by Azzopardi & Teixeira (1992) show that the mean drop velocities are approximately equal to the superficial gas velocity. It also relied on the observation for single-phase flow that, to a reasonable approximation, the extracted fluid came from the segment nearest the side arm. For annular flow, gas and film from the local segment are assumed to be taken off. At higher take off, the gas velocity in the main tube above the junction falls below the flooding velocity and liquid which has passed the junction falls back and is taken off. The film will react to the pressure increase across the junction and slow down. When the pressure increase is high and the inlet film momentum low the film can be brought to a complete stop. It is then easily extracted. The predictions of this model agree well with data. A systematic effect of diameter ratio has been reported by Azzopardi (1984). A decrease in the side arm diameter led to less liquid being taken off.

The model for annular flow postulated by Azzopardi & Whalley (1982) can be extended to horizontal main tubes and can be particularly successful if the circumferential variation of film flow rate is known and taken into account. An example is shown in figure 1. This data was taken at conditions (main tube dia = 0.032 m, side arm dia = 0.0126 m, gas superficial velocity = 21 m/s, liquid superficial velocity = 0.079 m/s, pressure = 2.5 bar) for which the circumferential film flow rate distribution has previously been measured by Butterworth & Pulling (1974). Cases with vertical upward (a), horizontal (b) and vertical downward (c) side arms are considered. The data is presented as fraction of the incoming liquid emerging through the side arm against the fraction of gas. In all cases the predictions made using the circumferential variation of film flow rate determined experimentally by Butterworth & Pulling (1974) gave good agreement with the measurements of flow split. In all three parts of the figure, the predictions made using the assumption that the film had a uniform flow rate all round the circumference are also plotted. There is significant over- and under-prediction in cases (a) and (c). Even in figure 1(b), where the local film flow rate might be expected to vary about the mean value, the agreement is not as good as that using the variation of film flow rate.

There has been very little work published which considers the effect of side arm orientation when the main pipe is horizontal. The work of Reimann *et al.* (1988) contains the majority of the available data. The results show the expected trends, more liquid is taken of when the side arm is vertically downwards than the horizontal case. For the vertically upward side arm there is the least liquid take off.

2. EXPERIMENTAL ARRANGEMENT

The apparatus used in the experiments described below used air and water as the two phases. It is shown schematically in figure 2. Filtered, metered air at constant pressure was taken from the laboratory compressed air main. It entered the horizontal flow tube (made from sections of stainless steel pipe of 0.038 m i.d.) through an entrance section 0.6 m long. Water was drawn from a storage tank by means of a centrifugal pump. The correct water pressure was attained by bypassing part of the flow. The flow to the test section was monitored by one of a number of calibrated rotameters. It then entered the flow tube through a section of porous wall. The junction, described below, was placed 3.2 m from the liquid entry point with 0.95 m of tubing beyond it. The side arm was

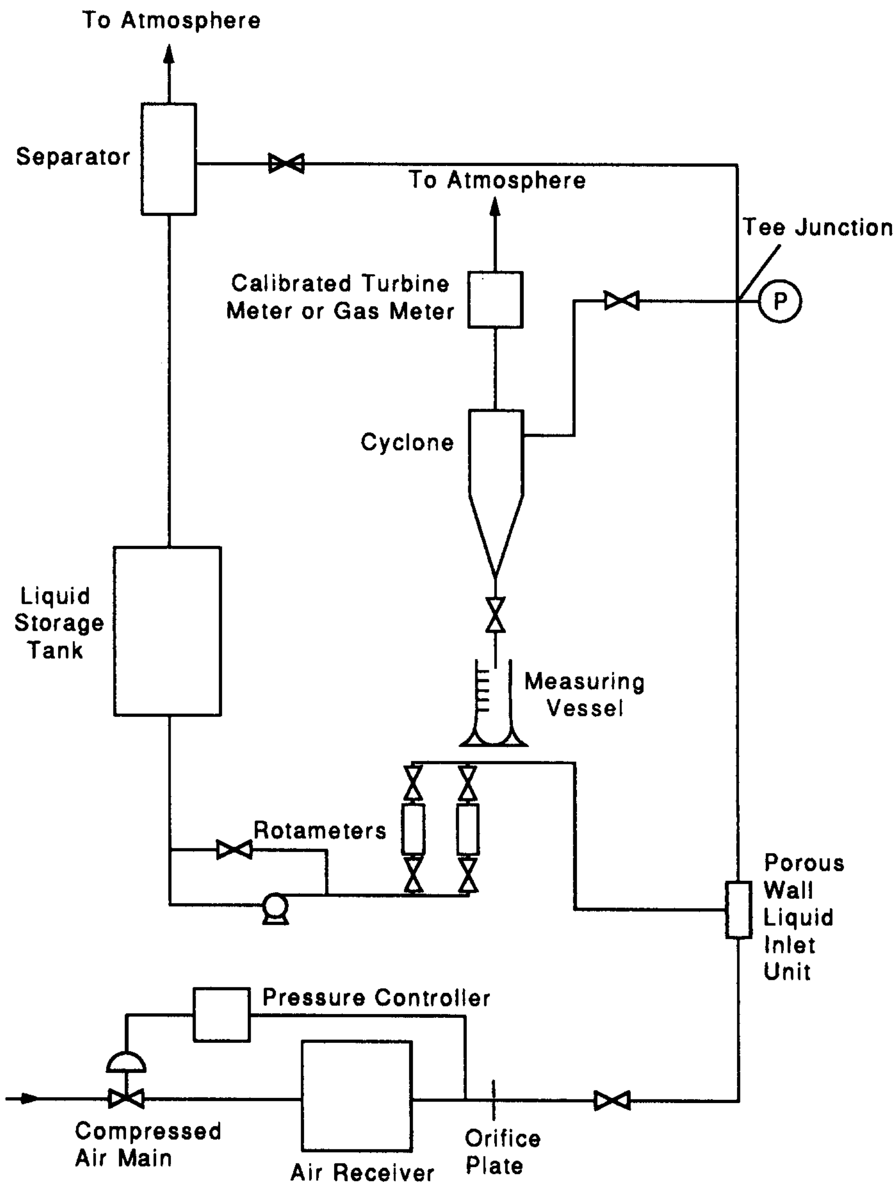

Figure 2. Experimental arrangement.

