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MEASUREMENTS AND OBSERVATIONS OF THE SPLIT OF ANNULAR FLOW AT A VERTICAL T-JUNCTION†

B. J. AZZOPARDI
Thermal Hydraulics Division, Harwell Laboratory, Didcot, Oxon. OX11 0RA, England

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Abstract—Measurements and observations have been made when annular flow divides at a vertical T. This work has extended earlier experiments in covering the entire range of take off. From the observations and measurements, three ways in which the liquid can be diverted into the side arm have been identified. A modification of an earlier model has been produced which correctly allows for two of the three phenomena.

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

1. INTRODUCTION

The split of a two-phase flow at a junction is complicated as either of the phases can emerge preferentially from one of the outlets. This split is important as it can have a strong effect on performance of equipment, particularly that downstream of the junction. Though there is a school of thought amongst engineers which suggests that junctions involving two-phase flow must be avoided, it is not always possible to do so. For example, during postulated accident conditions in nuclear power reactors of the pressurized water reactor type a leak in a pipe is effectively a T-junction. The amounts of steam and water which emerge can have a strong effect on subsequent stages of the accident. Another example is found in enhanced recovery of very viscous oils. Steam is injected to lower the oil viscosity. This is generated at a central boiler and is transmitted to a number of injection points about the field. This is inevitable condensation along the long transmission lines so that there is a two-phase flow division at the junctions leading to individual injection points. It is important to know the proportions of steam and water injected, as the water is not very effective at producing changes in the oil viscosity having lost the large amount of heat carried as latent heat. Knowledge of the two-phase flow splits can be used to insure correct injection of steam to each well.

The information available on two-phase flow splits has been reviewed recently by Azzopardi (1986) and Lahey (1986). They conclude that there were very few effective and physically realistic models of the flow split. Saba & Lahey (1984) published a mechanistic model limited to high take off. Another approach was initiated by Henry (1981) and Whalley & Azzopardi (1980), who suggested that when the annular flow approaches a junction it is the liquid in the wall film that is taken off. Azzopardi & Whalley (1982) also suggested that the film and gas taken off both come from the same segment of the inlet pipe. This approach has been shown by Azzopardi (1987) to be very effective for low values of take off. These ideas have been formalized by Azzopardi & Baker (1981) and Lahey *et al.* (1985), who introduce a probability of the liquid being taken off if the gas is taken off. The total amount of liquid taken off is obtained from the integral of the local flow rate times the probability. The probability is taken as the ratio of the local momentum of the phases. For annular flow, the film velocity is much lower than the gas velocity so that the film and gas will have similar momentum. In contrast, the drops whose velocity is approximately the same as the gas and whose density is high will have a momentum much higher than the gas. This can be expressed as the drops having a very low probability of being taken off whilst that of the film is high. Therefore the film will be taken off whilst the drops will not. This mechanism is dominant

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at low take off. Though it probably applies over the whole ranage of take off, there are other phenomena present at high take off. Recently, Azzopardi (1987) has suggested an approach to cover the entire range of take off for annular flow approaching a junction of a vertical pipe. He suggests that at low take off it is the film and gas from the local segment which is taken off whilst the undiverted fluids carry on up the main pipe past the junction. However, as more gas is taken off, the gas velocity in the main tube above the junction ceases to be large enough to carry up the liquid film which then falls back to the junction. There, because of its low momentum, this falling liquid is easily taken off. The low gas velocity also leads to a slowing down of the drops, and hence an increase in their concentration and in the amount of deposition. If yet more gas is taken off, the gas velocity above the junction falls below the flooding velocity and all of the liquid film falls back down to the junction. Azzopardi (1987) suggests that those drops which are not deposited would be carried up and away from the junction, though as the gas velocity falls the largest of these drops will become too large to be carried up and fall back to the junction. Further diminution of the gas velocity leads to progressively more and more drops falling back down and thence being taken off through the side arm. Azzopardi (1987) suggests flooding, deposition and drag equations which can be used to quantify the above processes. Though the above theory gives good prediction of available data, this data are confined to low take off and so do not provide a good test of the theory.

