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The split of annular two-phase flow at a small diameter T-junction

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Abstract

This paper extends the range of diameters (0.009–0.127 m) for which information on the maldistribution of the phases at a T-junction is available. Data are presented for a smaller T-junction whose diameter is 0.005 m in all branches. The flow rates studied result in annular flow approaching the junction. Gas superficial velocities of 46–60 m/s and liquid superficial velocities of 15–20 m/s were studied. When the present data are compared to those from larger diameter junctions for similar superficial inlet velocities, it is seen that decreasing the pipe diameter increases the fraction of liquid taken off. It is suggested that this trend is due to the lower entrained fraction and more uniform film around of the pipe circumference for the smaller pipes. The measured split data were compared with the predictions of published models. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Annular flow; Horizontal; T-junction; Gas–liquid

1. Introduction

When a two-phase flow is introduced into a T-junction, there is almost inevitably a maldistribution of the phases between the outlets. This can constitute a major problem when it occurs in chemical processes and oil and gas production, as the maldistribution can have a significant effect on the behaviour of equipment downstream of the junction. An example of this can be taken from natural gas distribution networks, where during winter months some of the heavier hydrocarbons can condense out of the gas flow. Even though small quantities of

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liquid itself will not cause a problem, observations during operation showed that the condensate could arrive in appreciable amounts at any one of the delivery stations. This is caused by liquid emerging preferentially from an outlet in one of the junctions used to split the flow between delivery stations.

However, this maldistribution of phases can be utilised as a useful tool in the processing industry, mainly as a phase separator. On offshore oil/gas production platforms, a phase separator is required to provide gas-free oil for pumping, and oil-free gas for transmission compressors. Current separators are large vessels, which are expensive to build and to place on the platform. Moreover, such vessels contain a large inventory of flammable material that should be minimised. The possibility of using the maldistribution that occurs at a T-junction for phase separation, although only partial separation, is an approach which is motivating research in this area.

The majority of junctions, which have been employed in studies of two-phase flow split, are of the side arm type. In these, there is a main pipe containing an inlet and one outlet, usually termed the run. Coming off the main pipe there is the pipe which forms the second outlet, the side arm.

The aim of this study was to investigate, experimentally, the split that occurs at a 0.005 m horizontal T-junction, and to compare the results with data from junctions of other diameters, and with theoretical models from published work. A 0.005 m junction is employed, so that the effect of a small diameter can be investigated to see if it follows previous trends. Small diameters are of interest because of the possibility of scaling down the size of plants, especially those manufacturing hazardous materials. Though there has been a substantial amount of work published in the area of flow split at T-junction, there has been none at such a small diameter. Here, the most relevant published data and models are reviewed, so as to place the present work in context. The experiments performed by Hong (1978) are of particular relevance to the current study, since the pipe diameter he employed (0.0095 m), is the closest to that utilized in the present work. Hong varied both the liquid and gas flow rates as well as the liquid viscosity, and found that increasing the inlet liquid superficial velocity decreased the fraction of liquid taken off in the side arm. He also found that increasing the gas flow rate increased the fraction of liquid taken off. Hong suggested a mechanism for this splitting phenomenon, which is similar to that originally proposed by Oranje (1973). Hong argued that an abrupt change in the direction of gas entering the side arm produced a centripetal force, which creates an under pressure inside the 90° bend, drawing liquid into the side arm. When the gas intake is small, the centripetal force and hence the under pressure is small compared with the inertial force of the liquid stream, so the liquid flows straight through the junction. Under these circumstances, liquid only enters the side arm after a higher portion of the gas is diverted into the branch.

Shoham et al. (1987) who used a junction with a larger diameter, 0.05 m, found a strong dependence on the splitting phenomena on the flow pattern approaching the junction. They reported trends similar to Hong and Oranje. The main difference between the findings of Shoham et al. and Hong is that at a low gas take off, Shoham et al. found a higher liquid take off than Hong, while at a higher gas take off they found a lower liquid take off. It is not known whether this disagreement is due to the difference in diameters used or to the difference in the pressures at which the experiments were performed.

