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THE EFFECT OF FLOW PATTERNS ON TWO-PHASE FLOW IN A *T* JUNCTION

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Abstract—Two-phase air-water flows have been studied in sharp edged *T* junctions. The behaviour of the flow is very dependent on the flow pattern upstream of the junction. If the flow pattern is annular or churn then usually the liquid preferentially enters the side tube. If the flow pattern is bubbly, then the gas preferentially enters the side tube. For annular flow the liquid entering the side tube comes from the thin film of liquid travelling on the walls of the tube rather than from the drops entrained into the gas. The proportion of the total liquid film entering the side tube is approximately linearly dependent on the flow rate of gas into the side tube.

1. INTRODUCTION

Two-phase gas–liquid flow in *T* junctions is important in many types of process plant and also in water cooled nuclear reactors. The main problem is that if the quality (the mass fraction of the total flow which is vapour) in the inlet tube is known, see figure 1, then there is no general method of calculating the quality in the main outlet tube or in the side tube, see for example Henry (1981). The simple assumption that the qualities in the main outlet tube and the side tube are equal (and therefore equal to the quality in the inlet tube) can be very far from the truth. This is illustrated in figure 2 given by Butterworth (1980) where it can be seen that under certain circumstances the *T* junction acts almost as a gas–liquid separator, the gas entering the side tube and the liquid flowing straight along the main tube. A similar result has been obtained by Honan & Lahey (1978).

In this work a number of simple experiments have been performed in vertical and horizontal tubes with side tubes. The two-phase flow pattern in the main tube was annular, churn or bubbly flow.

The main features of annular flow are illustrated in figure 3(a). The gas flows along the centre of the tube and the liquid flows partly as a thin film on the walls of the tube and partly as drops entrained into the gas flow. The drops are formed at the large disturbance waves which are found on the liquid film, and the droplet flow can form a substantial proportion of the total liquid flow. Because the liquid film flowrate can be substantially less than the total liquid flow, methods of determining the film flowrate have been developed. The main feature of churn flow, see figure 3(b), is that the flow is unstable and pulsating. At some times the flow is annular in character, and this feature of the flow will be used later. Bubbly flow in contrast, see figure 3(c), is stable and well behaved. The gas bubbles are approximately uniformly sized into diameters typically around 3 mm for an air–water system.

All the experiments described in this work were done with air–water mixtures, most of the work was done with vertical upflow in the main tube though some experiments, see section 4, were performed with the main tube horizontal. The tube inside diameter in the experiments described in sections 2, 3 and 4 was 32 mm.

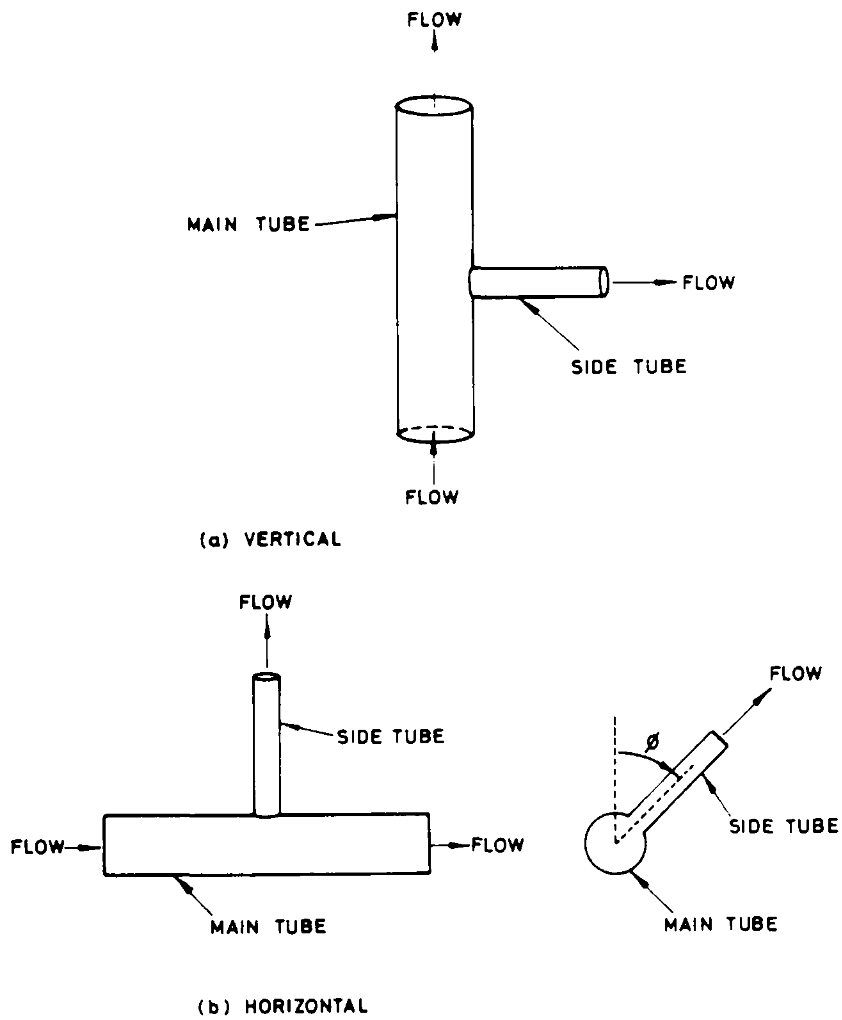

Figure 1. Schematic view of horizontal and vertical T junctions.

2. VERTICAL ANNULAR FLOW

2.1 *Film flow measurements*

One method of measuring the film flowrate in annular flow is to remove the film through a porous section of tube wall. The method is illustrated in figure 4, together with typical results. The sintered, and therefore porous, section of tube wall is typically about 75 mm long and when the main tube is vertical the sinter extends right around the 360 degrees of the tube periphery. The whole sinter arrangement has some resemblances to a T junction in that the flow leaves the main tube at 90 degrees to the main flow. It can be seen from figure 4 that if the liquid flowrate taken off through the sintered section of the tube wall is plotted against the gas flowrate taken off, then the liquid flowrate is almost independent of the gas flowrate except at very low values of the gas flowrate. This implies that the liquid film is removed through the porous wall very easily, but that the drops in the gas flow are only slightly deflected by the gas entering the sinter and that relatively few of the drops actually hit the sinter. It has become common to identify the plateau in figure 4 as being equal to the liquid film flowrate, and results derived on this basis have been found to be consistent with other methods of determining the film flowrate, see Hewitt (1978).