The present paper presents observations and measurements made to test, and if necessary improve, the ideas described above.

2. EXPERIMENTAL ARRANGEMENT

The apparatus used in the present experiments is described in detail by Azzopardi & Purvis (1987). It is shown schematically in figure 1. Filtered, metered air at constant pressure was taken from the laboratory compressed air main. Water flow to the test section was monitored by one of a number of calibrated rotameters. Air entered the vertical flow tube, which was made from sections of acrylic resin tubing (0.0318 m internal diameter), through an entrance section 0.5 mg long. Water then entered through a section of porous wall.

The junction, in which the main tube and side arm were of the same diameter, was machined out of a block of acrylic resin. It was placed 3.0 m beyond the liquid entry point with 0.7 m of tubing above it. The horizontal side arm consisted of 1.8 m of straight acrylic resin tubing followed by a length of flexible tubing. 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 (or a gas meter for the lowest gas flow rates), 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. The water was returned to the storage tank, the air being released to the atmosphere. At high rates of take off the connections were reversed and the two-phase flow from the main tube was metered. However, data were taken using both configurations for similar flow splits. In most cases data from the two experiments were indistinguishable. Valves on the two outlet tubes were used to control the division of the flow and maintain the pressure of the junction at 150 kPa.

Azzopardi & Purvis (1987) indicate that for most of the data the experimental uncertainty will be 1%.

Cine films were taken of the flow in the main tube just above the junction, as shown in figure 2. A length of tube 0.6 m was observed. Because direct access was not possible the cine films were taken through two mirrors which permitted the camera to be placed at a convenient position.

3. RESULTS

Measurements were made of flow split at the junction described in section 2 above. Data were taken over the entire range of take off. The results are plotted in figures 3 and 4 as fraction of liquid take off through the side arm vs fraction of gas taken off through the side arm. The data is tabulated in the report by Azzopardi & Purvis (1987). Figure 3 shows the effect of inlet gas flow rate, inlet liquid flow rate being constant. A systematic effect of gas flow rate can be seen with the fraction of liquid taken off increasing with decreasing gas flow rate. Figure 4 shows that the effect of inlet

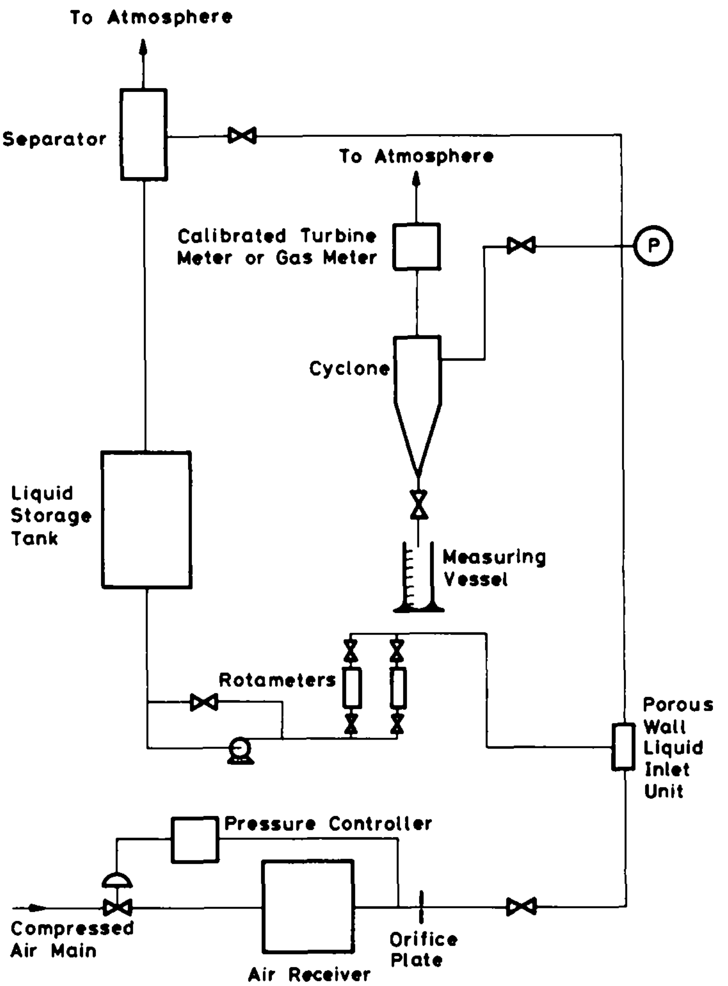

Fig. 1. Experimental arrangement.