positioned either horizontally or vertically upwards and consisted of 1.08 m of 0.0254 m i.d. pipe and a length of flexible tubing. In some of the horizontal cases side arms of 0.038 and 0.0126 m internal diameter were also used. The air and water emerging from the side arm were separated in a cyclone and metered. The air flow was measured using a calibrated turbine meter and the water flow rate was determined from weighing a timed efflux. The two-phase flow emerging from the main tube was also separated (though not metered) with the water being returned to the storage tank and the air being released to atmosphere. At high rates of take off the connections were reversed and the two-phase flow from the main tube was metered. In order to check the measurement technique, measurements were made, over the same range of take off, using each outlet in turn. The data were converted to fraction of gas or liquid emerging through the side arm. When plotted as fraction of liquid against fraction of gas, data fell along the same curve irrespective of the outlet at which the measurement has been made. Valves on the two outlet tubes were used to control the division of the flow and maintain the pressure at the junction at a constant value. In most cases this was 3 bar absolute, though a minority of the experiments were carried out at 1.5 bar.

In most experiments, the flow passed from the main tube to the separator through two flexible pipes. At the division there was a local constriction. In order to check whether there was a

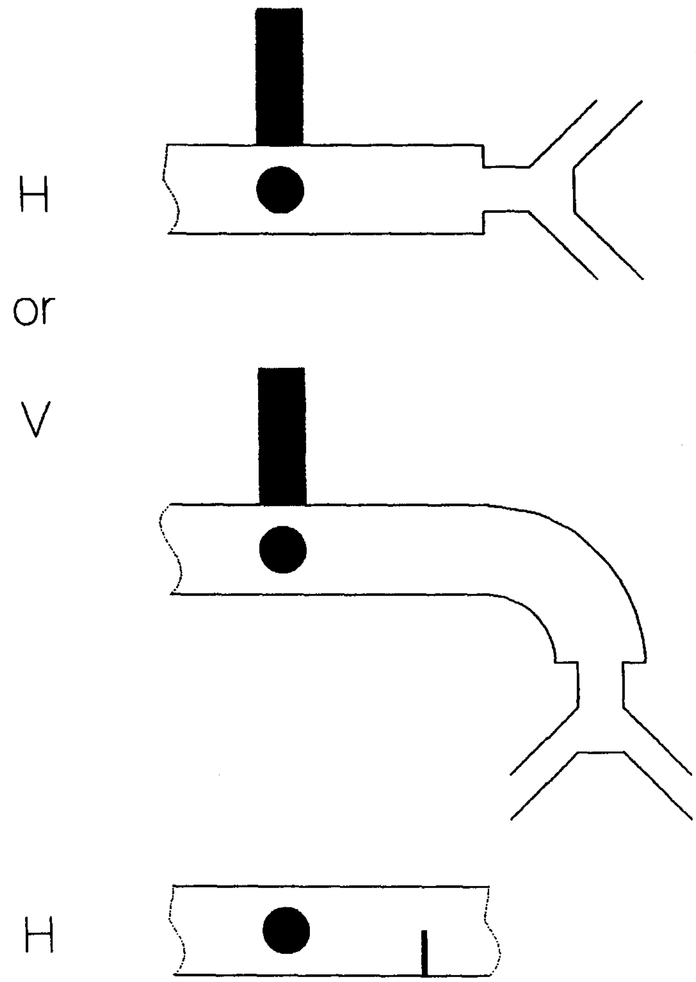

Figure 3. Schematic diagram of geometries used.

significant upstream feedback caused by the downstream geometry, some of the tests were repeated with a 90° bend placed between the main tube and the constriction. This would diminish any propensity for liquid to build up at the constriction. A limited number of tests were carried out in which a weir was placed in the main pipe 4.7D downstream of the T. This weir, with a horizontal edge, was 0).0177 (0.466D) high. The geometries are illustrated schematically in figure 3.

The T junction used in the present study was machined from an acrylic resin block. The main bore was 0.038 m dia, whilst the side arm bore was 0.0254 m dia (though 0.013 and 0.038 m side arm diameters were used in some experiments). The outside of the T-shaped block has been machined to a square cross-section (0.05×0.05 m) to minimize refraction problems during the observation part of the study. All surfaces were polished to facilitate observation. The junction block was provided with flanges at the three ends so as to mate with the rest of the test-section pipework. The block was 0.275 m long and the side arm portion was 0.13 m long. The junction was carefully machined with sharp corners thus setting the radius of curvature to a fixed and very low value.