Shoham et al. (1987) developed a model to predict the two-phase flow splitting in a horizontal T. The model is flow pattern dependent, with specific versions for stratified-wavy and annular flow. It uses the concept that the flow emerging into either side arm or run is delineated by a dividing streamline, one for each phase. They postulated that it is the competing inertial and centrifugal forces acting on the liquid phase, that forces it to flow into either the run or side arm. The gas dividing streamline was assumed to be an arc and its position was determined from the fraction of gas entering the side arm. Then, the position of the liquid boundary line is found by a momentum balance and used in geometric models to determine the fraction of liquid taken off. The main geometric model identifies the bounding streamline as a chord and uses the assumptions of a constant film thickness, no entrainment, and uniform velocity in each phase. The predictions of the model generally show the correct trends and reasonably good absolute values. However, the description of the fluids travelling in simple arcs is probably too great a simplification.

Azzopardi (1989) developed an alternative model for the split of annular flow at a T-junction, based on careful observation of the behaviour of the liquid. The first element of the model identifies that the liquid travelling as drops is most likely to be impelled past the junction because of its high momentum. The liquid film was assumed to be taken off from that periphery of the pipe corresponding to the area of main pipe, from which the gas was taken off. Initially, Azzopardi and Whalley (1982) suggested this to be the local segment of the main pipe. Later, Azzopardi (1984) proposed an empirical correction factor which allowed for 20% more film to be taken off when the side arm and main pipe diameters were equal. This factor became 1.0 when the side arm and main pipe diameters were in the ratio of 0.634. The concept behind this approach is supported by the observations of the area of take off for a single-phase flow by McNown (1954) and Charron and Whalley (1995). They found that the take-off boundaries were more convex (and thus would influence more of the film circumference) than the flat boundary defining a segment. When the main pipe approaching the T-junction was vertical, the film flow could be assumed uniform around the pipe, and the amount of liquid take-off determined simply from the fraction of circumference affected. For those cases where the inlet pipe to the junction is horizontal, the effect of gravity is to produce an asymmetry in the film flow rate and thickness. Knowledge of the circumferential distribution is required to determine the amount of liquid taken off through the side arm. Roberts et al. (1997) have employed the horizontal annular flow model of Fukano and Ousaka (1989) and successfully predicted the phase split. A further phenomenon is also related to momentum and refers to an observation at very low liquid flowrates. Here it was seen that at some critical gas take-off, the film was brought to a complete halt and then reacted to lateral pressure gradients, which dragged it into the side arm. This is attributed to an increase in pressure in the gas following from the deceleration in the gas flow caused by a fraction, that has been taken off at the side arm.

2. Experimental arrangement

Experiments were conducted on a two-phase, T-junction loop shown schematically in Fig. 1. Air was drawn from the compressed air main (1) and metered by one of the two rotameters (2) depending on the flow rate. From these, the air enters the horizontal stainless steel pipe of 0.005 m, internal diameter 0.2 m, upstream of the phase mixer (3). Water is drawn from a storage tank (4) by means of a centrifugal pump (5), metered by one of a bank of calibrated rotameters (6) before being introduced into the mixer. This mixer consisted of an annular section surrounding a porous wall section. Water enters the main pipe from the periphery to form a film on the wall whilst the air passes up the middle. Downstream of the mixer, the two phases flow horizontally along a 1.76 m development length of 0.005 m stainless steel pipe.

The T-Junction used in this study was manufactured from acrylic resin, so to allow experimental observations. The main and side arm diameters are 0.005 m. The outside of the T-shaped block has a rectangular cross section to minimize refraction problems during the observation of the flow. The undeviated two-phase stream travels along 0.95 m of horizontal pipe beyond the T-junction and then flows vertically down to a cyclone. The side arm consisted of 1.34 m of straight horizontal steel pipe followed by a vertically downward steel pipe to a second separator.

The flow rates of air and water emerging through the side arm and run of the T-junction was altered by opening and closing gate valves in the outlet legs of the T, just upstream of the cyclones (7, 8). The cyclones separated the phases and their flow rates were measured. The airflow rate was measured using one of a series of rotameters (9), while the water flow rate was determined by collecting the volume of liquid discharged at the bottom of each cyclone over a measured time (10).