liquid flow rate is similar: the lower the liquid flow rate, the higher the fraction of liquid taken off. Most of the data presented in these figures refers to annular flow approaching the junction. The only exceptions are the runs with the lowest gas flow rates in figure 3 which involves churn flow approaching the junction. The trends seen in figures 3 and 4 should not be surprising. If the simple description of the flow is used: the film is easily diverted into the side arm, whilst drops, because of their higher momentum, carry straight on past the junction. Decreasing both gas and liquid inlet flow rates decrease the fraction of liquid entrained, increases the fraction of liquid in the film and hence the fraction of liquid taken off.

The experiments aimed at determining the phenomenon which affect the flow split have involved direct observation and the taking of high-speed cine film (2000 fps). These observations were concentrated at three representative inlet conditions identified as A (gas flow rate = 0.0535 kg/s; liquid flow rate = 0.063 kg/s), B (0.0535 kg/s; 0.0126 kg/s) and C (0.01525 kg/s; 0.063 kg/s). The cine films were taken at conditions A (G', fraction of gas taken off = 0.59, 0.77, 0.9) and C ($G' = 0.52$, 0.73). These runs were chosen as being representative of annular flow, very high quality annular flow (low liquid rate) and of the churn/annular transition, respectively.

At the lowest take off in run A ($G' = 0.59$) the flow in the pipe above the junction can be seen to be all in the upwards direction. As the flow is being observed through the transparent tube wall, it is the movement of the liquid in the film that is being seen. At the next highest take off, $G' = 0.77$, the flow is significantly different with the film on the side nearest the side arm travelling upward, whilst that on the pipe wall opposite the side arm is falling back towards the junction. An area of disturbance which oscillates about a mean position can be seen about 0.6 m from the junction.

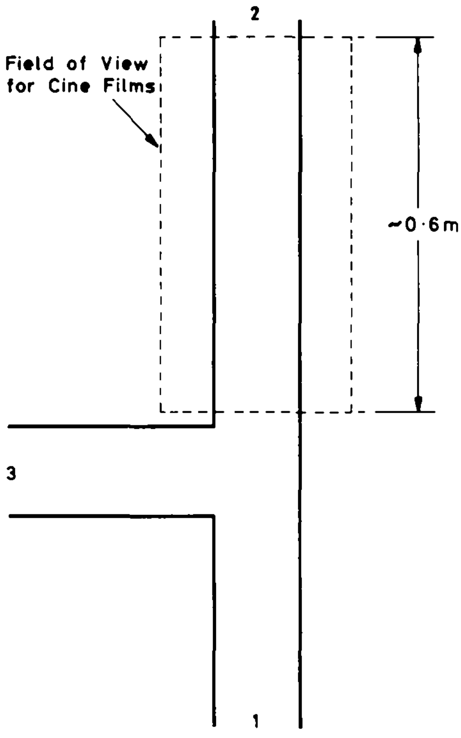

Fig. 2. T-junction showing the field-of-view for the cine films.

At the highest take off filmed ($G' = 0.9$) the upflow and downflow are still seen and they are more pronounced. At these conditions the disturbance is about 0.3 m from the junction and hardly any liquid is carried up beyond the disturbance.

In run B, the flow of the film in the pipe above the junction was upward in most of the cases observed. However, even when only 0.4 of the gas had been taken off, the film flow rate appeared to be very small. Moreover, at the junction a ridge of liquid could be seen about most of the circumference of the main pipe.