The tube length between the point where the air and water were mixed and the sinter device to measure the film flowrate was 4.3 m. The pressure at the sinter section was 1.5 bar. From

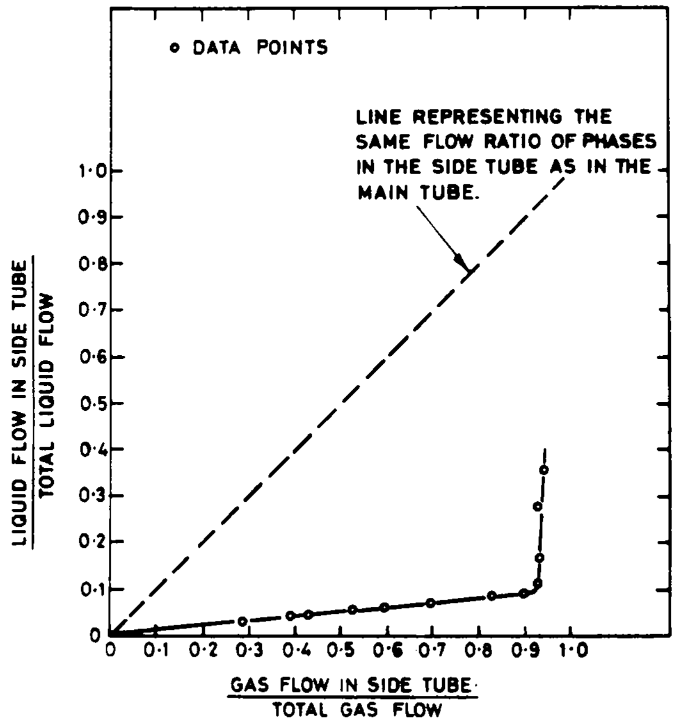

Figure 2. Typical experimental results for two-phase flow in a T junction (from Butterworth 1980).

figure 4b the liquid film flowrate can be determined. Also, it can be seen that once the gas take-off rate is high enough to remove the liquid film, then any increase in the gas take-off rate hardly leads to any increase in the liquid take-off rate. The complete tabulated results for the liquid film flowrate are given by Whalley & Azzopardi (1980).

2.2 T *junction experiments and results*

The T junctions used were machined out of a block of perspex; the actual junction area was not rounded in any way and so the T used was as square edged as possible. The T junctions were placed in the vertical tube in place of the sinter section. The side tube internal diameters of the junctions used were 6.35 mm, 12.7 mm and 19 mm giving diameter ratios with the main tube of 0.2, 0.4 and 0.6 and area ratios of 0.04, 0.16 and 0.36 respectively. The pressure at the T junction was 1.5 bar as this pressure was also used in the film flowrate experiments.

For each flow condition in the inlet tube to the T, the total flowrate in the side tube was gradually increased and the flowrate of air and water measured. This was done by separating the air and the water in a small cyclone and then measuring the flowrates separately. The full tabulated results are given by Whalley & Azzopardi (1980) and Whalley & Fells (1981).

2.3 *Discussion*

In all cases the air Reynolds number for the flow in the main tube is large (typically 120000) and so the flow will be highly turbulent. It can be argued that if the Reynolds number is large, the gas flow will be similar in structure if a fixed proportion of the air flow is taken from the side tube even if the air flow in the main tube before the T junction varies. The tendency of the liquid film to enter the side tube is possibly related only to the shape of the streamlines in the air.

The amount of liquid entering the side tube will clearly be related to the film flowrate. Thus the flowrate of liquid in the side tube was expressed as the apparent angle (θ, degrees) over

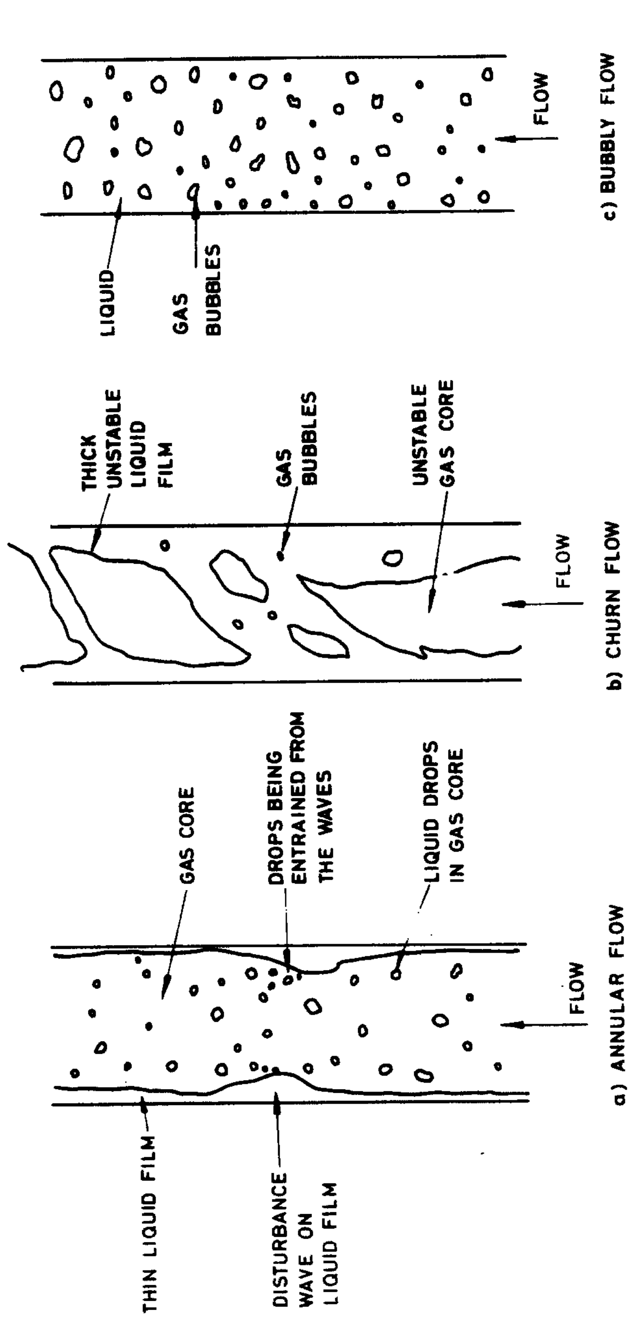

Figure 3. Flow patterns studied.