An assessment was carried out on the uncertainty on each of the measured parameters. They

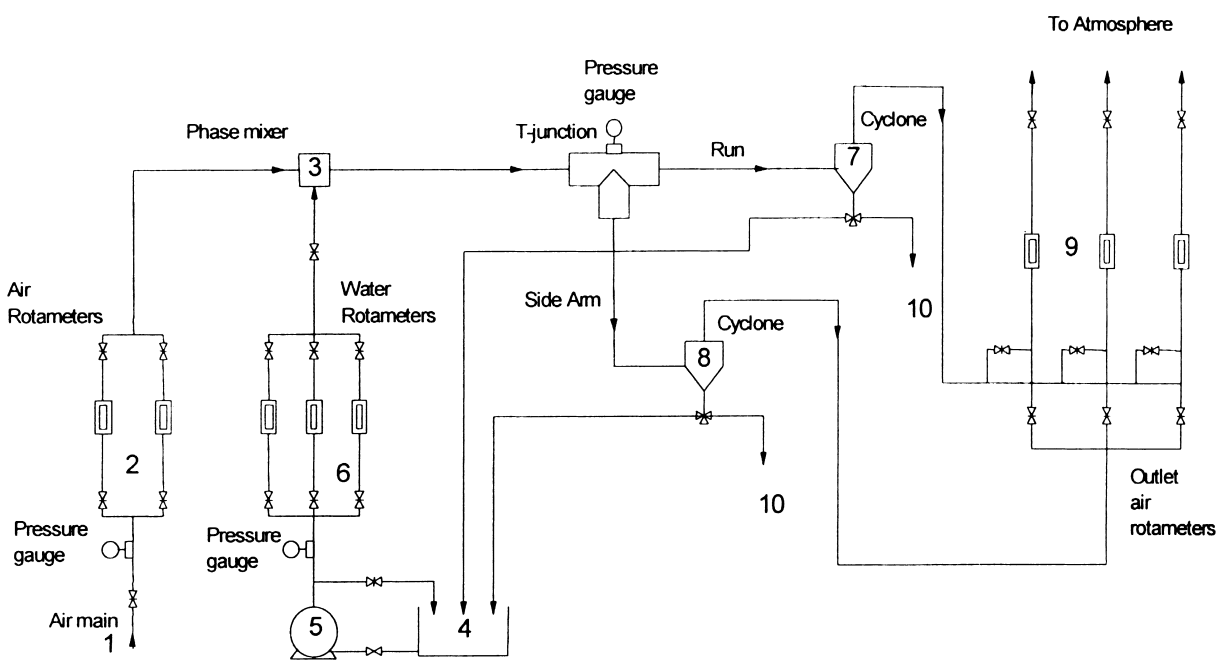

Fig. 1. Sketch of the two-phase, T-junction loop.

were all within $\pm 3\%$. From this the accuracy of the reported fractional take off data was determined and found to be $\pm 7\%$ with most points being well within this.

3. Results

Measurements of the flow-split data were taken for a number of inlet flowrates. Two gas superficial velocities were investigated, 15 and 20 m/s. Three liquid superficial velocities were employed, 0.11, 0.16 and 0.19 m/s, for each gas inlet condition. The pressure at the T-junction was always maintained at 148 kPa. The flow pattern was observed to be annular for all six inlet conditions. This was in agreement with the observations of Barnea et al. (1983) whose studies involved horizontal pipes with diameters in the range of 0.004–0.012 m.

The inlet flow rates employed were limited by the experimental equipment and flow patterns. For higher inlet liquid flows, the flow pattern changed from annular flow to slug flow. The presence of slugs produced large variations in the outlet airflow rate and it became impossible to obtain readings from the outlet air rotameters.

For each test, the flow rates emerging from both the side arm and run of the horizontal T-junction were recorded, and the fraction of the air and water flow taken off through the side arm was calculated. The data are tabulated in Table 1 and shown in Figs. 2 and 3. Typical overall errors are illustrated in these figures. For each point, mass balances were carried out between the inlet and outlet flows. For water, all reported points fell within $\pm 5\%$. For air they fell within $\pm 9\%$. Data where the imbalance was greater were discarded. To test the reproducibility of the data, tests were carried out at identical inlet conditions. No appreciable difference could be found between the two experiments when error was within the above restrictions.

