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TWO-PHASE FLOW REDISTRIBUTION PHENOMENA IN A LARGE T-JUNCTION

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Abstract—An experimental study into phase redistribution and pressure drop phenomena of two-phase (air–water) flow splitting in a horizontal upward reduced T-junction was carried out in an industrial-scale flow rig (inlet and run dia = 23 cm, branch dia = 10 cm). Measurements were performed with inlet conditions in the stratified smooth, stratified wavy and bubbly flow regimes. The inlet liquid mass flow was varied between 75 and 225 m^3/h, the inlet quality was $<0.03\%$. The experiments reveal that the flow split phenomena observed in this large-scale T-junction, generally, do resemble those reported in the literature for smaller scales. Within that region, several models developed for smaller scales can be used to qualitatively describe the flow split and pressure drop at larger scales as well. It was observed that flow phenomena and regimes *downstream* of the junction still have impact on the flow split. In particular, the occurrence of pulsations in the branch causes a striking change in the phase redistribution behaviour within the junction. The transition from churn flow to pulsating churn could be determined quite distinctively by monitoring the time signals of the various pressure transducers along the flow path and their fast Fourier transforms.

Key Words: two-phase flow, T-junction, phase redistribution, pressure drop

1. INTRODUCTION

In the past several decades, a lot of attention has been paid to the behaviour of two-phase flow passing a T-junction. Up to now, almost all experiments have been performed in small-scale laboratory equipment, with pipe diameters generally not over 5 cm. The chemical industry, however, is more interested in industrial-scale pipeline junctions. In this paper experiments on phase redistribution and pressure drop in a large-scale horizontal T-junction with an upward directed reduced diameter side arm are presented. No attempt is made to derive new theory, but the measurements are compared with predictions made by existing models developed and tested in smaller scale equipment.

When a two-phase flow passes a T-junction (for definitions see figure 1), the phases usually do not split evenly over the two downstream legs of the junction. In other words: a *phase redistribution* takes place (more often, the—less correct—term phase *separation* is used). Pressure differences across the T-junction are mutually connected with these redistribution phenomena. As mentioned by, for example, Seeger *et al.* (1986), the degree of the phase redistribution has, to date, been considered to be determined mainly by three effects:

—inertia differences of the phases;
—gravity effects;
—the distribution of the phases over the area, i.e. the flow regime present, in the *inlet*.

Azzopardi & Whalley (1982) investigated how the phase redistribution is affected by the orientation of the junction and by different flow regimes. The dependence on the inlet flow regime can be qualitatively explained by defining a *zone of influence* of the branch, as that geometrical part of the inlet from which the two-phase flow is supposed to enter the branch. This idea was originally developed for annular flow, but Azzopardi & Whalley (1982) defined equivalent zones of influence for churn flow. In this way they were able to predict the flow split rather adequately, at least in the lower mass extraction regime (see also Lahey 1986).

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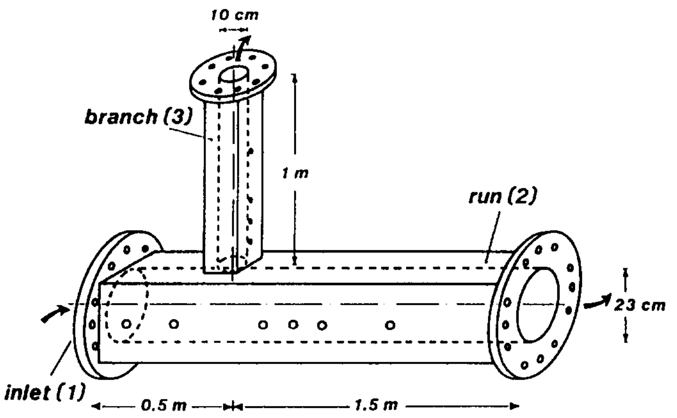

Figure 1. Definition and overview of the T-junction used.

In his Ph.D. thesis Zetzmann (1982) stated that at increasing mass extraction ratio (the mass fraction of the inlet flow that enters the branch, i.e. $\dot{m}_3/\dot{m}_1$) an increasing fraction of air, that enters the T-junction, enters the branch. He also considered the branch-to-inlet diameter ratio, D_3/D_1, to be the most important parameter in determining the phase redistribution. The influence of the diameter ratio was determined by several authors for different flow regimes (e.g. Azzopardi 1984; Azzopardi & Smith 1989; Shoham *et al.* 1989). All authors agreed that the phase redistribution is much more pronounced when a reduced T-junction ($D_3 < D_1$) is used. This effect is, however, much smaller at annular and stratified flow conditions (Azzopardi *et al.* 1990) than at other flow regimes. Lahey (1986) stated that the branch-to-inlet quality ratio x_3/x_1 is strongly affected by the mass extraction ratio $\dot{m}_3/\dot{m}_1$.

