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Brief communication

The effect of pressure on two-phase flow dividing at a reduced tee junction

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1. Introduction

Two-phase flow is encountered in many industrial applications such as the condensers and evaporators of refrigeration systems, conventional steam power plants, pressurized-water and boiling-water nuclear power plants, and in a wide variety of petroleum and chemical processing systems. In most, if not all, of these systems, the two-phase flow encounters dividing tee junctions as it passes through the system. Considerable research efforts in the recent past have shown that (a) in general the phases do not split evenly at the junction, (b) the manner in which the phases are distributed is a complicated function of the inlet flow rates, inlet flow regime, junction geometry and orientation, total mass split at the junction, and fluid properties, and (c) the existing models for predicting the pressure drop and phase distribution at dividing junctions are not yet adequate to handle all situations. A number of excellent reviews were reported by Azzopardi (1986), Lahey (1986), Muller and Reimann (1991), Azzopardi and Hervieu (1994) and Azzopardi (1999).

The experimental studies on this topic have succeeded in identifying important flow phenomena, either by visual observation or by deduction from the data analysis, that resulted in further refinement of the predictive models. Examples of the phenomena that were found to play important roles in the partition of the phases are: the ratio of the axial-momentum fluxes of the phases (Azzopardi and Whalley, 1982), film stoppage in horizontal annular flow and flooding in vertical annular flow (Azzopardi, 1988), the development of a hydraulic jump downstream of the junction for stratified/wavy flow at inlet (Azzopardi et al., 1988), and the suction applied to the liquid due to high-velocity gas flow in small-size branches for stratified/

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wavy flow at inlet (Walters et al., 1998). The identification of these phenomena emphasizes the importance of the experimental studies in furthering our understanding of this problem.

Walters et al. (1998) reported experimental data for the phase distribution and junction pressure drops of air–water mixtures at 1.5 bar in two reduced tee junctions. The purpose of the present investigation is to explore the effect of pressure on the phase distribution at a reduced tee junction. This was done by conducting experiments on one of the junctions tested by Walters et al. using air–water mixtures at 3.0 bar and nearly the same superficial velocities of gas and liquid at junction inlet.

2. Experimental

The experiments were conducted in a reduced tee junction with horizontal inlet, run, and branch sides using air–water mixtures. The inlet pressure at the junction was maintained at $P_1 = 3.0$ bar, and the temperature was near ambient. A brass piece was machined to produce a square-edged junction with inlet and run diameters $D_1 = D_2 = 38.1$ mm, and a branch diameter $D_3 = 7.85$ mm.

The flow loop was supplied with compressed air from a building supply line, and the air was passed through a filter, pressure controller, and turbine meter before entering the mixing tee. Distilled water was pumped into the flow loop from a reservoir tank and passed through a filter and turbine meter before entering the mixing tee. The two-phase mixture leaving the mixing tee was allowed to develop before passing through a visual section (where the inlet flow regime was observed). The mixture flowed through a further 41 pipe diameters before entering the tee junction. The run and branch streams leaving the junction were directed to individual separation tanks. The gas phase exited from the top of each separation tank and was metered by a separate bank of rotameters or turbine meters before exhausting to the room through silencers. The liquid phase flowed from the bottom of each separation tank and was metered by a separate bank of rotameters before returning to the reservoir tank. Thus, in each test, measurements were recorded for the gas and liquid mass flow rates in the inlet, W_{G1} and W_{L1}, respectively, the run, W_{G2} and W_{L2}, respectively, and the branch, W_{G3} and W_{L3}, respectively. Deviations between the inlet and outlet mass flow rates were within $\pm 6\%$ for both phases in all test runs. For more detailed description of the loop and the associated instrumentation, please refer to Walters et al. (1998) or Van Gorp (1998).

3. Results and discussion

The experimental investigation included 11 groups of tests with each group characterized by a given combination of J_{G1} and J_{L1}, where $J_{G1} = 4W_{G1}/(\pi D_1^2 \rho_{G1})$ is the inlet superficial gas velocity, $J_{L1} = 4W_{L1}/(\pi D_1^2 \rho_{L1})$ is the inlet superficial liquid velocity, ρ_{G1} is the inlet gas density, and ρ_{L1} is the inlet liquid density. A number of tests were conducted within each group by varying the extraction ratio W_3/W_1, where $W_3 = W_{G3} + W_{L3}$, and $W_1 = W_{G1} + W_{L1}$. The total number of tests in this study was 50, with measurements of the phase distribution and pressure drop due to the junction performed in each test (only the phase-distribution data are presented here). The inlet conditions for the 11 groups correspond to $2.7 \le J_{G1} \le 40$ m/s, and $0.0021 \le J_{L1} \le 0.0395$ m/s. According to visual observations, the present data correspond to three major flow regimes: stratified, wavy, and annular.