3. RESULTS

Data of the flow split at T junctions were taken for a range of inlet flow rates from 0.003 to 0.101 kg/s for the gas and from 0.009 to 0.076 kg/s for the liquid. These flow rates correspond to superficial velocities of 0.75–25 m/s for the gas and 0.008–0.067 m/s for the liquid. The experiments involved annular, wavy stratified or smooth stratified flow approaching the junction. Some inlet conditions were chosen to be at the boundaries between these flow patterns. Example results are

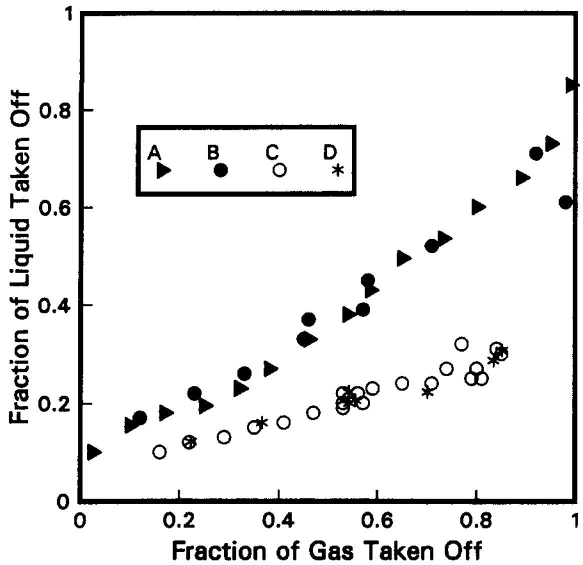

Figure 4. Effect of side arm orientation on the flow split —annular flow (gas flow rate = 0.101 kg/s; liquid flow rate = 0.063 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar). (A) horizontal side arm; (B) as (A) but with a bend; (C) vertical side arm; (D) as (C) but with a bend.

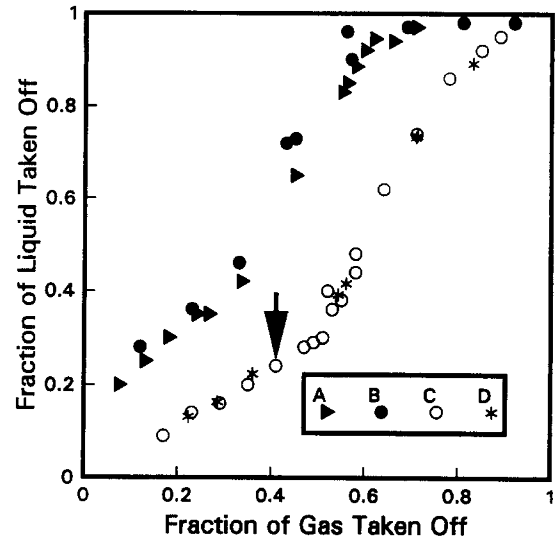

Figure 5. Effect of side arm orientation on the flow split —annular flow (gas flow rate = 0.101 kg/s; liquid flow rate = 0.0126 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar). (A) horizontal side arm; (B) as (A) but with a bend; (C) vertical side arm; (D) as (C) but with a bend.

shown in figures 4–10. The data are plotted as fraction of incoming liquid emerging through the side arm against fraction of gas. The complete set of data is tabulated in three internal reports. Azzopardi *et al.* (1988) contains information for the horizontal side arm with a diameter ratio of 1.0 and 0.67, Azzopardi *et al.* (1990) lists data for the horizontal side arm with a diameter one-third that of the main tube. Smith & Azzopardi (1990) tabulate data for the vertically upwards side arm and for the effect of the bend placed downstream of the junction for both horizontal and vertical side arm positions (diameter ratio = 0.67). In addition, they include the data for runs with the weir downstream of the junction.

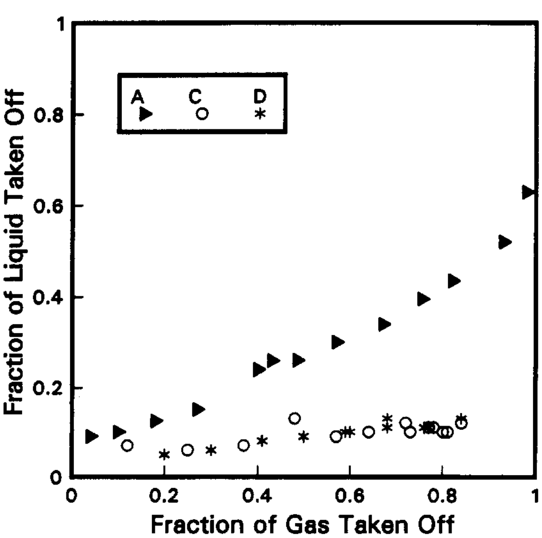

Figure 6. Effect of side arm orientation on the flow split —semi- annular flow (gas flow rate = liquid flow rate = 0.076 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar). (A) horizontal side arm; (C) vertical side arm; (D) as (C) but with a bend.

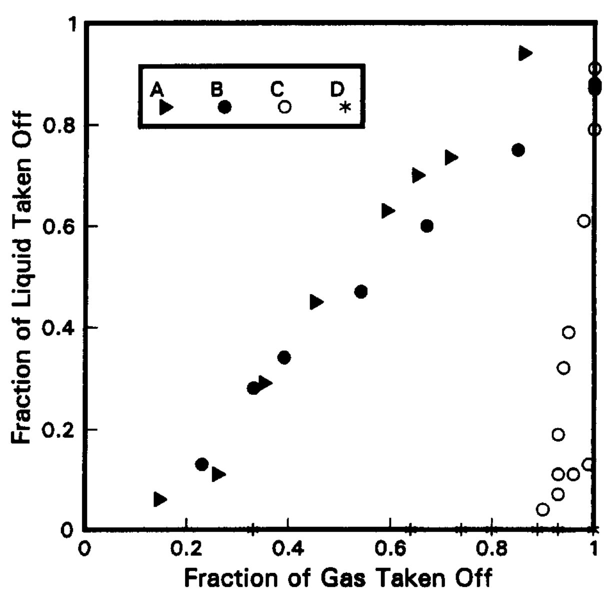

Figure 7. Effect of side arm orientation on the flow split —stratified flow (gas flow rate = 0.024 kg/s; liquid flow rate = 0.0126 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar). (A) horizontal side arm; (B) as (A) but with a bend; (C) vertical side arm; (D) as (C) but with a bend.