Several authors noticed that the orientation of the main pipe (inlet and run) of the T-junction does not exert a strong influence on the phase redistribution behaviour. Seeger *et al.* (1986) as well as Hwang *et al.* (1988) mentioned that data presented by Saba & Lahey (1984) in a horizontal T-junction quite closely resemble those of Honan & Lahey (1981) in a vertical T-junction, under essentially the same circumstances. Apparently, the inertia differences have a stronger impact than the gravity effects. However, in the case of a horizontal T-junction, the orientation of the branch has a rather large influence (e.g. Azzopardi & Whalley 1982).

2. MODELS FOR FLOW SPLIT PHENOMENA IN A T-JUNCTION

Various models for predicting the flow split and the pressure drop over the T-junction have been proposed. These models differ in many ways, but have one thing in common: none of them is generally applicable. All models have been developed and tested using small-scale test sections, and it is by no means clear if they are applicable for larger scales as well. Lahey (1986) stated that the models derived so far can be distinguished into three categories: theoretical, empirical and phenomenological flow regime based models. Theoretical models describe both the phase redistribution and the related pressure drop. These models comprise complete sets of conservation equations and invoke empirical correlations for closure only. Examples of theoretical models are those of Saba & Lahey (1984), Ma *et al.* (1990), Ballyk & Shoukri (1990) for annular flow, Hart *et al.* (1991) for separated flow with small liquid holdup and Lemonnier & Hervieu (1991) for homogeneous flow.

Models that are developed for predicting the *phase redistribution* only are generally empirical or phenomenological models. Two models based on geometrical considerations and flow regimes are those developed by Shoham *et al.* (1987) and by Hwang *et al.* (1988). An improved version of the latter was recently published by Kimpland *et al.* (1992). The "zone of influence model" of Azzopardi & Whalley (1982) can also be considered to be a phenomenological model. Several empirical models have been presented, generally giving expressions for the branch-to-inlet quality ratio x_3/x_1. They are all only applicable within strict limits. Zetzmann (1982) investigated a large area of interest for several T-junction geometries. Henry (1981) presented an empirical model for annular flow. For stratified flow in a horizontal T-junction with a small branch or break in the pipe, Reimann & Kahn (1984) and Smoglie *et al.* (1986, 1987) developed a number of correlations for predicting the flow split.

Seeger (1985; Seeger *et al.* 1986) proposed three empirical models for a horizontal T-junction with the three different branch orientations. For engineering purposes, Seeger recommended the following relationship for a straight T-junction ($D_3 = D_1$) with an upward directed branch:

$$\frac{x_3}{x_1} = \left(\frac{\dot{m}_3}{\dot{m}_1}\right)^{-0.8}. \qquad [1]$$

It might be expected that in a reduced T-junction, the phase separation may be more pronounced than predicted by [1]. The above equation may not be used at low values of $\dot{m}_3/\dot{m}_1$. Seeger stated that in the very low extraction region the branch quality $x_3 = 1$, which is supported by Reimann *et al.* (1988). The following equation was proposed to estimate the maximum value of $\dot{m}_3$ at which x_3 is still 1:

$$\dot{m}_{3,\mathrm{max,where}\ x_3=1} = c \cdot 0.23 \cdot A_3[gD_3(\rho_L - \rho_G)\rho_G]^{0.5}. \qquad [2]$$

In this equation, A_3 = branch cross-sectional area, $c = 0.5$ for bubbly flow and $c = 1$ for other inlet flow regimes.

Lahey (1986) stated that for the phase redistribution, the Azzopardi & Whalley (1982) model generally gives good predictions in the low mass extraction region, whereas the Saba & Lahey (1984) model is quite accurate for higher extraction ratios. He proposed a combination of these models, with in the intermittent region a maximum value of x_3/x_1, as given by Zetzmann (1982).