In presenting the phase-distribution results, special emphasis will be placed on discussing the possible phenomena (e.g., Bernoulli effect and axial-momentum effect) that could have played a major role in shaping the trend in the data. The axial-momentum effect predicts that the higher momentum phase will be less likely to turn the corner into the branch. Fig. 1 shows three groups of data corresponding to a stratified inlet flow regime with $J_{G1} = 2.7$ m/s and $J_{L1} = 0.0021$ m/s but different P_1 and D_3/D_1. In this figure, the data are presented in terms of the branch quality, $x_3 = W_{G3}/W_3$, versus the extraction ratio W_3/W_1. The ratio of inlet axial-momentum flux of gas and liquid $\dot{M}_{G1}/\dot{M}_{L1}$ was calculated for all three groups, where $\dot{M}_{G1}/\dot{M}_{L1} = (\rho_{G1}u_{G1}^2)/(\rho_{L1}u_{L1}^2)$, and u_{G1} and u_{L1} are the average inlet velocities of gas and liquid, respectively, based on the hold-up correlation of Spedding and Chen (1984). For the two data groups with $P_1 = 1.5$ bar, $\dot{M}_{G1}/\dot{M}_{L1} = 1.3$ was obtained, and the value $\dot{M}_{G1}/\dot{M}_{L1} = 2.6$ was obtained for the third group (with $P_1 = 3.0$ bar). Examination of Fig. 1 shows that the data group for $P_1 = 1.5$ bar and $D_3/D_1 = 1$ (reported earlier by Buell et al., 1994) has a trend consistent with the axial-momentum-flux effect. This data group has x_3 slightly lower than the inlet quality, $x_1 = W_{G1}/W_1$, which indicates a slight preference for the liquid to exit through the branch because $\dot{M}_{G1}/\dot{M}_{L1}$ is slightly larger than 1. However, the other two data groups in Fig. 1 do not seem to be impacted by the axial-momentum-flux effect. These two groups correspond to a small branch ($D_3/D_1 = 0.206$), and based on the void fraction α, calculated from Spedding and Chen's correlation ($\alpha = 0.979$), the gas–liquid interface is much lower than the branch entrance. Therefore, only gas was extracted in both data groups up to $W_3/W_1 = 0.3$. Beyond this extraction ratio, the gas flow in the branch produced an upward suction on the interface strong enough to entrain liquid into the branch. The combination of the interface location and the suction due to the gas flow in the branch is what we call here the "Bernoulli

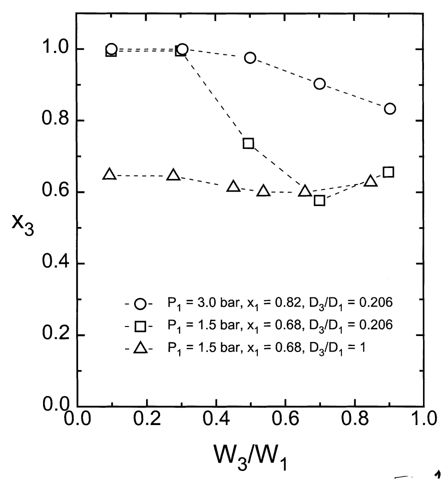

Fig. 1. Comparison between phase distribution data for $J_{G1} = 2.7$ m/s and $J_{L1} = 0.0021$ m/s at different values of P_1 and D_3/D_1.

effect". As we proceed beyond $W_3/W_1 = 0.3$, we note that x_3 drops faster in the data group with $P_1 = 1.5$ bar and $D_3/D_1 = 0.206$ (reported by Walters et al., 1998) than in the present data. This is because the mass flow rate of the gas is higher in the present experiment than in the experiment of Walters et al., both in the inlet and branch. The value of of x_3 appears to approach x_1 as W_3/W_1 approaches 1 for all data groups in Fig. 1. The evidence from Fig. 1 seems to suggest that the axial-momentum-flux effect did not play a major role in shaping the data trend for $D_3/D_1 = 0.206$, while the Bernoulli effect had a prominent role. The opposite is true for $D_3/D_1 = 1$.