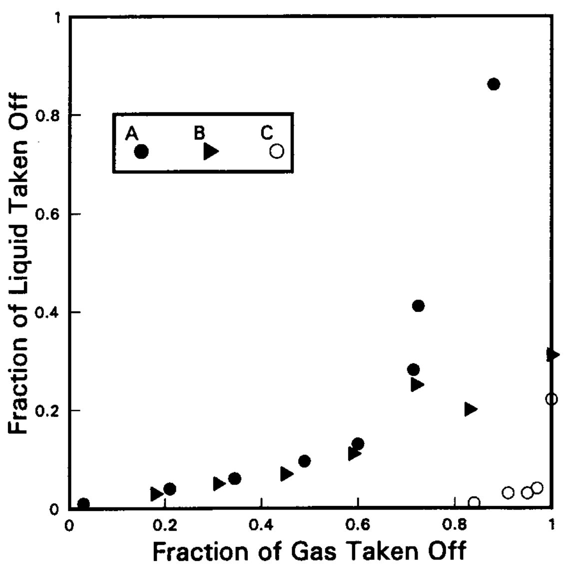

Figure 8. Effect of side arm orientation on the flow split—stratified flow (gas flow rate = 0.0174 kg/s; liquid flow rate = 0.063 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 1.5 bar). (A) horizontal side arm; (B) as (A) but with a bend; (C) vertical side arm.

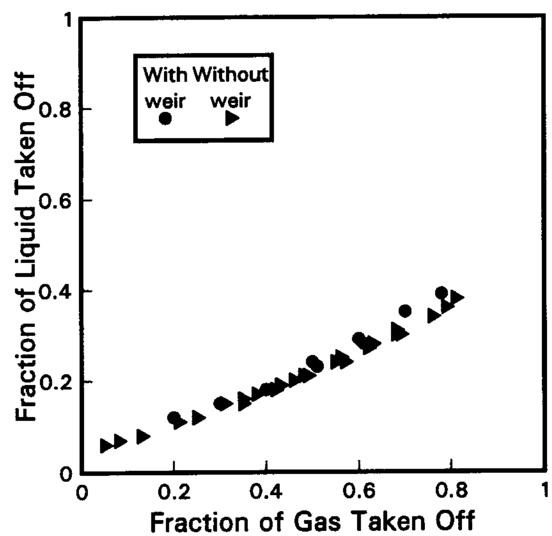

Figure 9. Effect of a weir just downstream of the junction on the flow split—semi-annular flow (gas flow rate = liquid flow rate = 0.076 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar).

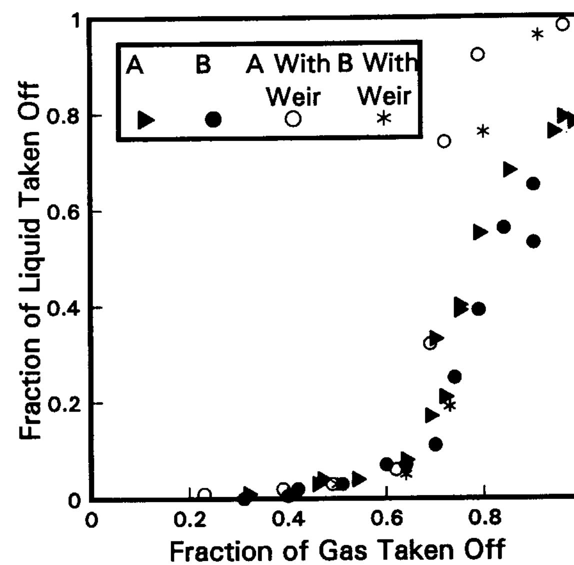

Figure 10. Effect of a weir just downstream of the junction on the flow split—stratified flow (liquid rate = 0.063 kg/s. (A) gas flow rate = 0.024 kg/s, pressure = 3 bar; (B) gas flow rate = 0.017 kg/s, pressure = 1.5 bar).