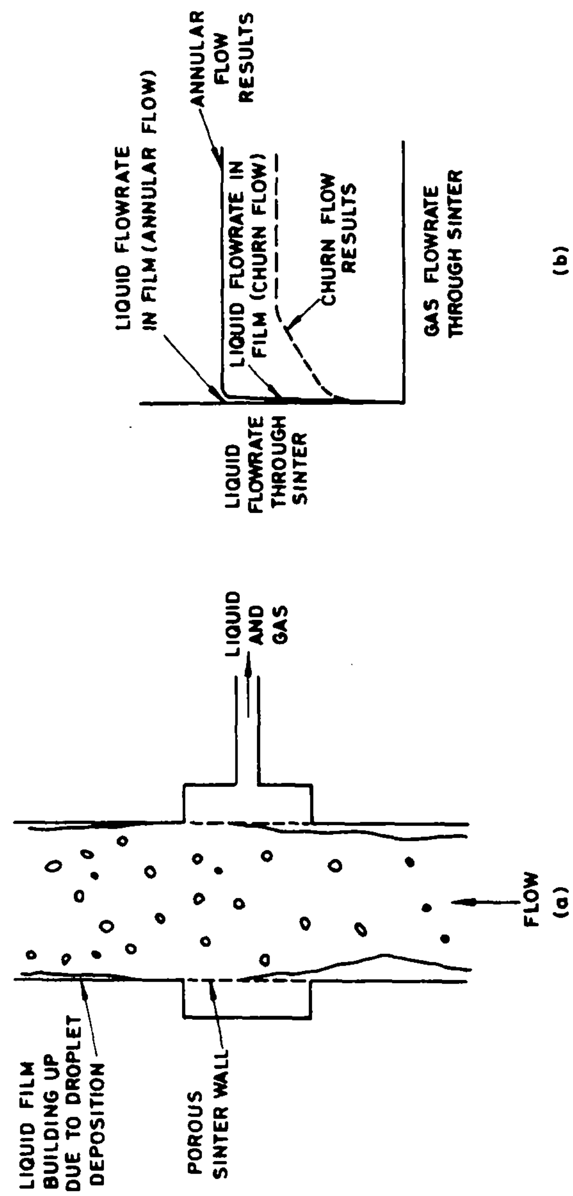

Figure 4. Determination of film flowrate by film removal in a vertical tube.

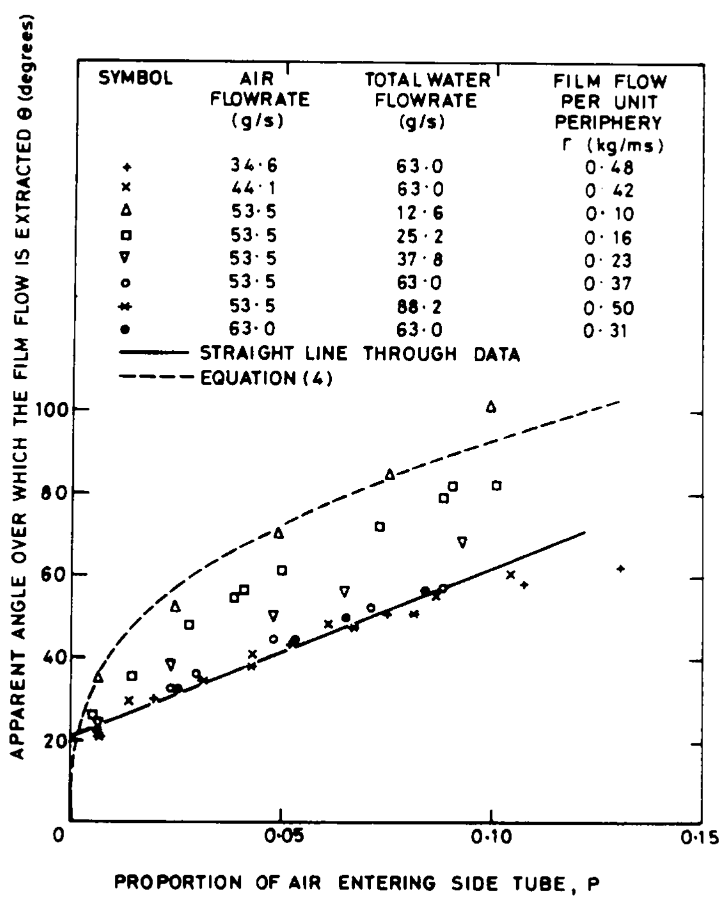

Figure 5. Variation of θ with P (side tube diameter = 6.35 mm) annular flow data.

which the film flowrate had been extracted. Here

$$\theta = \frac{360 \times \text{water flowrate in side tube}}{\text{Total water film flowrate}}. \quad [1]$$

Hence θ is plotted in figures 5–7 against the proportion of the air flow which is taken off in the side tube. It can be seen that the angle θ is for the majority of the points in figures 5 and 6 can be represented as a linear function of the proportion of the air flow which enters the side tube (P). The data which are not represented well by a linear function are those points where the total water flowrate and therefore the film flowrate are small. The lowest value of the film flow per unit periphery (Γ, kg/ms) for which the linear relationship works well is approximately 0.2 kg/ms. Figure 7, for a side tube diameter of 19 mm shows little sign of any linear relationship.

It seems possible that the liquid film in the main tube will be affected by the absolute value of the gas velocity or by the gas mass flux as the gas enters the side tube. The gas entering the side tube will tend to drag the liquid film with it into the side tube. Therefore the results for all three side tube diameters were replotted in the form of apparent angle over which the film flow is extracted versus the air mass flux in the side tube. These graphs are shown in figures 8–10. Reasonable straight lines can be drawn through the data points on all three graphs, again discounting the data points with very low values of film flowrate.

If G_G = air mass flux (kg/m^{2}s) in the side tube then the results can be expressed as a

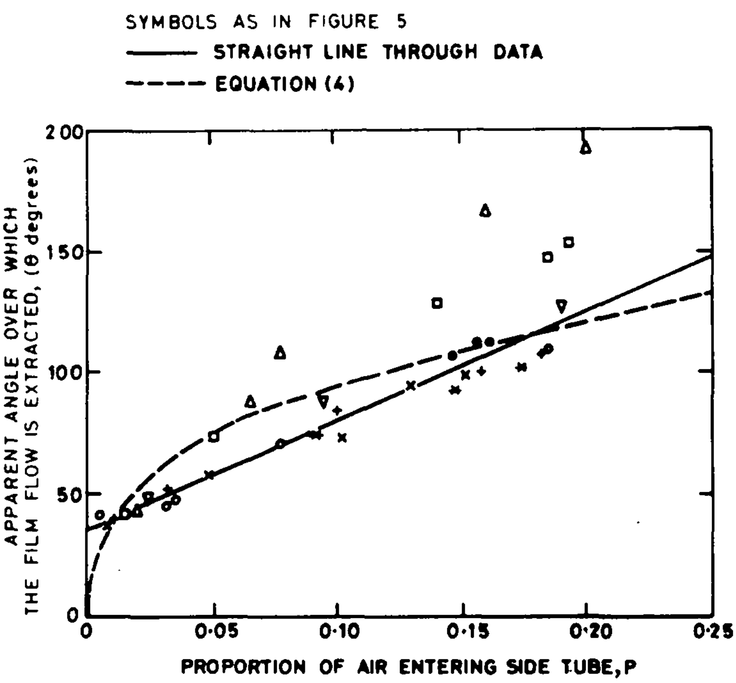

Figure 6. Variation of θ with P (side tube diameter = 12.7 mm) annular flow data.