Pressure differences connected to a flow split in a T-junction, $(\Delta p_{12})_J$ and $(\Delta p_{13})_J$, are usually split into a reversible and an irreversible pressure drop (Collier 1976):

$$(\Delta p_{1i})_J = (\Delta p_{1i})_{J,\mathrm{REV}} + (\Delta p_{1i})_{J,\mathrm{IRREV}} \qquad [3]$$

(with $i = 2$ or 3).

In a single-phase flow split, pressure drops are calculated using well-known Bernoulli-type models:

$$(\Delta p_{1i})_{J,\mathrm{REV}} = \tfrac{1}{2}(\rho_i u_i^2 - \rho_1 u_1^2) \qquad [4]$$

and

$$(\Delta P_{1i})_{J,\mathrm{IRREV}} = K_{1i} \cdot \tfrac{1}{2}\rho_i u_i^2. \qquad [5]$$

In single-phase flow, generally $\rho_1 = \rho_i$. The loss coefficients K_{1i} represent all irreversible losses due to the T-junction, and are mainly dependent on the diameter ratio D_3/D_1 and the mass extraction ratio $\dot{m}_3/\dot{m}_1$ (e.g. Seeger 1985).

For two-phase flow, modelling is much more complicated. Generally, the two-phase pressure drop is modelled analogously to the single-phase pressure drop:

$$(\Delta p_{1i})_J = (\Delta p_{1i})_{J,\mathrm{REV}} + K_{1i} \cdot \tfrac{1}{2}\rho_L \overline{u_1}^2 \cdot \varphi. \qquad [6]$$

Note that, in this case, in the expression for the irreversible pressure drop the mean *upstream* two-phase velocity is used, rather than the *downstream* velocity used in single-phase flow.

The reversible inlet-to-branch pressure difference is usually modelled according to Lahey & Moody (1977). This model can be simplified considerably by assuming homogeneity in all three branches. This yields the following expression for the reversible pressure drop:

$$(\Delta p_{1i})_{J,\mathrm{REV}} = \tfrac{1}{2}\overline{\rho_i}(\overline{u_i}^2 - \overline{u_1}^2), \qquad [7]$$

in which the mean density is taken as the harmonic mean of the phase densities,

$$\overline{\rho_i} = \left[\frac{x_i}{\rho_G} + \frac{(1 - x_i)}{\rho_L}\right]^{-1}, \qquad [8]$$

and the mean two-phase velocity is defined as (S denoting superficial velocity):

$$\overline{u_i} = \frac{(\rho_G u_{GS})_i + (\rho_L u_{LS})_i}{\overline{\rho_i}}. \qquad [9]$$

The parameter φ in [6] is the so-called two-phase loss multiplier, which accounts for all extra irreversible pressure losses due to the interaction of the phases. For this multiplier, various models exist.

The simplest model for describing the *inlet-to-branch* pressure drop is obtained by simply assuming homogeneity in the inlet and the branch. This model is termed the *homogeneous model* and defines the two-phase loss multiplier as

$$\varphi = \frac{\rho_L}{\rho_i}. \qquad [10]$$

The friction coefficient K_{13} is taken from single-phase experiments (e.g. Miller 1990).

Several more complicated models for predicting the two-phase loss multiplier have been presented (e.g. Chisholm 1967; Reimann & Seeger 1986; Ballyk & Shoukri 1987) for low takeoff rates.

For the *inlet-to-run* pressure drop, similar models exist, but as in our experiments this pressure drop could not be investigated with sufficient accuracy, they are left out of consideration in this paper.

It should be remarked that, in the models mentioned above, the mass extraction ratio is treated as playing the role of an independent parameter. However, $\dot{m}_3/\dot{m}_1$ can be controlled only indirectly, as it is determined by equipment geometry and process conditions, such as bends, valves and inlet flows.

3. EQUIPMENT AND EXPERIMENTAL METHOD

The equipment built is shown schematically in figure 2. From the buffer tank (volume 12 m^3) water was pumped by a centrifugal pump. In a vertical section air was injected by means of a specially designed sparger (see below). The two-phase flow thus generated passed a bend and—by design (see below)—immediately entered the T-junction. After having passed the T-junction both the branch and the run flow were split into their respective liquid and gas flows in two horizontal separator vessels. The branch tank had a volume of 3 m^3, the run tank comprised 5 m^3. The water flowed back into the large buffer tank, while the air leaving the separator tanks was released into the atmosphere. The total size of the flow rig was approximately 10 (length) × 6 (height) × 3 (depth) m^3, the total equipment thus comprised several stocks of a construction framework.