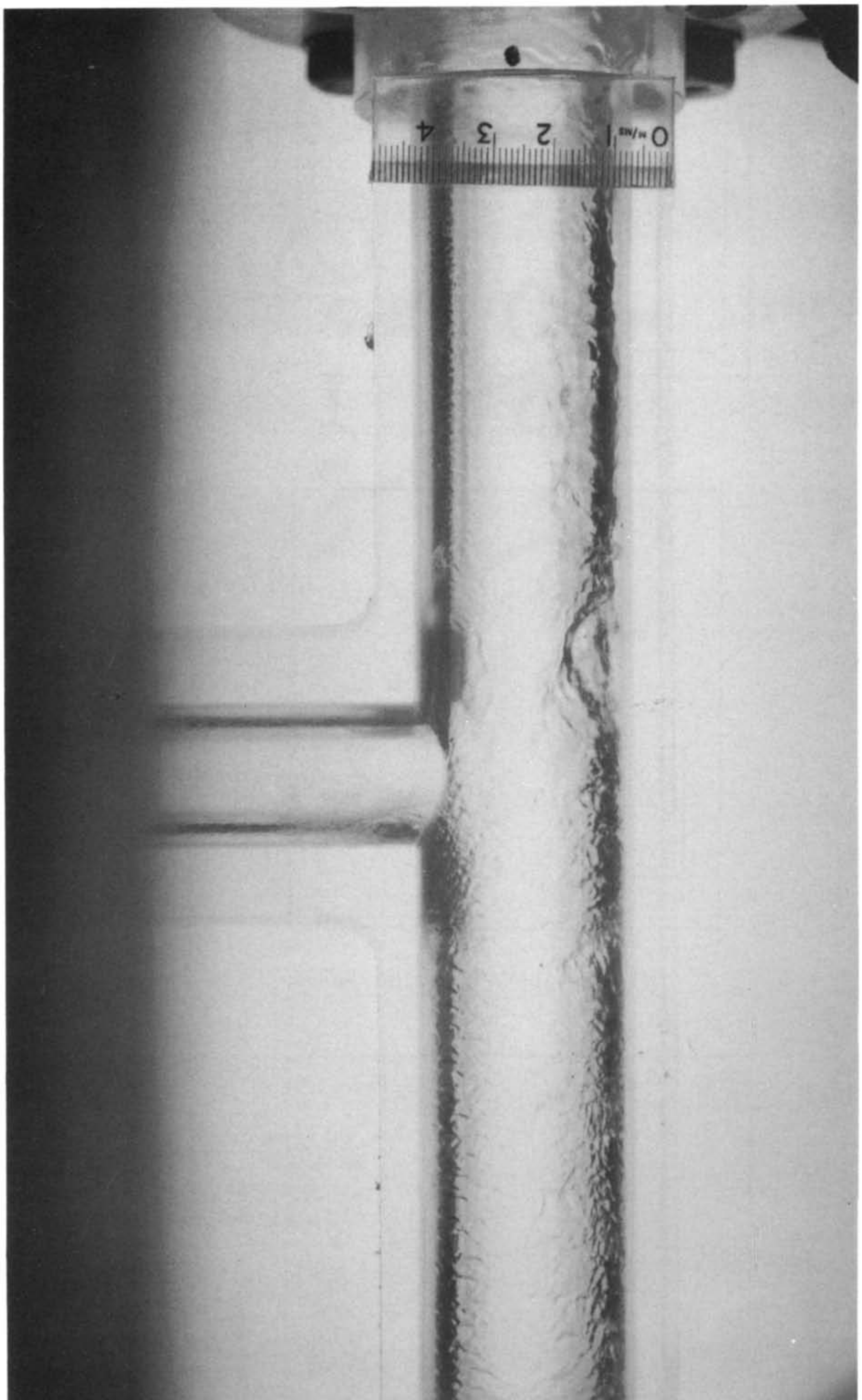

Figure 11. Example of liquid at the junction as part of the "film stop" mechanism (gas flow rate = 0.101 kg/s; liquid flow rate = 0.0126 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar).

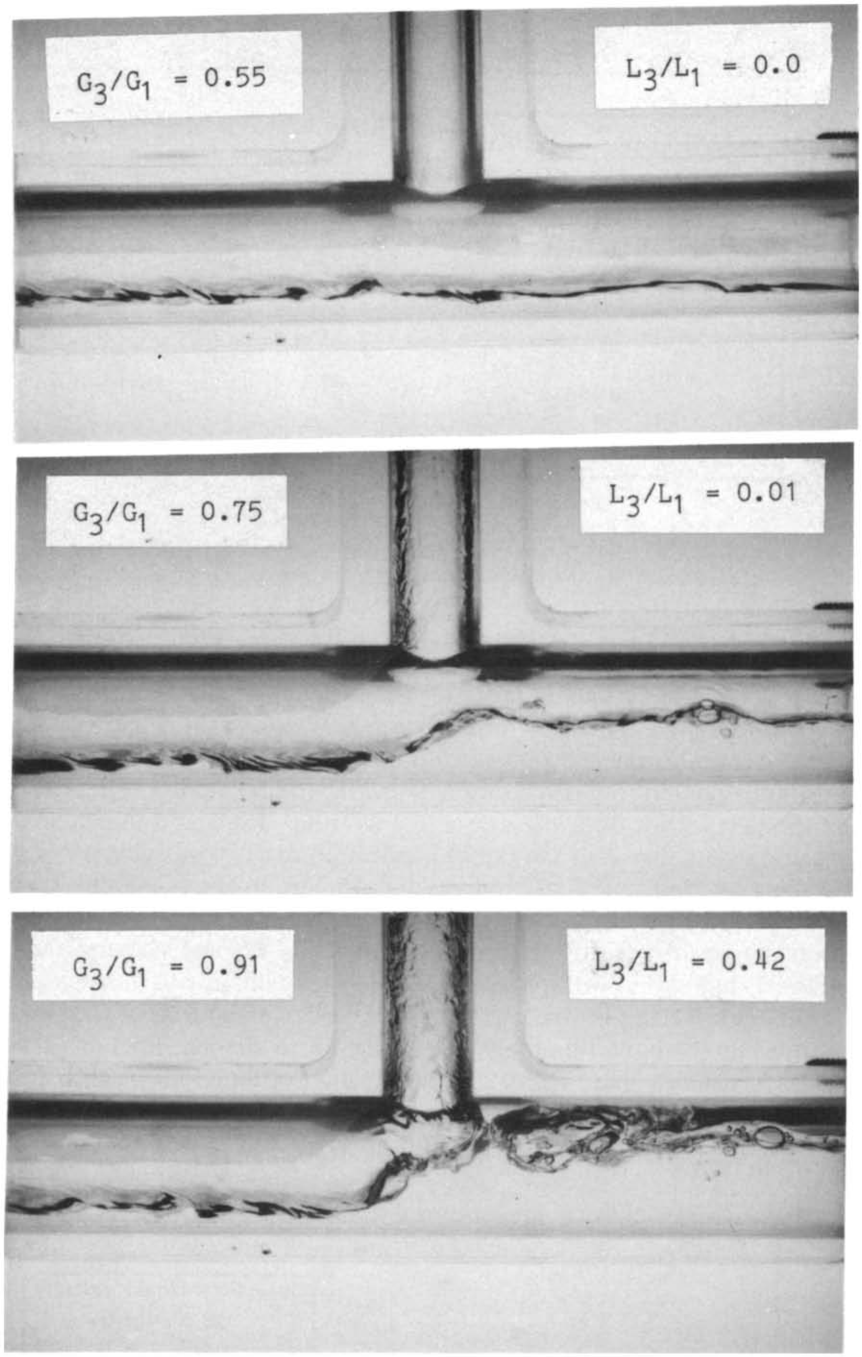

Figure 12. Example of the increase in the liquid level at the junction during stratified flow (gas flow rate = 0.024 kg/s; liquid flow rate = 0.063 kg/s; gas superficial velocity = 5.6 m/s; liquid superficial velocity = 0.056 m/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar).