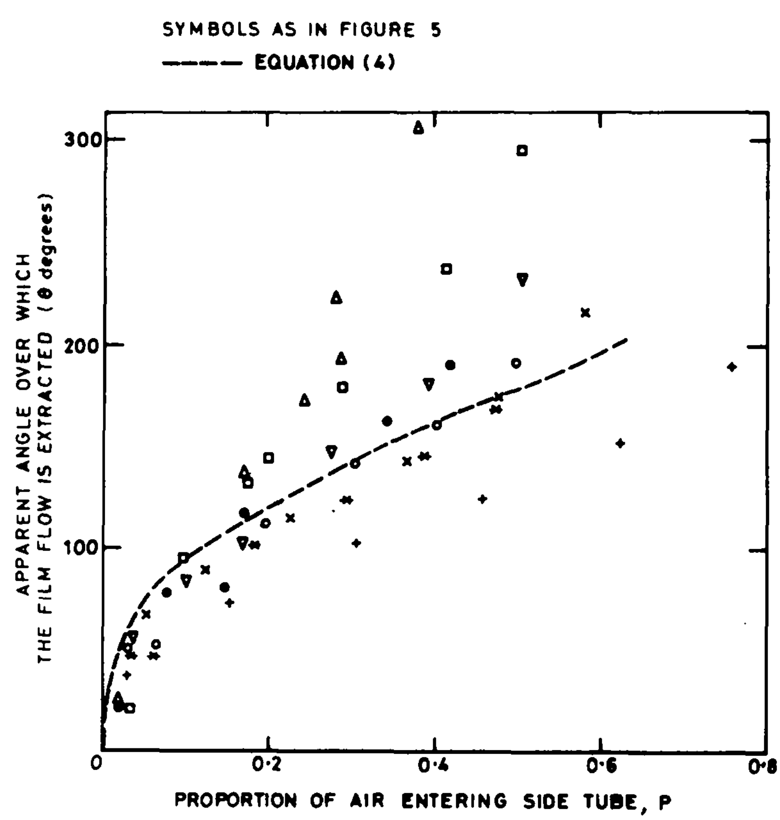

Figure 7. Variation of θ with P (side tube diameter = 19 mm) annular flow data.

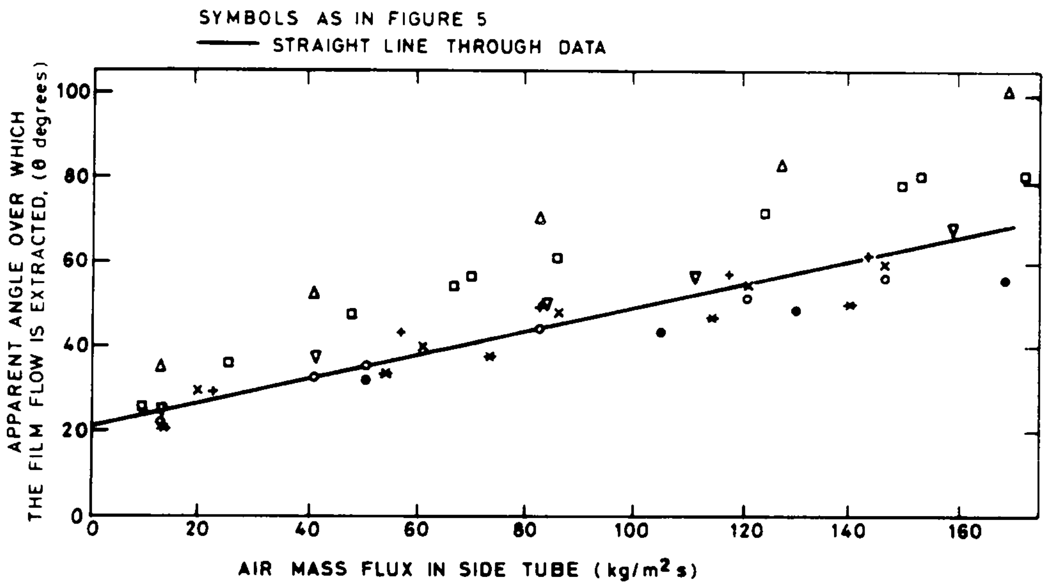

Figure 8. Variation of θ with G_G (side tube diameter = 6.35 mm) annular flow data.

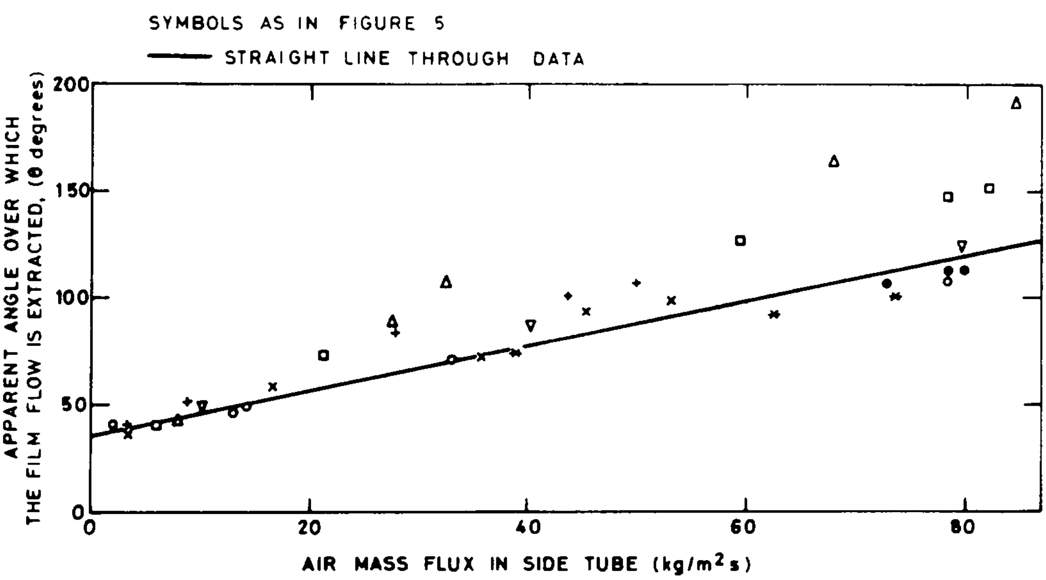

Figure 9. Variation of θ with G_G (side tube diameter = 12.7 mm) annular flow data.

dimensional equation of the form

$$\theta = A + BG_G \quad \begin{matrix} (G_G,\ \text{kg/m}^2\text{s}) \\ (\theta,\ \text{degrees}) \end{matrix} \qquad [2]$$

where A and B are constants the values of the constants are found to be:

Side tube diameter (mm)	A (degrees)	B (degrees m^{2}s/kg)
6.35	21	0.29
12.7	35	1.06
19.0	56	1.50