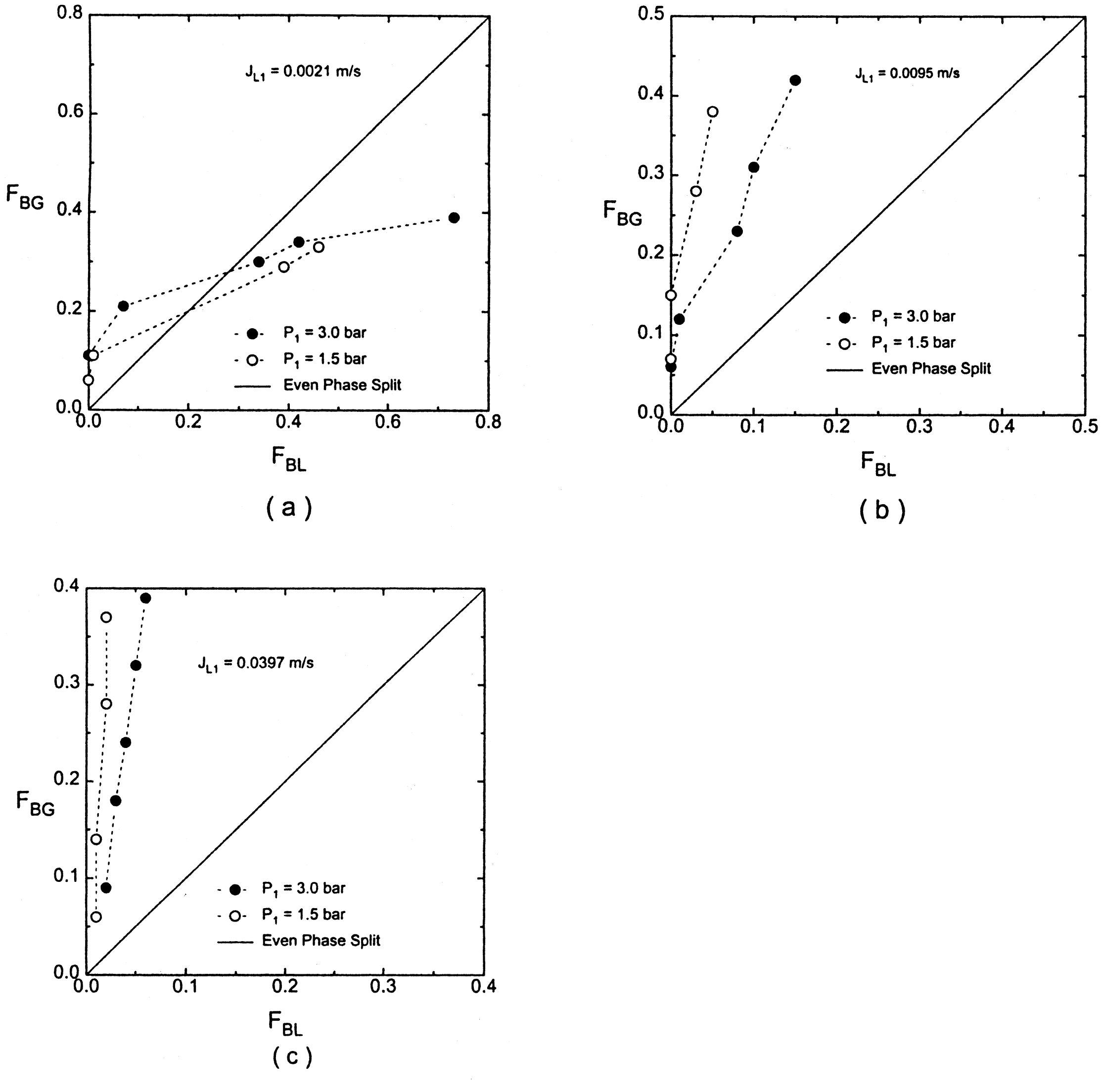

Fig. 2. Comparison between the present data ($P_1 = 3.0$ bar) and the data of Walters et al. (1998) ($P_1 = 1.5$ bar) for wavy flow with $J_{G1} = 10.8$ m/s.