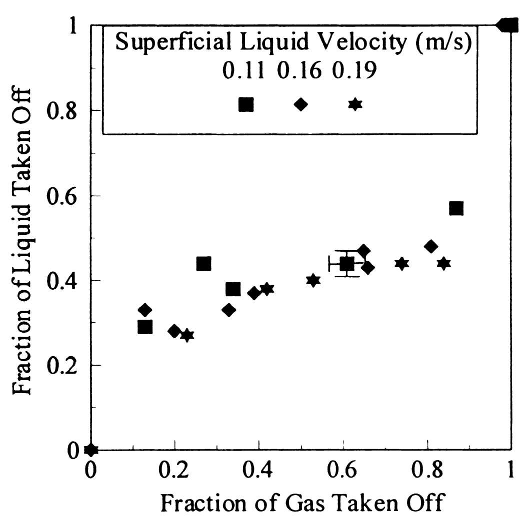

Fig. 2. Effect of liquid flow rate on phase split — gas superficial velocity = 15 m/s.

Table 1
The phase split data

Run	Gas inlet (kg/s) × 10^3	Liquid inlet (kg/s) × 10^3	Gas from run (kg/s) × 10^3	Gas from side arm (kg/s) × 10^3	Liquid from run (kg/s) × 10^3	Liquid from side arm (kg/s) × 10^3	Fraction of gas taken off	Fraction of liquid taken off	Air mass balance error (%)	Water mass balance error (%)
1	0.52	2.15	0.49	0.07	1.48	0.63	0.13	0.29	+7.7	−1.9
	0.52	2.15	0.42	0.14	1.28	0.94	0.27	0.44	+7.7	+3.3
	0.52	2.15	0.38	0.17	1.29	0.82	0.34	0.38	+7.1	+0.5
	0.52	2.15	0.24	0.31	1.17	0.94	0.61	0.44	+7.7	−1.9
	0.52	2.15	0.03	0.45	0.87	1.23	0.87	0.57	−6.5	−2.3
	0.53	2.15	0.00	0.55	0.00	2.09	1.00	1.00	+7.1	−2.8
2	0.53	3.02	0.52	0.00	2.97	0.00	0.00	0.00	−2.5	−1.7
	0.53	3.02	0.45	0.07	2.00	1.01	0.13	0.33	−2.5	−0.3
	0.53	3.02	0.42	0.10	2.10	0.86	0.20	0.28	−1.3	−2.0
	0.53	3.02	0.38	0.17	2.02	1.01	0.33	0.33	+5.1	+0.3
	0.53	3.02	0.28	0.21	1.83	1.12	0.39	0.37	−8.2	−2.3
	0.53	3.02	0.17	0.35	1.57	1.42	0.65	0.47	−2.5	−1.0
	0.53	3.02	0.21	0.35	1.70	1.29	0.66	0.43	+5.1	−1.0
	0.53	3.02	0.06	0.43	1.49	1.44	0.81	0.48	−6.9	−3.0
	0.53	3.02	0.00	0.52	0.00	3.07	0.98	1.00	−2.5	+1.7
3	0.53	3.79	0.52	0.00	3.78	0.00	0.00	0.00	−2.5	−0.3
	0.53	3.79	0.42	0.12	2.72	1.02	0.23	0.27	+0.6	−1.3
	0.53	3.79	0.33	0.22	2.42	1.45	0.42	0.38	+3.8	+2.1
	0.53	3.79	0.24	0.28	2.12	1.52	0.53	0.40	−1.3	−4.0
	0.53	3.79	0.19	0.36	2.09	1.68	0.74	0.44	+3.8	−0.5
	0.53	3.79	0.07	0.45	2.23	1.68	0.84	0.44	−2.5	−3.2
4	0.71	2.15	0.69	0.03	1.60	0.62	0.05	0.29	+1.9	+3.3
	0.71	2.15	0.33	0.42	1.15	0.94	0.58	0.44	+4.7	−2.8
	0.71	2.15	0.17	0.59	1.05	1.06	0.83	0.49	+7.0	−1.9
	0.71	2.15	0.00	0.76	0.00	2.08	1.00	1.00	+6.5	−3.3
5	0.71	3.02	0.76	0.00	2.92	0.00	0.00	0.00	+5.1	−3.3
	0.71	3.02	0.69	0.02	2.35	0.54	0.03	0.18	−1.4	−4.3
	0.71	3.02	0.59	0.14	2.09	0.87	0.19	0.29	+0.9	−2.0
	0.71	3.02	0.59	0.17	2.00	1.11	0.24	0.37	+5.5	+3.0
	0.71	3.02	0.31	0.40	1.68	1.44	0.55	0.48	−1.4	+3.3
	0.71	3.02	0.24	0.50	1.77	1.39	0.70	0.46	+3.2	+4.6
	0.71	3.02	0.00	0.76	0.00	3.10	1.00	1.00	+5.5	+2.6