The effect of the ratio of side arm to main tube diameter was to decrease the take off of liquid as the ratio was decreased though the data followed similar trends in all cases tested. This data will be presented in detail and discussed in a subsequent paper.

4. DISCUSSION

The behaviour of the phase split illustrated in figures 4–9 can best be explained if the data are grouped according to the flow pattern approaching the junction.

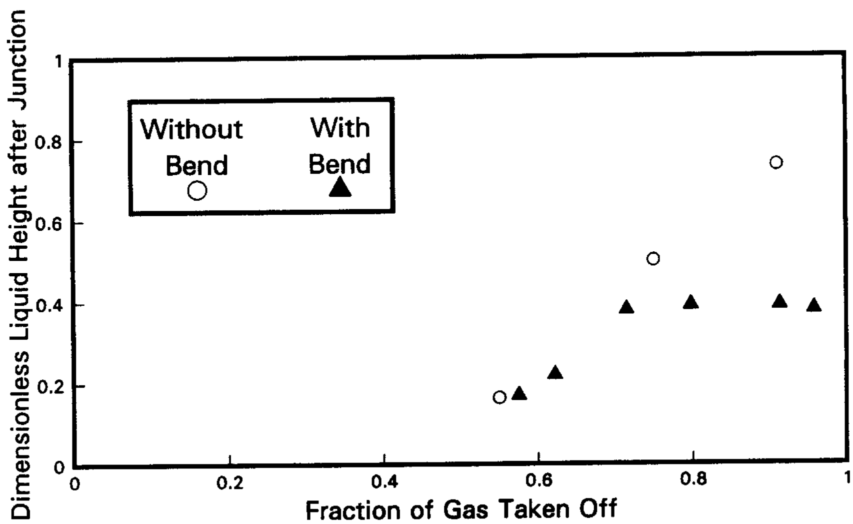

Figure 13. Variation of the liquid height at the junction with gas take off (gas flow rate = 0.024 kg/s; liquid flow rate = 0.063 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar).

For annular flow, figure 4, with the horizontal side arm there is initially higher liquid fraction taken off than gas; when more fluid is taken off gas is preferentially extracted. The trend of the data can be explained by the suggestion of Azzopardi & Whalley (1982) that it is the liquid in the wall film and the gas both from the segment nearest the side arm that is taken off. Initially, the ratio of liquid (film) fraction to gas fraction is large. As the take off is increased (i.e. the chord bounding the segment moves from the side arm), the ratio drops and preferential gas take off occurs. The fact that less than half the liquid is taken off at 50% gas take off is due to part of the liquid travelling as drops which are not easily diverted into the side arm. Calculations using the equation proposed by Dallman *et al.* (1984) for horizontal annular flow suggests that 16% of the liquid is travelling as drops. In the case of the vertically upward side arm the liquid take of shows similar trends but always with proportionally less take off, due to the liquid film flow being asymmetric with less travelling on the top than at the sides or bottom of the tube.

The explanations given above also apply at low take off to annular flow with lower inlet liquid flow rates, figure 5. The fact that there is a larger fraction of liquid taken off is probably due to there being a smaller fraction of liquid travelling as drops. From the equation of Dallman *et al.* (1984), 2% of the liquid is travelling as drops in this lower liquid flow rate case. It is suggested

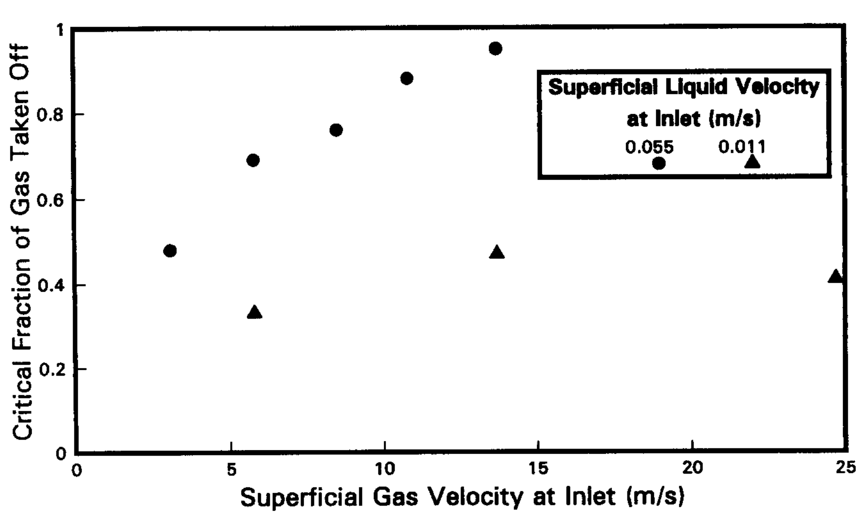

Figure 14. Gas take off at which the hydraulic jump type phenomenon is first observed (main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar). Vertically upwards side arm.