The T-junction itself (see figure 1) had a horizontal upward orientation and a reduced diameter ratio. It was made out of perspex, in order to enable visualization studies. To minimize distortion

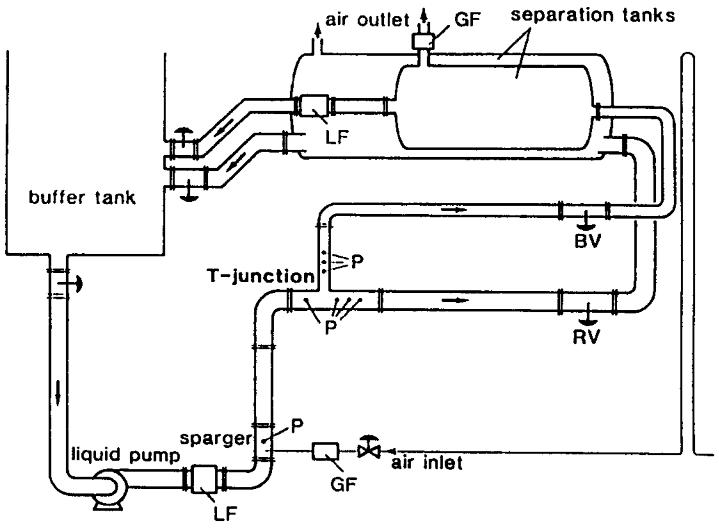

Figure 2. Overview of the experimental arrangement. LF = liquid flow meter; GF = gas flow meter; P = pressure transducer; RV = run valve; BV = branch valve.

problems the cylindrical tubes of the junction were put into square-shaped perspex boxes and the space between the tubes and these boxes was filled with demineralized water. The inlet-and-run consisted of a 2 m long, 23.0 cm inner diameter pipe, the branch (10.0 cm inner diameter) was 1 m long. The distance between the front end of the junction and the splitting point was 50 cm. Several pressure taps (P in figure 2) were made at different positions in the inlet, run and branch. These taps were fitted in such a way, that the front ends of the pressure transducers (Druck type PDCK 820) were flush with the inner surface of the tube. Special attention had to be given to the air inlet, as up to 60 Nm^3/h had to be injected and the bubbles should not be too large. No conventional ring spargers could cope with both these requirements without becoming unacceptably large. The sparger section used was machined out of PVC, in the shape of a venturi-tube. At the throat 50 holes (3 mm dia) were made, through which the air was injected into the venturi. In this way, a satisfactory mixing of air and water was accomplished, as could be easily observed since the pipe segment immediately following the sparger was made out of perspex as well.

The flow split was determined in the following way: two magnetically inductive flow meters (Altoflux type K300, LF in figure 2) were used to measure the inlet and branch water flows. The run liquid flow was taken as the difference of these two. The inlet and outlet air flows were measured with two gas mass flow meters (Brooks type 5813, GF in figure 2). By using two three-way valves it was possible to measure either the branch or the run gas flow.

The signals from the pressure transducers and the flow meters were read and processed with a Hewlett Packard workstation. The four flow signals were monitored continuously in order to detect disturbances from the steady state. Small problems could still have large consequences, as the equipment contained approx. 20 m^3 of water. In order to prevent the separator tanks from overflowing, liquid level switches were installed in these, which switched off the liquid pump in case of danger of flowing over.

The liquid superficial velocity was varied between 0.5 and 1.5 m/s (i.e. flow rates of 75 to 225 m^3/h), while the gas superficial velocity was between 0.05 and 0.15 m/s, resulting in inlet qualities of up to 0.03% (i.e. gas holdup up to 15%, since pressure within the equipment was slightly above atmospheric). The phase redistribution behaviour was investigated within the region of "interesting" takeoff rates, which in practice meant mass extraction ratios up to about 50%. All measurements were performed at room temperature and no special higher-pressure conditions were required.

Using flow maps (e.g. Spedding & Nguyen 1980) it could be expected that the flow regime in the inlet would be stratified in the lower liquid velocity region and bubbly in the higher. However, the main regime of interest was bubbly flow. To cope with this, a vertical pipe was built in the setup, just preceding the T-junction. As could be determined from flow maps, vertical flows with velocities within the ranges of interest would quite definitely be bubbly. Because the two-phase flow was sent through a bend and immediately entered the T-junction, it could be expected that at the splitting point of the junction the flow regime would still be bubbly flow. In this way, it was possible to study the flow split phenomena in bubbly flow circumstances at lower inlet velocities than required for creating fully developed bubbly flow. Obviously, the price paid for doing so is that from these measurements only a fair estimate of the pressure drops can be obtained.