6	0.71	3.79	0.62	0.10	2.70	1.14	0.14	0.30	+0.5	+1.3
	0.71	3.79	0.66	0.10	2.72	0.97	0.14	0.26	+5.0	−2.6
	0.71	3.79	0.59	0.17	2.48	1.16	0.24	0.31	+5.5	−4.0
	0.71	3.79	0.45	0.28	2.39	1.38	0.38	0.36	−1.8	−0.5
	0.71	3.79	0.42	0.31	2.14	1.52	0.43	0.40	+0.9	−3.4
	0.71	3.79	0.42	0.35	2.22	1.44	0.48	0.38	+5.5	+3.4
	0.71	3.79	0.35	0.40	2.16	1.56	0.55	0.41	+2.8	−1.8
	0.71	3.79	0.24	0.52	1.98	1.65	0.72	0.44	+5.5	−4.2
	0.71	3.79	0.14	0.59	2.07	1.77	0.81	0.47	+0.9	+1.3
	0.71	3.79	0.14	0.62	1.99	1.79	0.86	0.47	+5.5	−0.2
	0.71	3.79	0.07	0.66	2.04	1.86	0.91	0.49	+0.5	+2.9
	0.71	3.79	0.10	0.68	1.93	1.87	0.94	0.49	+7.8	+0.3
	0.71	3.79	0.00	0.73	0.00	3.69	1.00	1.00	+0.5	−2.6

4. Discussion

The effect of the inlet gas flow rate is shown in Figs. 2 and 3. From the results it is seen that the superficial gas velocity has only a minor effect on the flow split, since there is no clear definition between the split lines of the conditions tested. This trend is different to that found in the work of Azzopardi and Memory (1989), who showed that a change in the gas inlet velocity had an effect on the liquid take off. The difference between the two studies can be explained by the fact that the gas velocities employed in the present work were all in annular flow, while in the work of Azzopardi and Memory, the flow patterns extended from annular to stratified flows.

The effect of varying the liquid superficial velocity is also shown in Figs. 2 and 3. Fig. 3 shows a small but clear trend of increasing the liquid flow rate at constant gas velocity, which causes a decrease in the fraction of liquid removed for a given fraction of gas taken off though the side arm (typically 15%). This trend is similar to that reported in the work of Hong (1978), Shoham et al. (1987) and Azzopardi and Memory (1989). Azzopardi and Memory suggested an explanation for this trend, which involved the level of entrainment, and proposed that decreasing the liquid flow rate decreases the amount of entrainment, which would then increase the level of liquid at the wall film. Since the liquid taken off in the side arm comes from the wall film, an increase in the fraction of liquid taken off is expected.

The results of this work can be used to examine the effect of the pipe diameter. Data for flow rates similar to those used here are available for pipe diameters of 0.009 m (Hong, 1978), 0.038 m (Buell et al., 1994) and 0.127 m (Rea, 1998). Fig. 4 illustrates data with a gas superficial velocity of ~43 m/s and a liquid superficial velocity of 0.1 m/s. The data for Hong was not actually taken at the conditions shown, but extrapolated using trends shown in his data set. The figure shows that decreasing the pipe diameter increases the fraction of liquid removed down the side arm for a set gas take off. This