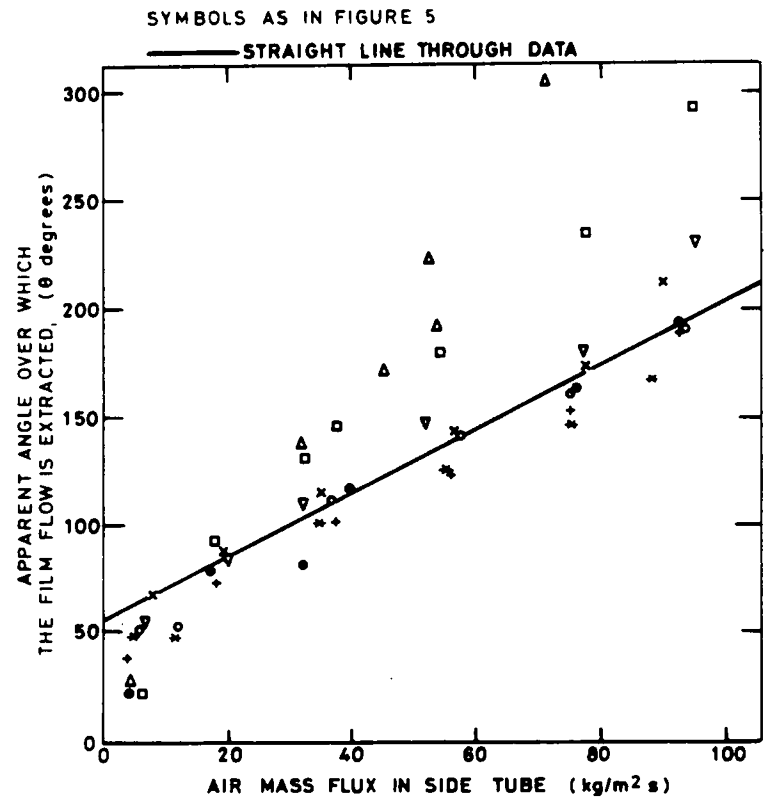

Figure 10. Variation of θ with G_G (side tube diameter = 19 mm) annular flow data.

The constant A can be interpreted as the limiting angle over which the film is extracted as the gas extraction rate tends to zero. This can be compared to the physical angle subtended by the side tube at the axis of the main tube, and also to the angle subtended by a square hole of the same cross sectional area as the side tube:

Side tube diameter (mm)	A (degrees)	Actual angle subtended by side tube (degrees)	"Equivalent square" angle subtended by side tube (degrees)
6.35	21	23	20
12.7	35	47	41
19.0	56	74	64

As can be seen there is a reasonable correspondence between A and the actual physical angle (particularly the angle subtended by the equivalent square hole).

The constant B would be expected to increase with the diameter of the side tube because the greater volume of gas entering a large side tube will affect the liquid film to a greater extent than the same mass flux in a small tube. This is simply because the gas flow in the main tube will be more disturbed by a large volume flow entering the side tube than a small volume flow. However, it is difficult to see how in detail the constant B would be related to the side tube diameter or to any other parameters of the system as the flow into the side tube is quite complex.

The first method of presenting the data (plotting P, the proportion of the gas flow extracted in the side tube against θ) can be rationalised by imagining that the situation is as in figure 11. As a first approximation the gas extracted in the side comes from the shaded area of the flow in

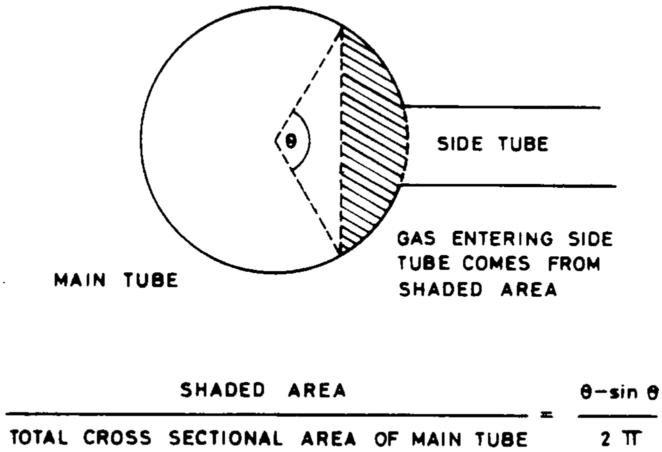

Figure 11. Simple model of gas extraction.

the main tube below (upstream) of the T junction. This assumption is confirmed in single phase flow by the experimental observations McNown (1954). Then

$$P = \frac{\text{shaded area in figure 11}}{\text{tube cross sectional area}} \qquad [3]$$

or

$$P = \frac{1}{2\pi}(\theta - \sin\theta) \qquad (\theta, \text{radians}). \qquad [4]$$

Equation [4] is shown in figures 5–7 and it can be seen to represent the data well in figure 6 (side tube diameter = 12.7 mm), but less well in figures 5 and 7 (side tube diameters 6.35 mm and 19 mm).

2.4 *Axial view photography of the flow near the* T *junction*

Axial view photographs, both high speed ciné and stills, were taken of the flow using a camera looking along the main tube axis and focussed at the T junction. The technique was originally described by Arnold & Hewitt (1967). An annular flow is passing up a vertical tube with some flow being taken off at a T junction and the T junction is illuminated by a flash unit. The illuminated zone can be viewed through a window, above which is positioned a camera focussed on the plane of illumination. The window is kept free of liquid by passing an air purge over it and down the viewing tube. The fluids passing up the channel are diverted into an exit chamber and then, via return lines, to the separation tank.

The results have been dominated by the events occurring downstream of the T junction and therefore no deductions have been possible regarding the behaviour of the flow actually at the T junction. The cine films show an area of high entrainment of liquid into the gas flow just downstream of the side arm. The entrainment from this area occurs in bursts which have a higher frequency than the natural disturbance waves in the main flow. This extra entrainment occurs because of the thickening of the film caused by the gathering of liquid at that point and the locally lower gas velocity. The liquid gathers at that point because gas entering the side arm drags part of the film round and not all this liquid is successful in entering the side arm. The extra entrainment has important implications for the flow in the main tube and any subsequent take off point.

3. VERTICAL CHURN FLOW

A few additional experiments were performed in the annular flow-churn flow transition region and in the churn flow region by reducing the gas velocity. Viewing churn flow as a highly disturbed and unstable form of annular flow, the value of the "film flow rate" was determined using a porous sinter section of wall. A typical variation of liquid take-off through the sinter with gas take-off is shown in figure 4(b); this is considerably different to the annular flow behaviour. There are two characteristic flow rates in the churn flow data, see figure 4(b), one at the knee point, and a second at the plateau. However, if the liquid proportion of the churn flow is assumed to be in the form of rather large waves it could be expected that these would be more difficult to extract than the smaller waves of annular flow, which would explain the three part extraction curve seen in figure 4(b). Therefore, the plateau value should be taken as the equivalent film flow rate.

Experiments on the take-off characteristics of churn flow were performed using the 12.7 mm side tube. The apparatus used and pressure were similar to the annular flow work reported in section 2. The results are plotted in figure 12 in the form of θ against P. It can be seen that the results are generally consistent with the annular flow results, though the scatter in the data is greater. Plotting θ against G_G, the gas mass flux in the side tube gives very scattered results for the churn flow data.