A measurement series consisted of about 10 measurements at different mass extraction ratios. Each measurement was repeated 5 times and the results were averaged. During one series the inlet liquid and gas flows were kept constant, as it took a long time before a new steady state was reached after a small change in these. A desired mass extraction ratio could be established by adjusting the setting of the run and branch valves (RV and BV in figure 2).

4. RESULTS AND DISCUSSION

As the T-junction was made of perspex, a lot of visual observations could be made. As expected, the flow regime in the inlet was stratified or bubbly. At low superficial liquid velocity (generally stratified flow) the T-junction acted as an almost perfect phase separator, with only very small amounts of gas entering the run. At increasing "bubbly character" (i.e. mainly increasing inlet liquid velocity) of the flow, this separation behaviour decreased. It was possible to observe a "zone of influence", as in the upper part of the run directly behind the branch no gas was present.

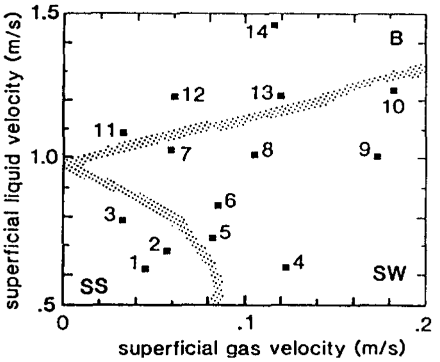

Figure 3. Flow map for the inlet-and-run, as obtained from observations. SS = stratified smooth; SW = stratified wavy; B = bubbly flow; ■, measurement series.

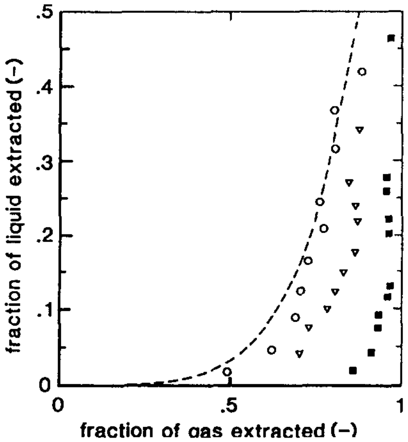

Figure 4. Decrease of phase separation behaviour with increasing liquid inlet velocity. ■, Series 5 ($u_{LSi} = 0.7$ m/s, $u_{GSi} = 0.08$ m/s); ▽, series 10 ($u_{LSi} = 1.2$ m/s, $u_{GSi} = 0.19$ m/s); ○, series 14 ($u_{LSi} = 1.5$ m/s, $u_{GSi} = 0.12$ m/s); ---, Seeger model.

Apparently all the gas in the corresponding inlet section had been extracted into the branch. At still higher liquid flow rates, it was possible to observe a "vena contracta" (see Reimann & Seeger 1986) in the branch, however not a very distinct one. Several secondary flows were observed by following bubble trajectories.

In the branch churn flow was present. At higher takeoff rates, no distinct zones of relatively high or low gas fraction could be observed. At decreasing mass extraction ratios, the branch flow changed into a more pulsating appearance, in which quite clearly intermittent zones of higher and lower gas fraction could be observed. Most likely this phenomenon indicated the onset of slug formation.

Phase redistribution measurements

By varying the inlet liquid and gas flows with the branch valve closed, a flow map for the horizontal inlet-and-run pipe was constructed. This flow map is given in figure 3. As mentioned, the regimes of interest were stratified (smooth and wavy) and bubbly flow. Measurements series were performed in all three regimes (see figure 3). The results of a few of the phase redistribution experiments are summarized in figure 4, which gives the fraction of liquid extracted into the branch, F_L, vs the fraction of gas diverted, F_G (a so-called *fraction plot*). In the figure, the Seeger model is given as a dashed line. At low inlet liquid velocity the phase separation is almost complete, as the plot is near to the "total separation line" (when all the gas flows into the branch, i.e. $F_G = 1$).