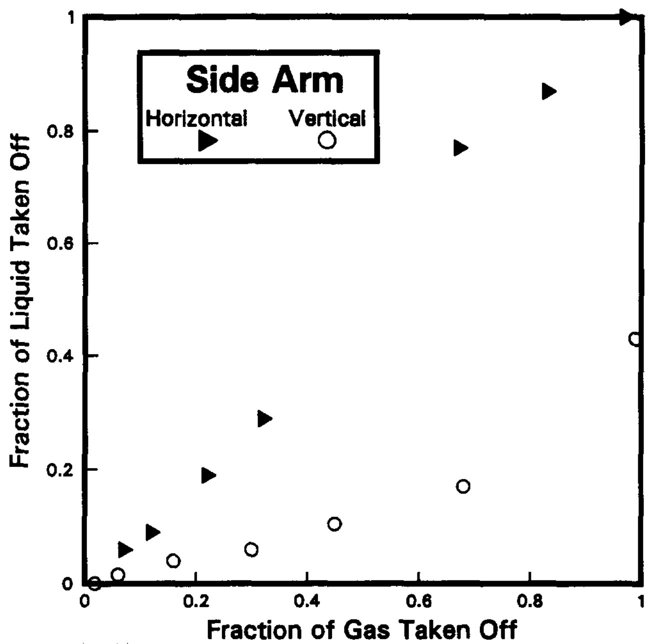

Figure 15. Flow split data of Reimann *et al.* (1988) (gas superficial velocity = 20 m/s; liquid superficial velocity = 0.1 m/s; main tube dia = 0.05 m, side arm dia = 0.026 m; pressure = 6.86 bar).

that the sudden change in slope is due to the "film stop" mechanism put forward by Azzopardi (1989), the low momentum liquid slowing down to accommodate the pressure rise in the main tube and at a critical gas take off the liquid is stopped. Though the change of slope occurs at different gas take off for the horizontal and vertically upward side arms, it was noted that the accumulation

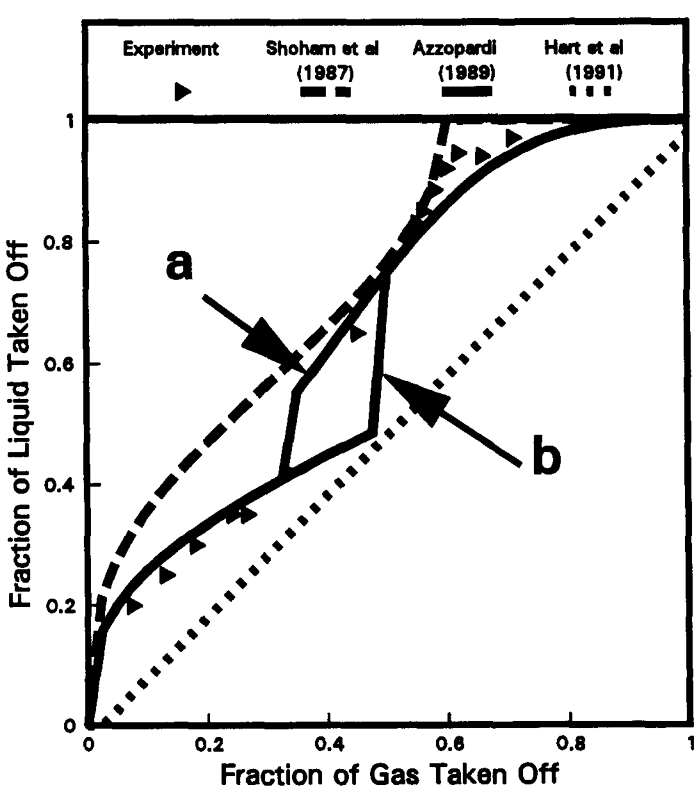

Figure 16. Comparison with models—annular flow (gas flow rate = 0.101 kg/s; liquid flow rate = 0.0126 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar).

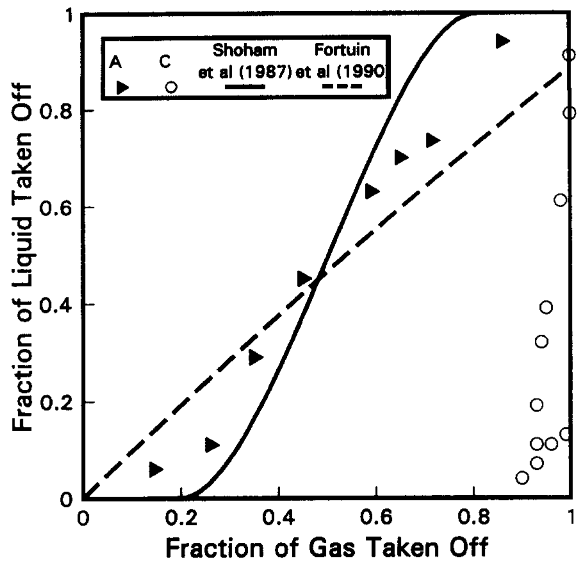

Figure 17. Comparison with models—stratified flow (gas flow rate = 0.024 kg/s; liquid flow rate = 0.0126 kg/s; main tube dia = 0.038 m, side arm dia = 0.025 m; pressure = 3 bar). (A), Horizontal side arm; (C), vertical side arm).

of liquid which is an essential feature of this mechanism, and which is illustrated in figure 11, first occurs for the vertically upward case at the point marked with the arrow in figure 5. This coincides with the change of slope for the horizontal case. Obviously, a higher gas take off is required to remove this accumulated liquid through the top outlet.

When the inlet flow is close to the boundary of annular flow (semi-annular flow), the fraction of liquid travelling as drops tends towards zero. Thus the liquid take off might be expected to be greater in figure 6 than in figure 4, the opposite of what is observed. A much more important effect is probably the greater circumferential variation of film flow rate at the conditions of figure 6, a majority of the liquid flows in a layer along the bottom of the tube.

In the case of stratified flow, figures 7 and 8, the liquid is all in the layer at the tube bottom. In this case, there is even greater difference between the horizontal and vertical cases.