Thus, it appears the churn flow data can be viewed as consistent with the annular flow data if an equivalent film flow rate can be defined. The complete tabulated data for the churn flow experiments are given by Azzopardi & Baker (1981).

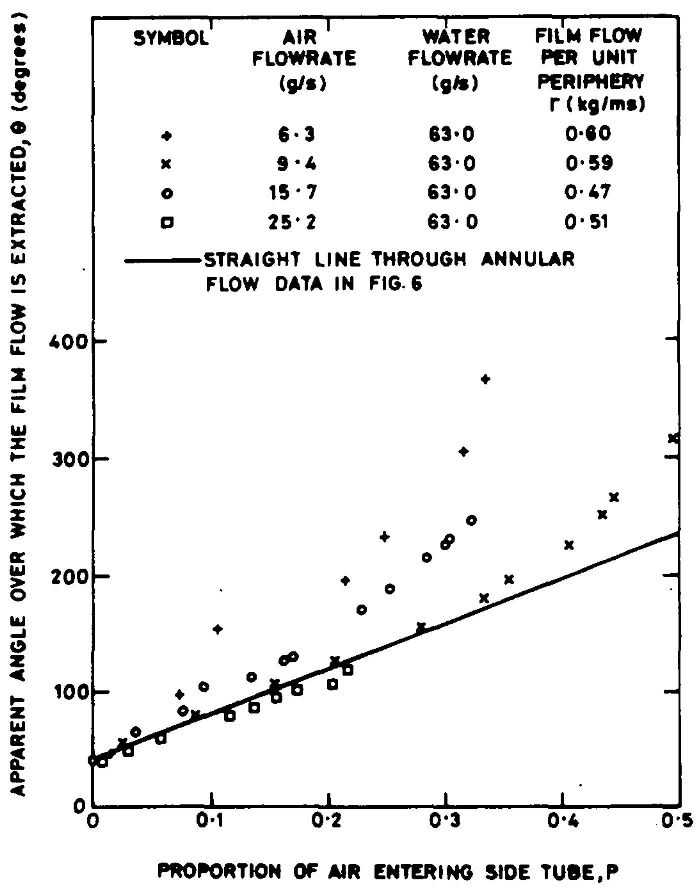

Figure 12. Variation of θ with P (side tube diameter = 12.7 mm) churn flow data.

4. HORIZONTAL ANNULAR FLOW

4.1 *Film flow measurements*

The film removal technique has also been adapted to measure liquid film flowrates in annular flow in eccentric annuli (see Butterworth 1969), in horizontal tubes (see, for example, Butterworth & Pulling 1973) and in flow in helically coiled tubes (see, for example, Whalley 1980). The main adaptations which have to be made in the technique for non-vertical flow arise because the film flowrate is not uniform around the tube periphery. Indeed, the variation of liquid film flowrates around the periphery of the tube is very substantial, being commonly ten times greater at the bottom of the tube than at the top. The adaptations to the technique made by Butterworth and Pulling were that the sintered part of the tube wall only covered a 25 degree arc and that guide vanes were placed on either side of the sinter, see figure 13, in an effort to prevent the liquid on the film adjacent but not on top of the sinter from entering the sinter.

Butterworth & Pulling (1973) have reported two sets of film flow measurements in horizontal annular flow. Only one set of results were used here because the film flowrates in the other set were very low at the top of the tube—values as low as 0.02 kg/ms were found. The flow conditions which gave higher values of the film flowrate at the top of the tube (approximately 0.17 kg/ms) were:

tube internal diameter = 32 mm
air flowrate = 64.0 g/s
total water flowrate = 51.0 g/s
pressure at measuring section = 2.5 bar.

It can be seen that these conditions are well within the range covered in the vertical tests, although the pressure is 2.5 bar instead of 1.5 bar. The film flowrate was reported as a function of peripheral position for the two different guard fin arrangements around the sinter, as shown in figure 13. The results were typically between 10 and 20% different, but in this work a curve was fitted between the two sets of results, and this curve is shown in figure 14.

It should be noted that the measurements shown in figure 14 are not local measurements of film flowrate but are averages over an arc of 25 degrees. This averaging effect was disregarded in the present work, and the measurements were treated as local measurements. The effects of this assumption are likely to be minimal.

4.2 T *junction experiments and results*

Experiments in a horizontal *T* junction, see figure 1, were made with a side tube of diameter 12.7 mm. The experimental measurements were made at the conditions quoted in section 4.1, thus the pressure in these experiments was not 1.5 bar but 2.5 bar. The distance between the point where the air and water were mixed was 3.6 m. The experimental results for the flowrates in the side tube are tabulated by Whalley & Azzopardi (1980) for various angles of inclination of the side tube. The experimental results were plotted in the form of water flowrate against air flowrate for the side tube. From graphs of this type, the water flowrate in the side tube was estimated when the proportion of the total air flow extracted in the side tube was zero, 0.1 and 0.2. The value for zero air flow in the side tube had to be obtained by extrapolation. The results from this procedure were then plotted on figure 15. This was done so that a convenient method of comparing the experimental results with predictions extrapolated from the vertical annular flow results could be carried out.

4.3 *Prediction of horizontal* T *junction results from vertical flow data*

It was assumed that [2] for the apparent angle of film extraction could be applied in the case of flow along a horizontal tube.

The predictions were made by the following procedure:

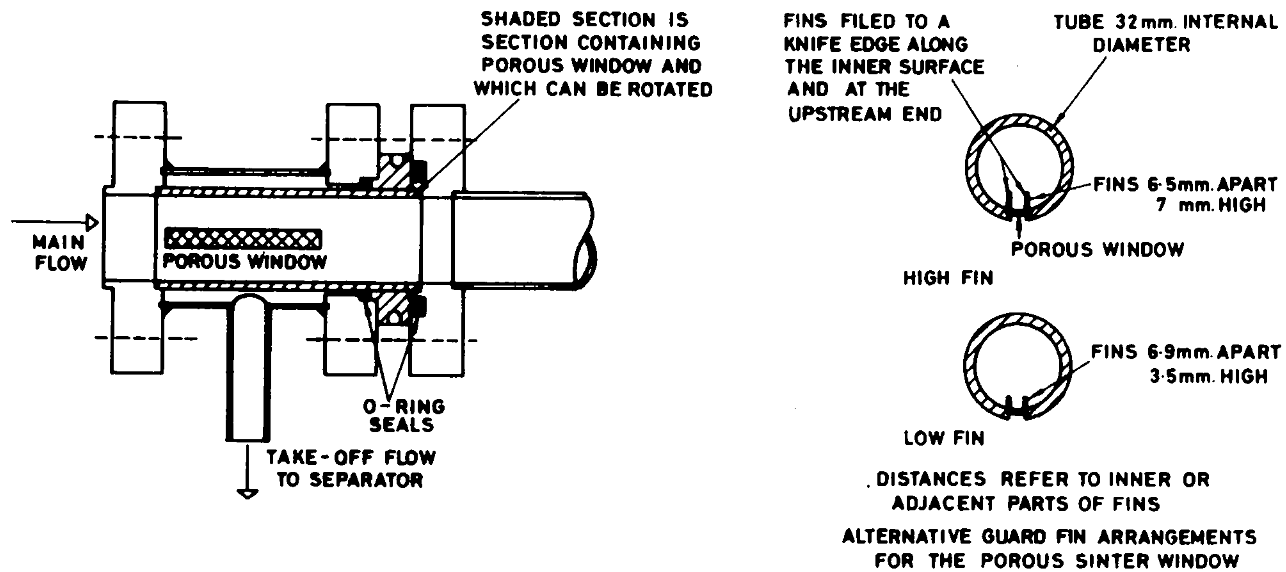

Figure 13. Apparatus for the determination of film flowrate by removal in a horizontal tube (from Butterworth & Pulling 1973).