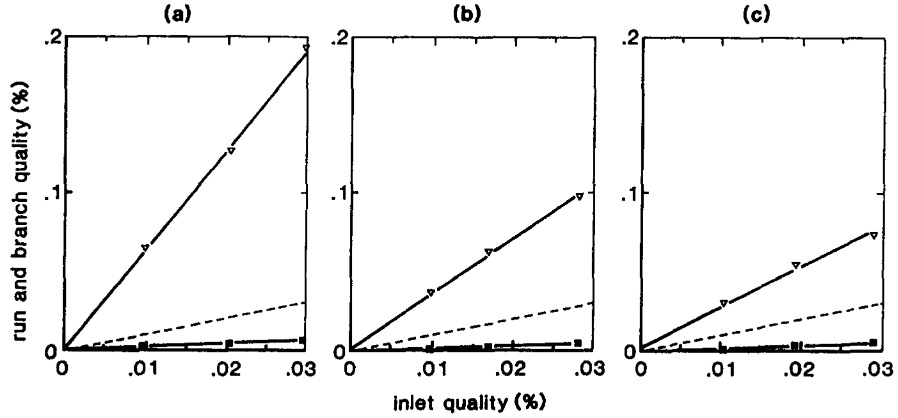

Figure 5. Illustration of the proportionality of x_3 (▽) and x_2 (■) with x_1. $u_{LSi} = 1.2$ m/s (series 10, 12 and 13); $\dot{m}_3/\dot{m}_1 = 0.13$ (a), 0.24 (b), 0.32 (c); ---, line of equal phase redistribution ($x_3 = x_2 = x_1$).

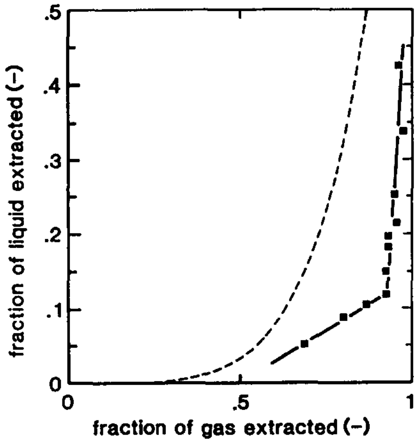

Figure 6. The pulsating branch effect: sharp kink in the *fraction plot*. ■, Series 9 ($u_{\mathrm{LSI}} = 1.0$ m/s, $u_{\mathrm{GSI}} = 0.18$ m/s).

At increasing inlet liquid velocity more and more bubbles stay in the inlet-to-run flow, and the data gradually move away from the $F_{\mathrm{G}} = 1$ – line in the direction of the Seeger model. This kind of behaviour in small T-junctions has been reported by several authors (e.g. Lahey 1986; Azzopardi & Smith 1989). At even higher inlet liquid velocities the phase redistribution may well be less strong than indicated by Seeger's model, as this model does not say much more than that the phase redistribution curves will be somewhat beneath the total phase separation curve. Seeger himself recommends the model "only for engineering purposes". The expression of Seeger for the maximum branch flow at which no liquid enter the branch [2], does not hold for this equipment. It was found that at constant takeoff rates, the branch and run quality are directly proportional to the inlet quality. This is illustrated in figure 5(a–c) and is in accordance with observations made by Zetzmann (1982) in a small T-junction.

A closer look at the fraction plots showed an interesting feature not mentioned before in the literature. When decreasing the takeoff rate ($\approx$decreasing F_{L}), at a certain point the deviation of the measurements from the total phase separation line quite suddenly starts to increase quicker than before. A clear example of this phenomenon is given in figure 6, in which a sharp kink in the plot is visible. The occurrence of this kink quite closely coincides with the earlier mentioned regime transition in the branch. The occurrence of this transition, which was rather sharp, could be noticed in two ways, using the pressure transducers in the branch: first, because the variance in the pressure signals increased considerably across the transition (by approx. a factor of 2.5); and second, because the appearance of the signals changed. The latter is shown in figure 7: the pulsating signal clearly contains a periodic component in the low-frequency region, whereas the non-pulsating signal does not. This can be illustrated quite clearly by means of the fast Fourier transforms (FFTs) of the signals (also in figure 7). The periodicity of the "pulsating churn" is shown very clearly by the presence of two distinct peaks in the FFT signal, which are not present at non-pulsating churn