When the inlet flows are close to the transition between churn and annular flows (C) the behaviour is less clear cut. There is less evidence of downward flow of the liquid film on the side opposite the side arm. Part of the time the liquid film appears stationary. Liquid appears to accumulate and then move up the main tube above the junction as a mass.

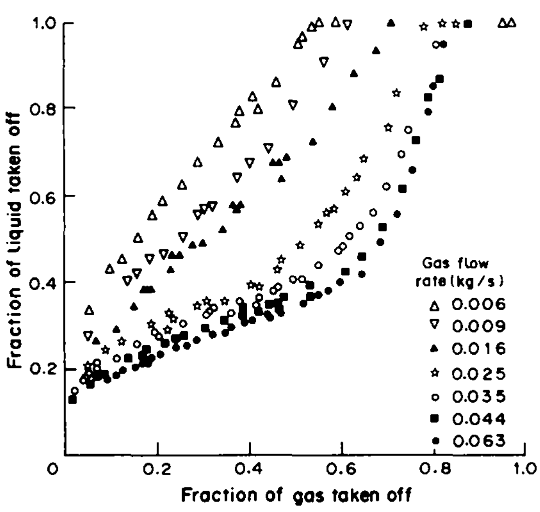

Fig. 3. Flow pattern map showing conditions at which the data was taken.

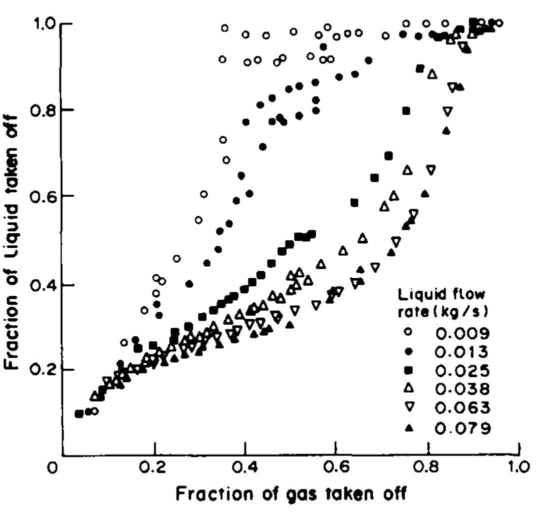

Fig. 4. Effect of gas flow rate on flow split (liquid flow rate = 0.063 kg/s).

4. DISCUSSION

This section describes phenomena which, it is considered, are occurring during the flow split. It will be shown that the observations and measurements described in the previous section provide support for the suggested phenomena. The relationship between these phenomena and the model suggested by Azzopardi (1987) will be discussed and an improved version of the model will be presented. Finally, the limits of applicability of the model are identified.

The phenomena which it is believed are influencing the split at the T-junction are most easily described by first considering what happens at very low take off rates. Increases in the first take off rate and their consequences will then be examined. At the lowest take off, the film and gas in the segment of main pipe will be extracted through the side arm. The rest of the gas and liquid film as well as the drops continue on past the junction. This is illustrated in figure 5(a). When more gas is taken off the gas continuing up the main pipe cannot relax instantly to fill the pipe. The gas is drawn over to the side of the pipe nearest the side arm with its axial velocity essentially unchanged. A recirculation zone appears on the side opposite the side arm, figure 5(b). Further downstream, the gas once more can relax to give upflow in the entire pipe. Here the velocity is lower than that before the junction. Because of their momentum, drops continue on past the junction. However, the sidewards motion of the gas will have some influences on them and some will deposit on the pipe wall above the side arm. If the gas velocity above the junction falls below the critical value for flow reversal, part of the liquid which has reached this far will drain back to the junction, figure 5(b). This liquid will be mainly that which travelled past the junction in drop form but which has subsequently deposited. As this draining liquid arrives back at the junction with low momentum there is a strong probability of it being extracted through the side arm. The fate of the liquid film which is not taken off (mainly that on the pipe walls opposite the side arm) depends on its momentum and whether flooding has occurred in the pipe above the junction. If there is high film momentum and no flooding, the momentum of the film is sufficient for it to be carried past the recirculation zone (which is tending to drag it down) and into the upflow region beyond. It would then be carried on out of the pipe. This type of flow was seen in run A ($G' = 0.59$) described in the previous section. If the gas velocity above the junction is still large enough to carry up liquid and there is no flooding/flow reversal but the film momentum approaching the junction is lower, the liquid will not be able to overcome the effects of gravity and the downwards shear at the recirculation zone. It will then pile up as a ridge or collar at the junction. Here, because of its negligible momentum it will respond to pressure gradients and be extracted through the junction.