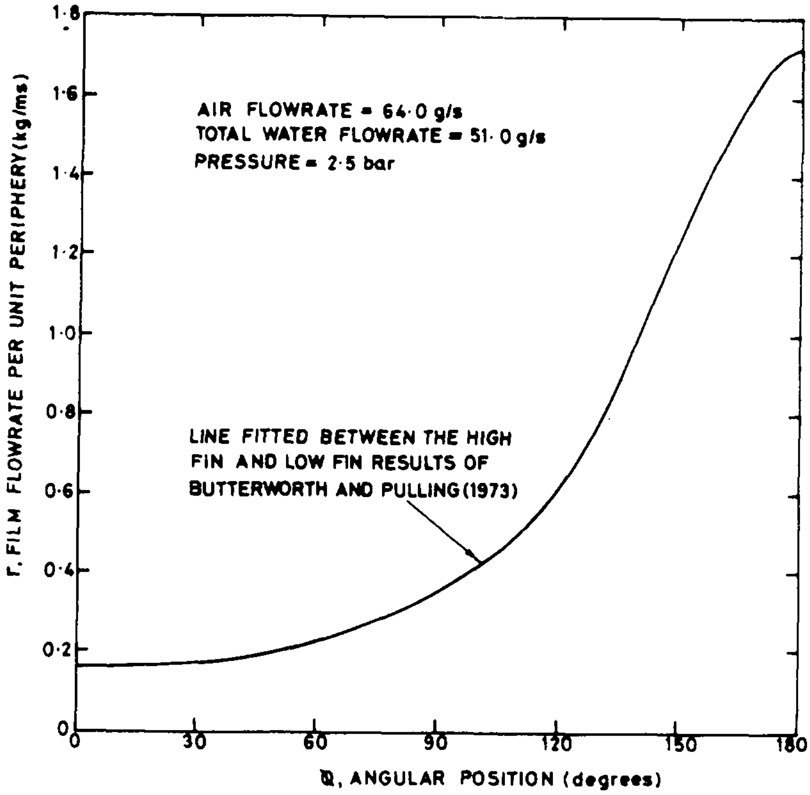

Figure 14. Film flow results of Butterworth & Pulling (1973) for flow in a horizontal tube.

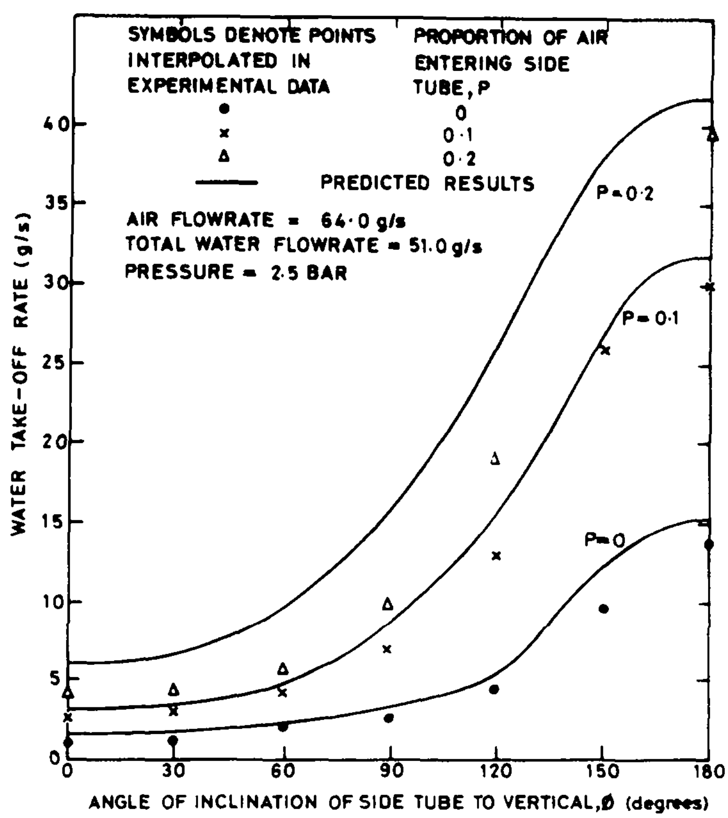

Figure 15. Predicted and experimental air and water flowrates in the side tube of a horizontal T junction.

(i) From the proportion of the air flow extracted through the side tube and from [2], the apparent angle over which the film was removed (θ) was calculated.

(ii) It was assumed therefore that all the water film flow between the angles $\phi + \theta/2$ and $\phi - \theta/2$ was removed when the side tube was inclined at an angle of ϕ to the vertical, see figure 1.

(iii) The water flow rate in the side tube (W_{ls}) was then calculated from [5]

$$W_{ls} = \frac{\pi}{180}\int_{\phi-\theta/2}^{\phi+\theta/2} r\Gamma(\phi)\,\mathrm{d}\phi \qquad [5]$$

where $\Gamma(\phi)$ is the film flowrate per unit periphery as a function of angle (kg/ms), r is the radius of the main tube (m), and $\pi/180$ is the conversion factor for degrees to radians.

By this procedure the prediction of water flowrate against air flowrate in the side tube shown in figure 15 was made for the experimental conditions quoted in section 4.1 for which Butterworth & Pulling (1973) measured $\Gamma(\phi)$.

The mean error in the predicted liquid flowrates in figure 15 is 30 per cent, the predicted flowrate always being larger than the experimental value. The best results were obtained when the proportion of the total air flow extracted in the side tube was zero or 0.1.

5. VERTICAL BUBBLY FLOW

5.1 *Experimental results of Hewitt and Shires*

Experiments on T junction take off in air–water upflow in the bubbly flow pattern have been reported by Hewitt & Shires (1964) and by Honan & Lahey (1978). Hewitt and Shires studied flow in a main tube of internal diameter 32.4 mm and a side tube of the same diameter. The pressure in the experimental results quoted here was 3.05 bar. The air mass flux in the main tube was varied from 7.6 to 22.9 kg/m^{2}s and the water mass flux from 760 to 2290 kg/m^{2}s.