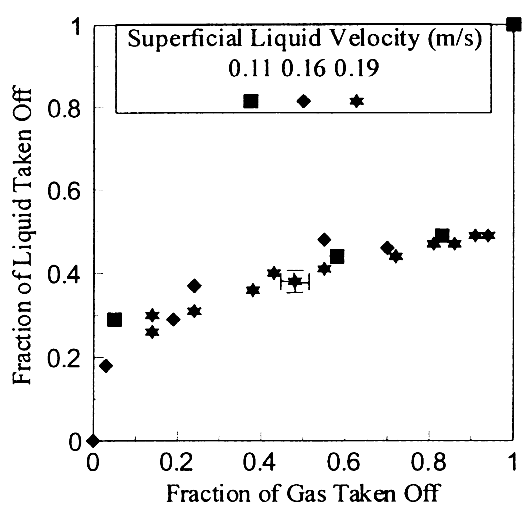

Fig. 3. Effect of liquid flow rate on phase split — gas superficial velocity = 20 m/s.

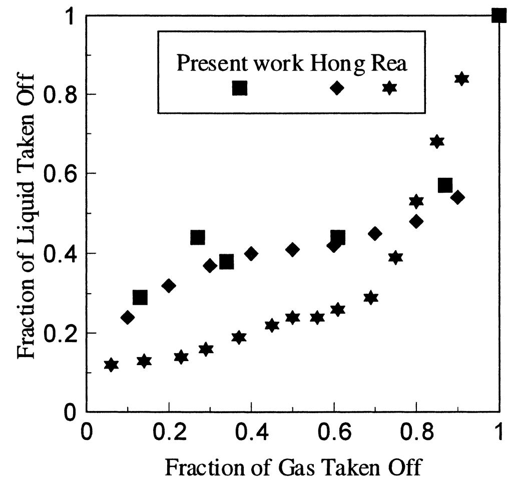

Fig. 4. Comparison between data from different diameter junctions. Present work: diameter = 0.005 m; gas superficial velocity = 15 m/s; liquid superficial velocity = 0.11 m/s. Hong (1978): diameter = 0.009 m; gas superficial velocity = 27 m/s (extrapolated); liquid superficial velocity = 0.11 m/s (extrapolated). Rea (1998): diameter = 0.127 m; gas superficial velocity = 12 m/s; liquid superficial velocity = 0.1 m/s.

trend is supported by Fig. 5, which considers data for gas and liquid velocities of $\sim$20 and 0.2 m/s, respectively.

The experimental data have been compared against the predictions of the models of Shoham et al. (1987) and Azzopardi (1989). Both models give reasonable predictions as shown in Figs. 6 and 7. The model of Azzopardi (1989) overpredicts the fraction of liquid removed at a set gas take-off, particularly at higher gas take off. However, when the diameter correction factor

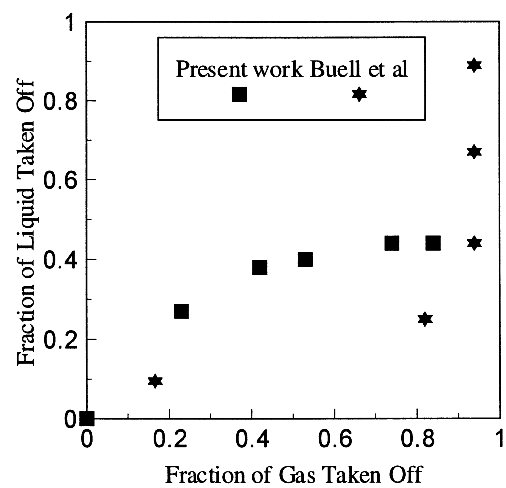

Fig. 5. Comparison between data from different diameter junctions. Present work: diameter = 0.005 m; gas superficial velocity = 15 m/s; liquid superficial velocity = 0.19 m/s. Buell et al. (1994): diameter = 0.038 m; gas superficial velocity = 11 m/s; liquid superficial velocity = 0.18 m/s.

proposed by Azzopardi (1984) is not applied, the model gives better predictions, slightly underpredicting at lower flow rates, Fig. 6, and giving very good agreement at higher flow rates, Fig. 7. Interestingly, the predictons of the Azzopardi model without the diameter correction agree well with the Shoham model. This, in spite of the Azzopardi model, allows for the presence of drops carried by the gas. These constitute 7 and 20% of the liquid for the cases shown in Figs. 6 and 7 respectively. Shoham assumes all the liquid travels in the film. The agreement is probably caused by inaccuracies in each model, which compensate for each other.