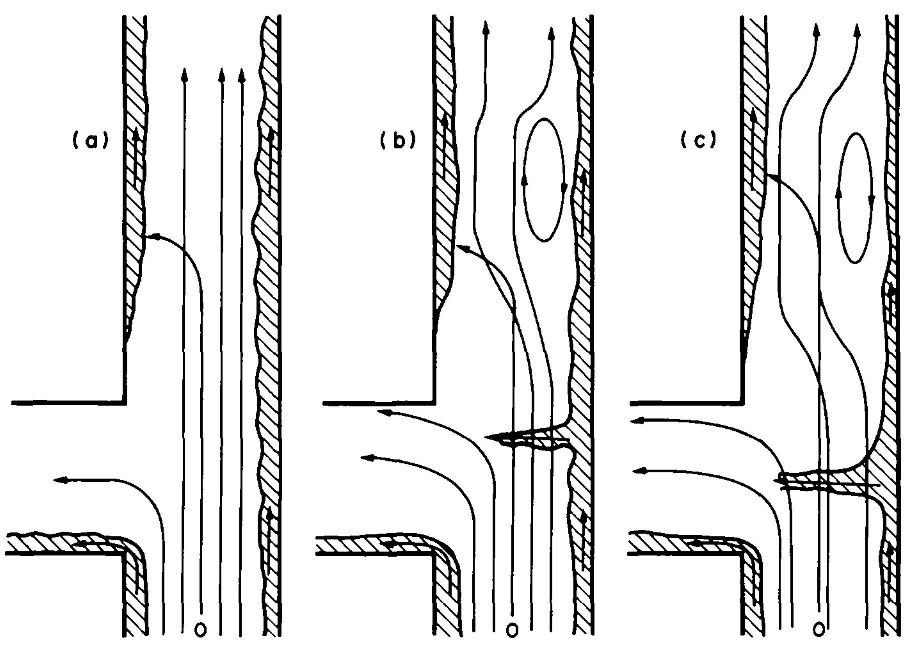

Fig. 5. Effect of liquid flow rate on flow split (gas flow rate = 0.0535 kg/s).

This is illustrated in figure 5(c) and is what was seen at conditions identified as B. Obviously, there will be conditions where not all of the liquid is retained at the junction, some being retained whilst some can continue up the pipe. The proportions will depend on:

(i) film momentum

and

(ii) the effects of gravity and the downwards gas shear in the recirculation zone.

If flow reversal has occurred above the junction, liquid will drain back past the recirculation zone. It is probably impossible for liquid to drain back on the side of the pipe above the junction as there is a strong jet stream of upward moving gas here whose velocity is well above that for flow reversal. Once there is a downflow of liquid occurring, the upward moving film is easily brought to a halt and extracted through the side arm. This corresponds to the regions of steep slope in figures 3 and 4.

The model proposed by Azzopardi (1987) and described in section 1 is a reasonable description of the phenomena observed with two exceptions. These are that: (i) the model does not take into account the low momentum film cases where liquid can be brought to a halt and diverted into the side arm before flooding occurs; (ii) Azzopardi (1987) assumes that not all the drops deposit and that these are carried up after flooding. It has become clear that all drops do deposit or are caught by the flooding wave. It appears that the model can be brought closer into line with reality if the assumption is changed to total deposition of drops.