The data points lie within the area indicated on figure 16 for bubbly flow. For comparison the areas for the annular flow and churn flow data are also given on this figure.

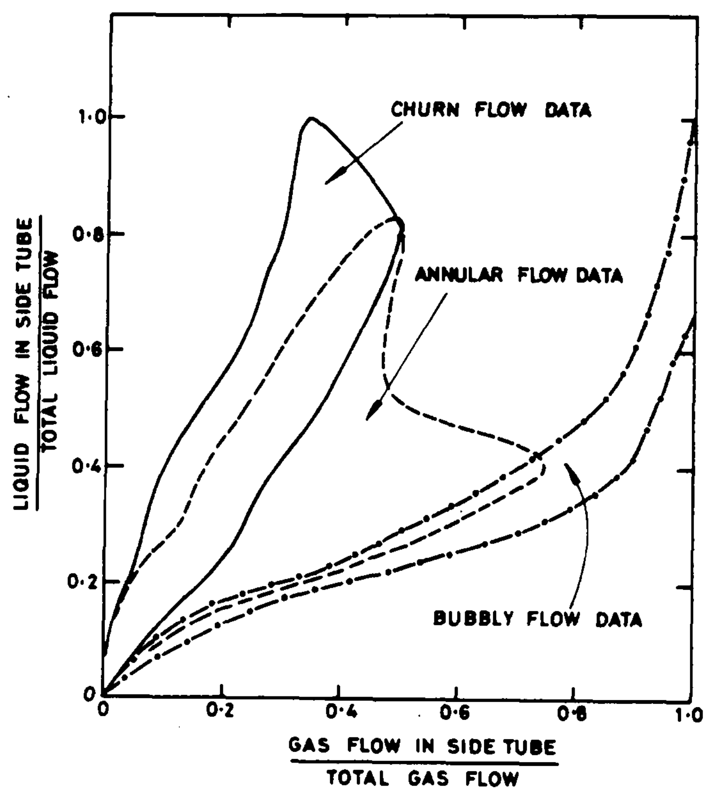

Figure 16. Flow split at a T junction—effect of flow pattern.

5.2 *Discussion*

Looking at figure 16, the obvious question is why are the results so different for various flow patterns? In the flow of a fluid in a *T* junction, the local momentum flux of the fluid is probably a good measure of the resistance of any part of the flow to be diverted into a side arm. This axial momentum flux is destroyed when fluid is diverted. Therefore it is suggested that in a two-phase flow it is the liquid with momentum flux near that of the gas that is diverted into the side arm and that the gas and liquid come from the same region of the main tube, see figure 11. This concept can be detailed for specific flow patterns.

Annular flow can be divided into the liquid film where the momentum flux is low (high density and low velocity), the gas where the momentum flux is also low (low density and high velocity) and drops with high momentum flux (high density and high velocity). The momentum fluxes of the three items are approximately in the ratio 1:5:2500. In this case the gas and liquid from the film can be expected to be diverted but the drops can be expected to carry straight on. The large area of figure 16 occupied by the annular flow pattern occurs because the proportion of the total liquid in the film can be very different for different flows.

In the case of bubbly flow, the flow can be divided into a liquid layer near the wall with a momentum flux near that of the bubbles and a liquid core with a much higher momentum flux. Therefore it could be expected that bubbles and liquid from the slow layer near the wall be diverted into the side arm. Azzopardi & Baker (1981) have extended this idea of a momentum flux criterion for diversion, and with some rather specific assumptions have obtained a reasonable fit to the bubbly flow results of Hewitt and Shires.

6. CONCLUSIONS

Two-phase flow even in a single *T* junction, without any of the interaction effects in a manifold, has been seen to be a complex subject. Some general conclusions can, however, be reached.

(1) The behaviour of the flow is very sensitive to the two-phase flow pattern upstream of the junction.

(2) The behaviour of the flow in annular and churn flow patterns can be explained by means of the assumption that the liquid drops cannot be diverted into the side arm, but the liquid in at least part of the film can be diverted.

(3) The behaviour of the flow in the bubbly region can also be explained. The gas enters the side tube preferentially because it generally has a lower momentum flux than that of the liquid.

(4) Even though these explanations of behaviour can be given, the problem of predicting the flow split in even the simplest and most ideal *T* junction still remains.

(5) In view of the above conclusions it is recommended that two-phase flows are not passed through *T* junctions and manifolds unless a very severe maldistribution of phases at outlet can be tolerated.

It should be emphasised that these conclusions are based on one fairly small main tube diameter (32 mm), and other effects may be important in larger diameter tubes. It should also be noted that the experiments performed covered a fairly small range of flow conditions (phase flow rates and pressure). The systematic coverage of a realistic spread of conditions is a very large task; perhaps this is one reason why the understanding of two-phase flow in junctions is unsatisfactory.

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REFERENCES

ARNOLD, C. & HEWITT, G. F. 1967 Further developments in the photography of two-phase gas–liquid flow. UKAEA Report No. AERE-R 5318.

AZZOPARDI, B. J. & BAKER, D. R. 1981 Two-phase flow in a *T* junction: the effect of flow pattern in vertical upflow. UKAEA Report No. AERE-R 10174.

BUTTERWORTH, D. 1969 Air–water climbing film flow in an eccentric annulus. *Co-current Gas–Liquid Flow*, pp. 145–201. Plenum Press, New York.

BUTTERWORTH, D. 1980 Unresolved problems in heat exchanger design. Presented at *Interflow 80—The Fluid Handling Conference*, Harrogate, England. *Inst. Chem. Engrs Symp. Ser.* No. 60, pp. 231–248.

BUTTERWORTH, D. & PULLING, D. J. 1973 Film flow and film thickness measurements for horizontal, annular air–water flow UKAEA Report No. AERE-R 7576.

HENRY, J. A. R. 1981 Dividing annular flow in a horizontal tee. *Int. J. Multiphase Flow* 7, 343–355.

HEWITT, G. F. 1978 *Measurement of Two-phase Flow Parameters*. Academic Press, New York.

HEWITT, G. F. & SHIRES, G. L. 1964 Private communication.

HONAN, T. J. & LAHEY, R. T. 1978 The measurement of phase separation in Wyes and Tees. Rensselaer Polytechnic Institute Report, New York (USNRC Contract NRC-04-76-301).

MCNOWN, J. S. 1954 Mechanisms of manifold flow, *Trans. Am. Soc. Civil Engrs* **119**, 1103–1142.

WHALLEY, P. B. 1980 Air–water two-phase flow in a helically coiled tube. *Int. J. Multiphase Flow* 6, 345–356 (see also UKAEA Report No. AERE-R 8845).

WHALLEY, P. B. & AZZOPARDI, B. J. 1980 Two-phase flow in a *T* junction. UKAEA Report No. AERE-R 9699.

WHALLEY, P. B. & FELLS, N. S. 1981 Further measurements of two-phase flow in a *T* junction. UKAEA Report AERE-M 3149.