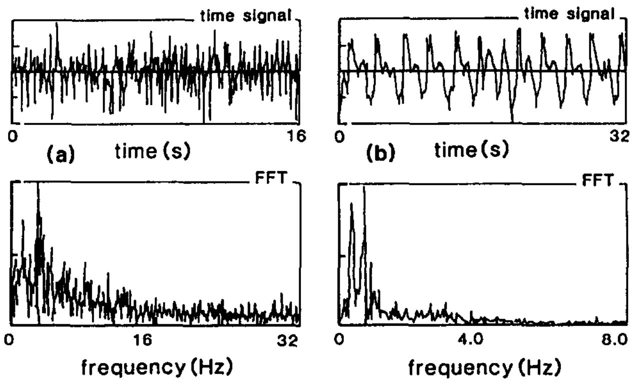

Figure 7. Characteristic churn (a) and pulsating churn (b) time signals and their FFTs (arbitrary units).

conditions. The peaks in the FFT of this "heartbeat signal" can be considered as eigenfrequencies of the system, and may depend on the properties of the fluids and the geometry of the T-junction and surrounding equipment. Most likely the equipment geometry downstream of the junction, in this case mainly the bend in the branch, has a strong impact on the occurrence of non-pulsating or pulsating churn. Notice that, in figure 4, kinks similar to the one in figure 6 can be observed.

When the flow split was examined visually and by means of video, it was observed that the pulsating of the flow in the branch was the cause of the decrease of the amount of gas flowing through the branch. Bubbles, that had initially entered the branch, were pushed back into the junction, where they were re-captured in the inlet-to-run flow and so eventually ended up in the run. Hence, this effect results in a considerable increase in the amount of gas flowing into the run. This phenomenon was named the *pulsating branch effect*. As mentioned, it was observed that the transition from non-pulsating to pulsating branch flow was rather sharp. One might expect that, at constant branch flow, this transition is independent of the *run* flow. However, additional experiments with the run valve closed showed that in the latter case the transition was much smoother, and the formerly user criteria in determining the regime transition showed a gradual increase in pulsating character as well. The reason for this difference is that when the run valve is closed all the gas and liquid is *forced* through the branch. When the junction actually operates as a T, at incipient pulsating conditions, the liquid, experiencing an increased flow resistance due to this pulsating, will flow into the run rather than into the branch. Hence the liquid flows into the run, which has the effect of reducing the branch flow resistance. This will result in a periodic increase–decrease in the inlet-to-branch flow resistance, an effect which cooperates with the incipient branch pulsations and thus will considerably narrow the transition. We presume that this narrowing is related to the frequency locking phenomena mentioned in the literature on non-linear dynamics (e.g. Jackson 1991). The behaviour mentioned above does show some resemblance to the observations of Azzopardi (1988) concerning the redistribution of annular flow in a vertical T-junction. He mentioned a sharp increase in the liquid fraction extracted (in this case flowing into the *branch*), if the *run* showed flow reversal or flooding phenomena. It should be noted that, due to the complex geometry, the position of the transition in a flow map for the branch does not coincide with the usual boundary for the slug–churn transition in vertical air–water upflow (Spedding & Nguyen 1980). Instead, it is located somewhere in the bubbly-slug regime.

Obviously, the downstream geometry is an important parameter in determining the occurrence of branch flow pulsation. This adds a new aspect to the knowledge of the redistribution behaviour, as up to now the regime in only the *inlet* was mentioned to be important in determining the flow split behaviour. It is expected that similar phenomena can be observed at smaller scale if the geometry is chosen accordingly. It should be realized that the pressure pulses caused by the pulsating flow propagate through the equipment in the downstream as well as in the upstream direction with the velocity of sound. As the average two-phase velocity is much smaller than the two-phase velocity of sound [which in this case is in the order of 30 m/s (see Wood 1941)], the pressure pulses can be felt upstream of their source. This was confirmed by the fact that the pressure pulses were registered by a pressure transducer in the sparger section, several meters *upstream* of the T-junction. This phenomenon could also be observed visually by means of the perspex part in the vertical pipe section following the sparger: at pulsating branch conditions the bubbles would enter the equipment in a pulsating way.