The essential equations of the model are

$$\frac{\dot{M}_3 x_3}{\dot{M}_1 x_1} = \frac{1}{2\pi}\left\{\frac{2\pi \dot{M}_3(1-x_3)}{K\dot{M}_1(1-x_1)(1-E)} - \sin\left(\frac{2\pi \dot{M}_3(1-x_3)}{K\dot{M}_1(1-x_1)(1-E)}\right)\right\}, \qquad [1]$$

where $\dot{M}$ is a flow rate, x is a quality, E is the fraction of liquid entrained and the subscripts 1, 2 and 3 identify the pipes comprising the junction (see figure 2). K is a factor which accounts for the effects of the ratio of side arm to main pipe diameters. Here an equation suggested by Azzopardi (1984) is used:

$$K = 1.2\left(\frac{D_3}{D_1}\right)^{0.4} \qquad [2]$$

Defining the fraction of gas and liquid taken off, G' and L' respectively as

$$G' = \frac{\dot{M}_3 x_3}{\dot{M}_1 x_1} \qquad [3]$$

and

$$L' = \frac{\dot{M}_3(1-x_3)}{\dot{M}_1(1-x_1)}, \qquad [4]$$

[1] can be rewritten as

$$G' = \frac{1}{2\pi}\left[\frac{2\pi L'}{K(1-E)} - \sin\left(\frac{2\pi L'}{K(1-E)}\right)\right]. \qquad [5]$$

This equation relates the liquid film and gas which are taken off from the segment local to the side arm. To determine whether there is any flow reversal the equation of Wallis (1961) is used. Azzopardi (1987) has argued that though there are equations which predict the available data more accurately, this equation gives reasonable predictions and has the merit of simplicity. Wallis' equation is

$$V_G^{*\frac{1}{2}} + V_L^{*\frac{1}{2}} = C = 0.88, \qquad [6]$$

where

$$V_G^* = U_{G2}\sqrt{\frac{\rho_G}{gD_1(\rho_L - \rho_G)}} \qquad [7]$$

and

$$V_L^* = U_{L2}\sqrt{\frac{\rho_L}{gD_1(\rho_L - \rho_G)}} \quad [8]$$

and where ρ_L and ρ_G are the liquid and gas densities and g is the acceleration due to gravity. In the above we can write

$$U_{L2} = \left(\frac{4}{\pi D_1^2 \rho_L}\right)\dot{M}_1(1 - x_1)(1 - L') \quad [9]$$

and

$$U_{G2} = \left(\frac{4}{\pi D_1^2 \rho_G}\right)\dot{M}_1 x_1(1 - G'). \quad [10]$$

The condition at which reversal of the film first occurs can be determined from [6] if V_L^* is set equal to 0. After rearranging,

$$G' = 1 - \frac{0.7744}{U_{G_1}}\sqrt{\frac{gD_1(\rho_L - \rho_G)}{\rho_G}}. \quad [11]$$

The condition at which no liquid is carried up can be obtained by combining [5]–[11]:

$$1 - \frac{1}{2\pi}\left[\frac{2\pi L'}{K(1-E)} - \sin\left(\frac{2\pi L'}{K(1-E)}\right)\right] = U_{G1}\sqrt{\frac{gD_1(\rho_L - \rho_G)}{\rho_G}} \times \left\{0.88 - \left[\sqrt{\frac{\rho_L}{gD_1(\rho_L - \rho_G)}}\frac{4\dot{M}_1(1 - x_1)}{\pi D_1^2 \rho_L}(1 - L')\right]^{\frac{1}{2}}\right\}^2. \quad [12]$$

This equation is solved by the method of *regula falsi* for L' from which G' is determined using [5]. To calculate the amount of liquid taken off [5] is used until the value of G' obtained from [11] is exceeded. From thence, until G' exceeds the value of G' obtained from [12], [5] is used to determine the amount of liquid taken off after passing the junction and falling back as a falling film. When the value of G' exceeds that determined from [12] it is assumed that all of the liquid is taken off.

Comparisons have been made between the modified model described above and the present flow split data. E was determined from the Ishii & Mishima (1981) equation which Azzopardi & Purvis (1987) have shown gives the best prediction for the present conditions. The results are shown in figures 6–8. From these it can be seen that the model gives good predictions of the data. Where there are differences, for example figures 7(d) and 6(a,b). These are probably due to errors in the value of E used. The runs shown in figures 7(a,b) are from churn flow.