Fig. 2 shows data for wavy flow from the present investigation and from Walters et al. (1998) corresponding to $J_{G1} = 10.8$ m/s and $D_3/D_1 = 0.206$. These data are plotted in terms of F_{BG} versus F_{BL}, where $F_{BG} = W_{G3}/W_{G1}$ and $F_{BL} = W_{L3}/W_{L1}$. The gas–liquid interface in the inlet side of the junction is well below the branch entrance in all these data, as predicted by the correlation of Spedding and Chen (1984). Fig. 2(a) shows that for both data groups, the branch intake is initially in the form of gas flow up to some value of W_3/W_1 beyond which liquid entrainment into the branch is initiated with a subsequent sharp increase in F_{BL}. There is no significant difference between the two data sets, which suggests that the difference in the axial momentum flux had no impact on the trend in this segment of data. In Fig. 2(b) and (c), both data sets show strong preference for the gas to exit through the branch with higher F_{BL}-values (at the same F_{BG}) in the present data than in the data of Walters et al. (1998). This increase in F_{BL} at the same F_{BG} is consistent with the following two effects: (a) the higher values of $\dot{M}_{G1}/\dot{M}_{L1}$ in the present data compared to the data of Walters et al. (1998), and (b) the higher suction on the interface due to the higher gas flow rate in the branch (at the same F_{BG}) in the present experiment compared to the experiment of Walters et al. (1998). Further study is required to determine whether one or both of these effects are applicable to the data in Fig. 2.

The data for annular flow are shown in Fig. 3. The low-momentum liquid film traveling along the wall is sucked into the branch more preferentially than the gas. This same trend was noted by Buell et al. (1994) for $D_3/D_1 = 1$ and by Walters et al. (1998) for $D_3/D_1 = 0.5$ at the values of J_{L1} and J_{G1} considered in Fig. 3. The effect of P_1 seen in Fig. 3 is very small; however, the data did not cover a wide range of W_3/W_1 due to the high values of branch-to-inlet pressure drop experienced during the experiment.

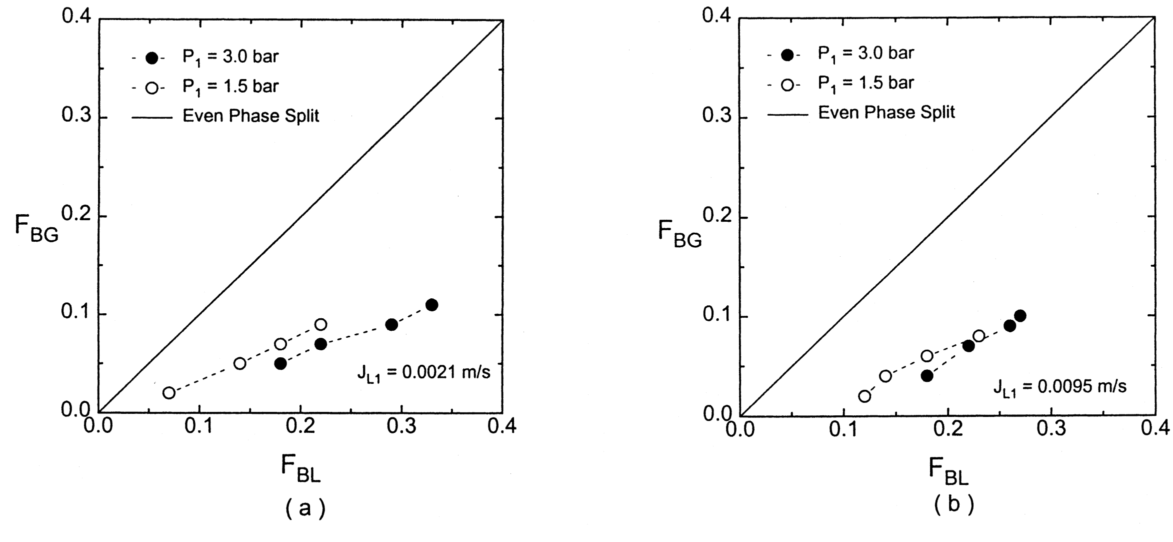

Fig. 3. Comparison between the present data ($P_1 = 3.0$ bar) and the data of Walters et al. (1998) ($P_1 = 1.5$ bar) for annular flow with $J_{G1} = 40$ m/s.

4. Concluding remarks

New experimental data have been generated for two-phase flow at a reduced tee junction ($D_3/D_1 = 0.206$) using air–water mixtures with a junction pressure of 3 bar. The data cover the three major flow regimes of stratified, wavy, and annular. These data, together with previously reported data from Walters et al. (1998) for the same J_{G1}, J_{L1}, and D_3/D_1, were used to investigate the effect of $\dot{M}_{G1}/\dot{M}_{L1}$ on the phase distribution. It was found that the upward suction on the interface, due to the Bernoulli effect, is a dominant factor in shaping the trend for the stratified and wavy data. For annular flow, the influence of system pressure was found to be small over the covered range of W_3/W_1.

It must be emphasized that the above conclusions are based on the values of P_1 and D_3/D_1 considered here. Totally different trends may prevail at other values of these parameters.

Acknowledgements

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