For some data there is a sudden change in the slope of the graph, e.g. figures 8 and 10. This change of slope and consequent increase in liquid take off has been identified with the increase in the height of the liquid layer that can occur at the junction, figure 12. This was taken at superficial velocities of 5.6 m/s for the gas and 0.056 m/s for the liquid. In this figure, G_3/G_1 is the fraction of gas taken off whilst L_3/L_1 is the liquid fraction. Values of the downstream height, non-dimensionalized with respect to the main pipe diameter, are given in figure 13. These are instantaneous values taken from photographs. However, examination of high-speed videos (1000 fps) taken of the flow show these are reasonably representative values. The increase in height appears to be a form of hydraulic jump. In the experiments with a vertically upwards side arm, the conditions at which the hydraulic jump was first observed have been noted. In figure 14, this parameter is plotted against the superficial inlet velocity for two different inlet liquid flow rates. A distinct dependence on these two parameters can be seen. It is known that smooth-stratified flow can be very sensitive to downstream geometry. It is possible that there would be greater differences between the phase splits for these two geometries with such a flow pattern approaching the junction.

Examination of figures 4–6 and 9 shows that there is hardly any effect of downstream geometry on the flow split for annular or semi-annular flow even when the "film stop" mechanism occurs. This is not surprising as there is no upstream feedback effect in these cases. The liquid accumulation which is seen in the film stop case is very local to the junction. Figure 8 shows that the presence of the wire has no effect when annular flow approaches the junction.

The presence of the bend produces hardly any effect in stratified flow at low take off (before the occurrence of the hydraulic jump). When the jump is present there are some differences between the two downstream geometries. This can be seen in both the take off, figures 7 and 8, and the downstream liquid height, figure 13 (note the latter graph is based on data from different inlet conditions to the former). However, this is only significantly different when the gas take off is very high, i.e. when the velocity in the downstream main pipe is very low indeed. It is interesting to note that the hydraulic jump occurs irrespective of downstream geometry and differences manifest themselves through the actual values of the downstream liquid height. This, in turn, affects the take off. The weir also produces a change in the fraction of liquid taken off though this only manifests itself at higher gas take off, figure 9. There, the presence of the weir causes an increase in the slope of the liquid/gas take off plot. Take off of liquid is thus more catastrophic.

The fact that the flow split with annular flow is unaffected by downstream geometry was noted several years ago by Fouda & Rhodes (1974). Their experiments involved a horizontal main tube and a vertically upward side arm. They found significant phase maldistribution which was unaffected by baffles (or weirs) of 1/4 and 1/2 of the main tube diameter which were placed at the junction. It was only when a 3/4D baffle was used that the flow split was affected to any noticeable degree.

It is interesting to note that certain of the phenomena described above occur in data gathered by other workers. For example, figure 15 shows measurements taken by Reimann *et al.* (1988). These illustrate the lower liquid take off when the side arm is vertical compared to the equivalent horizontal case. This data was from runs with a superficial liquid velocity of 0.1 m/s, gas superficial velocity = 20 m/s, main tube diameter = 0.05 m, side arm diameter = 0.026 m and pressure = 6.86 bar. For other data at higher liquid flow rates, the differences caused by side arm orientation were less clear cut.

Consideration of available predictive models shows that the approach of Azzopardi & Whalley (1982) extended by Azzopardi (1989) could handle the effect of side arm orientation, though only for annular flow. Moreover, information about the circumferential variation of film flow rate are required as input, as in the case illustrated in figure 1. Other models are confined to the horizontal side arm configuration.

Comparisons have been made between the predictions of published models and the experimental data presented in this paper. The data are presented as fraction of liquid take off through the side arm vs fraction of gas. Figure 16 shows data for annular flow (gas superficial velocity = 25 m/s, liquid superficial velocity = 0.011 m/s. In the case of the model of Azzopardi (1989), two curves are shown. These are the result of using the two alternative equations for mean film thickness suggested by Laurinat *et al.* (1984). The results in figure 16 indicate that the model is sensitive to the value of film thickness. The prediction from the first equation of Laurinat *et al.* (a) was 0.83 10^{-4} m, whilst that from the second equation (b) was only 11% greater. The models of Shoham *et al.* (1987) and Hart *et al.* (1991) follow the general trend of the data though over- and under-predicting, respectively. Moreover, neither of these two models reproduce the changes of slope seen in the experimental data and in the predictions of the model of Azzopardi (1989).

For stratified flow, figure 17, both Shoham *et al.* (1987) and Hart *et al.* (1991) give reasonable predictions of the experimental data.

The present work provides pointers as to the successful design of multi-tube slug catchers. For example, the flow in the individual pipes should be low, so as to avoid any annular flow as this can lead to significant liquid carry over particularly at lower liquid rates such as the minimum in a time-varying flow. However, unless combined with a correct downstream geometry, a case with a low inlet gas rate can lead to liquid carry over at gas take off fractions lower than specified. Current designs, where the main pipe has a downward slope, would decrease the occurrence of phenomena such as hydraulic jumps and encourage separation.

5. CONCLUSIONS

From the above the following conclusions can be drawn:

(1) A number of important phenomena which affect the phase split at T junctions have been identified; in annular flow some phenomena become important only after a certain fraction of the flow has been diverted through the side arm.

(2) As expected there is a strong effect of orientation of the side arm on the flow split. For stratified flow there can be complete phase separation, in one case in the range 0–55% of gas take off;
(3) Downstream geometry in the main pipe only affects the split if there is stratified flow in the pipe leading to the junction;
(4) Though presently available models give reasonable predictions of the phase split for cases with horizontal side arms, their inability to follow the detailed trend of the data indicate that they are not taking account of all the important phenomena.

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