The sensitivity of the model to the value of the constant C in the Wallis (1961) equation has been tested. When values of C of 0.7 and 1.0 were used the steep portion of the curve was shifted to higher and lower values of the fraction of gas taken off, G'. For the case shown in figure 6(c) values of G' for $C = 0.7$ and $C = 1.0$ were within 7% of that predicted for $C = 0.88$. Obviously the model shows a dependence on Wallis' constant C. However, the sensitivity is acceptable as the values we have tested cover the range of C-values published in the literature.

In figures 8(a–d) a systematic deviation can be seen. The value of G' at which the divergence commences getting smaller as the inlet liquid flow rate decreases, from (d) to (a). Obviously, the momentum of the film becomes smaller the lower the flow rate so that the deviation is due to the film being brought to a halt by gravity and the downward shear in the recirculation region before flooding occurs. Evidence of this can be found in figure 8. The fractional gas take off at which the experimental data start to deviate from the predictions is plotted against the momentum flux of the liquid film approaching the junction, figure 9. It can be seen that there is a linear relationship between the fractional gas take off (which might be expected to be related to the strength of the recirculation eddy beyond the junction) and the approaching film momentum. However, there appears to be no deviation in the case of figure 8(e). This is probably because the take off at which deviation might be expected to occur is beyond that at which flow reversal occurs. Therefore any deviation is masked by the effect of falling liquid. There is a need to allow for this phenomenon in the model.

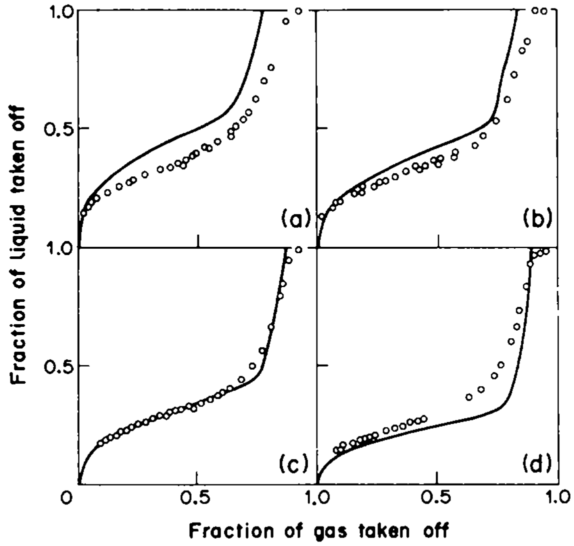

Fig. 6. Effect of quality flow rate on flow split (total mass flux = 160 kg/m^2 s).

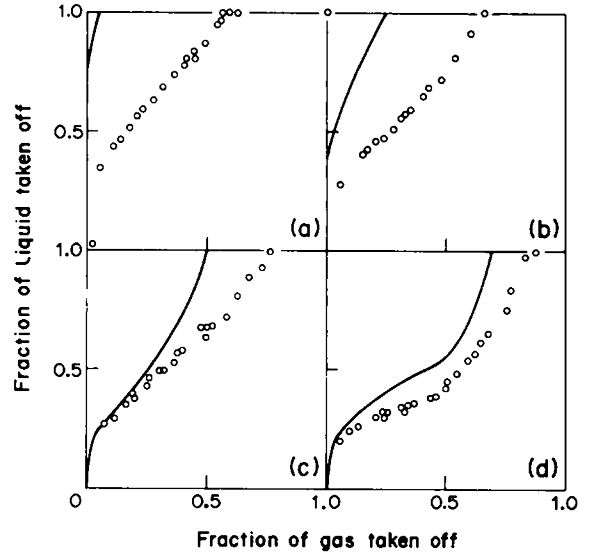

Fig. 7. Sketches illustrating the principal phenomena of flow split.