The effect of asymmetry of the film flow rate caused by gravity on the present results has also been considered. The horizontal annular flow models of Fukano and Ousaka (1989) and Hurlburt (1997) are designed to provide the circumferential distribution of film flow rate. However, neither model gave solutions for a 0.005 m diameter pipe. In recent work Hurlburt (1997) has suggested that the asymmetry of the liquid film can be quantified via the ratio of mean thickness to that at the bottom of the pipe. He provided a correlation for this parameter. When applied to the present data, this ratio had values of 0.66–0.88. This indicates a small asymmetry. In contrast, values of 0.25 were obtained for the data from the 0.127 m junction illustrated in Fig. 4.

Examination of the data presented in Figs. 2 and 3 indicate that they do not show a strong deviation from the equal split or $x = y$ line. Therefore, unlike other geometries and flow rates, the present case is not a good candidate for phase separation.

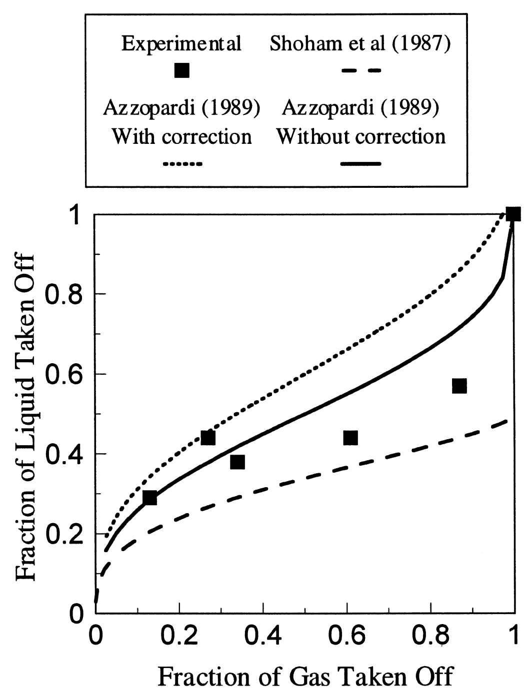

Fig. 6. Comparison between experimental data and models — gas superficial velocity = 15 m/s; liquid superficial velocity = 0.11 m/s.

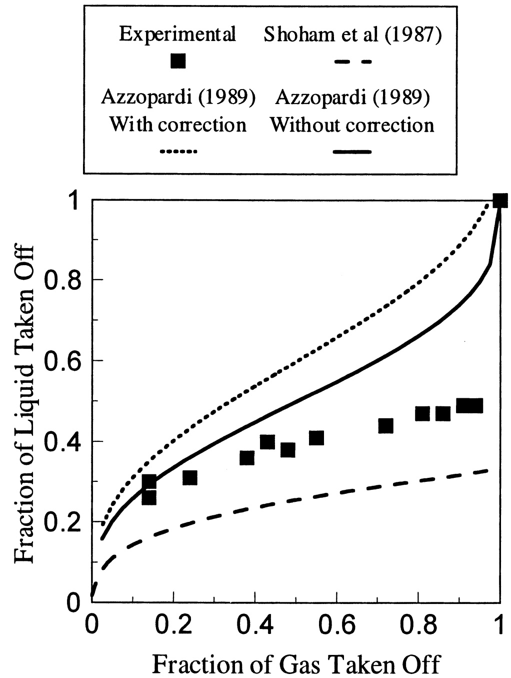

Fig. 7. Comparison between experimental data and models — gas superficial velocity = 20 m/s; liquid superficial velocity = 0.19 m/s.

5. Conclusions

1. For annular flow dividing at a 0.005 m diameter T-junction, increasing liquid flow rate decreases the fraction of liquid removed for a given gas take off. There is very little effect of inlet gas flow rate on the take off.
2. Decreasing the pipe diameter increases the fraction of liquid removed through the side arm for a given fraction of gas taken off. It is suggested that this is due to an increase in the fraction of liquid travelling as a film on the pipe walls, making more liquid available for take-off.
3. The models of Shoham et al. (1987) and Azzopardi (1989) predict accurately the flow split under the given inlet conditions.
4. For the geometry and flow rates considered in the present experiments, the junction is not very suitable for phase separation

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