Pressure drop measurements

The *inlet-to-branch* flow showed a clear pressure drop, up to about 0.2 bar in the higher inlet velocity and higher takeoff region. This pressure drop is, on the one hand, due to irreversible pressure losses, but at higher takeoff rates the influence of the velocity increase should not be underestimated either. The measured inlet-to-branch pressure drop was corrected for the two-phase hydrostatic pressure difference and compared to the predictions made by the homogeneous model. In figure 8 typical results are shown, given in the form of a pressure drop ratio (defined as the pressure drop predicted by the homogeneous model divided by the measured pressure drop). It should be realized that neither the inlet flow nor the branch flow is fully developed. However, we believe that the data may be used to get a qualitative impression of the applicability of the small-scale models. In some cases, the pressure drop ratio curves show a rather sudden decrease

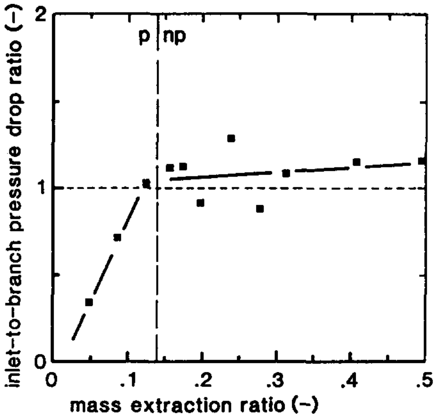

Figure 8. Comparison of measured inlet-to-branch pressure drop with predictions by the homogeneous model (■). p = Pulsating branch flow; np = non-pulsating branch flow; ■, series 12 ($u_{LSi} = 1.2$ m/s, $u_{GSi} = 0.06$ m/s).

similar to the kink in the fraction plots, as can be seen in figure 8. However, from our measurements this coherence cannot be concluded unambiguously. In figure 8, the transition from non-pulsating (np) to pulsating (p) branch flow is shown as the vertical dashed line. When comparing these data with similar results acquired with the homogeneous model at small scale, as given in, for example, Reimann & Seeger (1986), it can be observed that, even for this rather simple model and non-developed inlet and branch flows, the model renders large-scale predictions with comparable inaccuracy to those at small scale. The same observations go for the Chisholm model and the Reimann & Seeger model. On lowering the takeoff rate, eventually the homogeneous model gives too low predictions for the inlet-to-branch pressure drop. This is not in accordance with small-scale results (Reimann & Seeger 1986), in which at low mass extractions the models generally render too high predictions. This difference may again well be caused by the occurrence of the pulsating churn flow, which can lead to a considerable loss of energy, and thus an increase in the *mean* pressure drop. Furthermore, the pulsation itself can cause the *instantaneous* pressure drop (and thus the corresponding pressure drop ratio) to vary over a large range. This should be kept in mind when designing two-phase flow pipeline systems. At higher takeoff the pressure drop ratio apparently heads for unity, so it might be expected that at near-one extraction ratios the homogeneous model will render good predictions. This is in agreement with observations in small T-junctions, as mentioned in the literature (Seeger 1985). The inlet-to-run flow showed a pressure rise, varying in order of magnitude from about 100 Pa in the low inlet velocity region to about 1000 Pa in the higher. This can be attributed to the decrease in velocity due to the flow split. However, as the run length did not meet the criterion required for full flow development and the inlet-to-run pressure differences are rather small, no significant comments can be made about the predictability of small-scale models for the inlet-to-run pressure drop.

5. CONCLUSIONS

The experiments in the industrial-scale flow rig have extended the data bank on the two-phase flow split in a T-junction and have broadened the view on the phase redistribution phenomena occurring in two-phase flow in a dividing T-junction. The use of pressure transducers in combination with computerized signal processing proved a powerful tool in characterizing two-phase flows, their transitions and the relation with flow split phenomena.

Whereas, to date, only the flow regime upstream of the T-junction was considered to be important in determining the phase redistribution, the experiments have revealed that the influence of the flow regimes downstream of the T-junction must not be underestimated. This is clearly illustrated by the "pulsating branch effect", as mentioned in this paper. The downstream geometry of the equipment plays an important role in this effect.

At low inlet liquid velocities, the T-junction acts as an almost total phase separator. With increasing inlet liquid velocity, the phase redistribution curve gradually moves towards the Seeger engineering model. The occurrence of pulsating churn flow in the T-junction has a strong impact on the mean inlet-to-branch pressure drop. The most simplified model predicts much too low pressure drops at low takeoff rates. Furthermore, due to the puslations, the instantaneous pressure drop can deviate even further from the predictions. As long as the mentioned pulsation effects do not occur, it is quite possible to describe large-scale flow split phenomena qualitatively using observations and models that have been developed using small-scale equipment, at least with comparable (in)accuracy.

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