The model is based on the assumption that the film momentum is of the same order as that of the gas so that it is as easy to divert the film as the gas. However, at very high liquid flow rates Azzopardi (1987) has calculated that the film momentum can be larger than that of the gas. The simple model embodied in [1] cannot apply to these cases. A check must be carried out to ensure that this assumption is valid before the model is used. In addition, further analysis is necessary to extend the model to encompass these cases.

5. CONCLUSIONS

From the above it can be concluded that:

1. There are three phenomena which influence the flow split of annular flow at a vertical T. These are: (a) removal of low momentum liquid in the film neighbour-

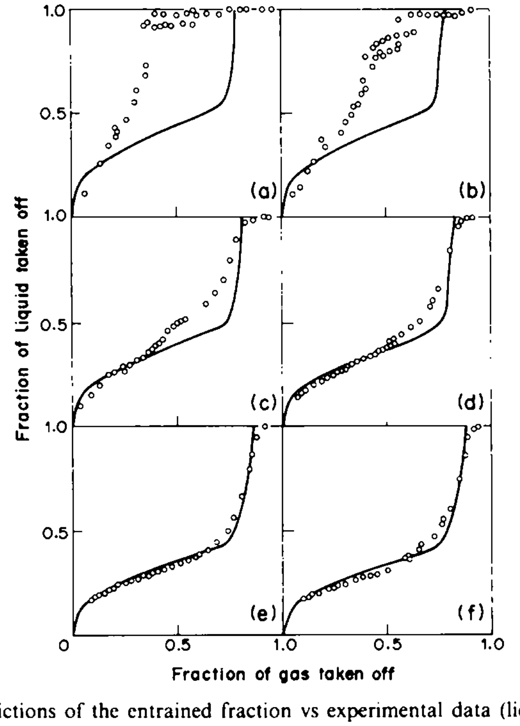

Fig. 8. Comparison of predictions of the entrained fraction vs experimental data (liquid flow rate = 0.063 kg/s).

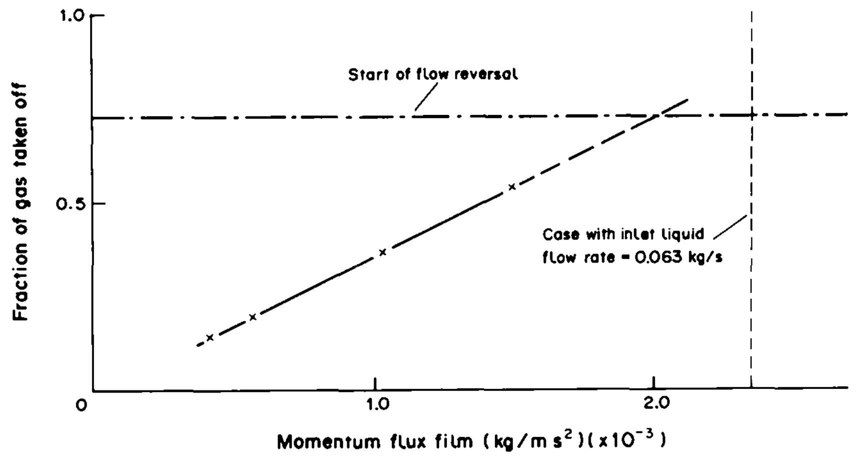

Fig. 9. Comparison of predictions of the entrained fraction vs experimental data (gas flow rate = 0.0535 kg/s).

ing the junction—this region depends on the amount of gas taken off but can encompass the whole film; (b) draining back of liquid which has passed the junction because of flow reversal/flooding above the junction—this liquid is easily taken off; (c) liquid in the film travelling on the walls opposite the side arm which can be brought to a halt and diverted into the side arm if its original momentum is insufficient to carry it well past the junction and the forces trying to stop it. Phenomenon (a) occurs over most of the range of take off but can be supplemented by (b) or (c) according to individual conditions.

2. A simple modification of the model of Azzopardi (1987) gives good predictions of the take off for those cases where phenomena (a) and (b) are controlling.
3. An extension of the model is required to account for the third phenomenon, (c).

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