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Split of two-phase plug flow with elongated bubbles at a microscale branching T-junction

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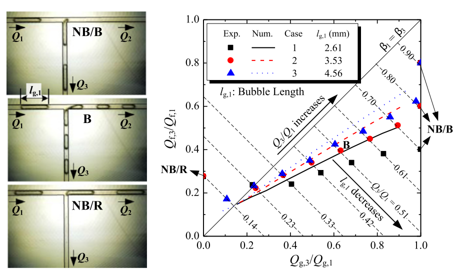
HIGHLIGHTS

- Phase-split ratio of plug flows at a micro T-junction was measured and predicted.
- Three distribution modes were identified for breakup and flow direction of bubbles.
- Flow mal-distribution was predominant with shorter bubbles and liquid-slugs.

GRAPHICAL ABSTRACT



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ABSTRACT

In the present work, the behavior of the elongated bubbles in two-phase plug flow at a microscale branching T-junction was studied both experimentally and numerically, and the effect of the bubble length on the split ratio of the gas flow to the branch was tested. The T-junction consists of a main, branch and a run with their cross section of 0.6 mm × 0.6 mm. Air and water were taken as the test fluids and the instantaneous motion of the nose, body and the tail parts of the bubbles at the T-junction region was examined in detail. Only the body part appeared longer with the longer bubbles while the shapes (and volumes) of the nose and the tail parts remained unchanged. When the body part occupied the T-junction region, the volumetric flow rates of the gas to the branch maintained constant and became almost equivalent to the total volumetric flow rate to the branch. (Similarly, when a liquid slug occupied the T-junction region, the volumetric flow rate of the liquid to the branch appeared the same with the total volumetric flow rate to the branch.) On the other hand, the volumetric flow rates of the nose and the tail parts to the branch varied drastically with time due to the complicated flow patterns around them. Thus, for given flow rates of the gas and the liquid phases at the main, the flow mal-distribution was more likely to occur with the shorter bubbles because the relative portions of the nose and the tail are larger in a unit cell, which consists of a bubble and a liquid slug. Hence, for accurate prediction of the splitting behavior of the two-phase plug flow at branching T-junctions, the length information of the unit cell is essential in addition to the flow rate of each phase at the main.

1. Introduction

When a gas–liquid mixture is introduced to a microscale channel with a moderate velocity, the plug flow is most likely to occur due to the surface tension effect, where the elongated bubbles are separated by liquid slugs and surrounded by a thin liquid film along the periphery. Similar flow regime is observed

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with immiscible liquid–liquid flows as well. For this flow regime, the mixing (Tanthapanichakoon et al., 2006), pressure drop (Kreutzer et al., 2005; Choi et al., 2011) and the heat transfer (Majumder et al., 2013) characteristics have been studied based on the regularity of the unit cell that consists of an elongated bubble and a liquid slug as depicted in Fig. 1. Thus, the behavior of the plug flows at the branching T-junctions (Ménétrier-Deremble and Tabeling, 2006; Azzi et al., 2010; Hong et al., 2010; He et al., 2011; Wolden, 2012; Chen et al., 2012, 2013; Wang et al., 2014) or at the impacting T-junctions (Link et al., 2004; Jullien et al., 2009; Leshansky and Pismen, 2009; Fu et al., 2011; Afkhami et al., 2011; Hoang et al., 2013; Bedram and Moosavi, 2013; Samie et al., 2013) could be well predicted by analyzing the dynamics of the unit cell, provided that the distance between the bubbles (or the length of the liquid slugs) is long enough to avoid mutual interaction between them. Here, the branching T-junction implies a straight channel with a perpendicular side arm, whereas the impacting T-junction has two downstream channels both perpendicular to the upstream channel but pointing out in opposite directions from each other (Chen et al., 2014). In the branching T-junction, the upstream and downstream parts of the straight channel and the side arm are termed to be the main, run and the branch, respectively.

For an immiscible two-phase flow at a symmetric and impacting T-junction, Link et al. (2004) showed that the volume fraction of two daughter drops was proportional to the fraction of total volumetric flow rates in downstream channels and resulted in even distribution of the drops as expected. However, with the impacting T-junctions, the breakup phenomenon of the drops has been the primary research interest. Link et al. (2004) reported that the drops are disintegrated by the Rayleigh–Plateau instability of the lubricating flow of the continuous phase between the drop and the wall, and a correlation for the critical drop length ($l_{\mathrm{d,cr}}$) was proposed in terms of the capillary number ($Ca=\mu_c j_1/\sigma$) through the scale analysis as follows:

$$Ca = a\,\frac{l_{\mathrm{d,cr}}}{\pi h}\left[\left(\frac{\pi h}{l_{\mathrm{d,cr}}}\right)^{2/3} - 1\right]^2 \tag{1}$$

On the other hand, Leshansky and Pismen (2009) argued that the pressure of the obstructed liquid (continuous phase) at the upstream of the impacting T-junction enhances necking (and hence breakup) of the obstructing drop. They proposed a power-law correlation for the critical drop length in terms of Ca as well as below.

$$\frac{l_{\mathrm{d,cr}}}{h} = b\,Ca^{-0.21} \tag{2}$$

Both correlations showed good agreement with the experimental results of Jullien et al. (2009) and Fu et al. (2011) for high-Ca flows, while the correlation of Leshansky and Pismen (2009) appeared better for low-Ca flows than that of Link et al. (2004). Later, Fu et al. (2011) presented an improved power-law relationship, similar to the correlation of Leshansky and Pismen (2009).

$$\frac{l_{\mathrm{d,cr}}}{h} = c\,Ca^{d} \tag{3}$$

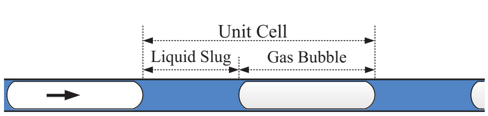

Fig. 1. Plug flow and a unit cell.

In the above three equations, a, b, c and d are the fitting parameters (to the measured data) which depend on the viscosity ratio of the fluids ($\lambda=\mu_d/\mu_c$) and the channel geometry. Regarding the numerical approach, VOF (volume of fluid) method is being widely adopted to track the interfaces between two immiscible fluids at impacting T-junctions with a reasonable accuracy, represented by the recent works of Afkhami et al. (2011), Bedram and Moosavi (2013) and Hoang et al. (2013).

In branching T-junctions, unlike the cases with impacting T-junctions, even distribution to the downstream channels cannot be achieved due to their inherent geometrical asymmetry. For gas–liquid two-phase flows, when all the bubbles approaching the T-junction are regularly broken up to the daughter bubbles, the time-averaged split ratio of the gas phase to the branch (or the run) becomes the same with the volume fraction of each single bubble separated out to the branch (or the run) and the unit-cell approach should be valid. For given flow rates of the gas and liquid in the main, the length of the unit cell (and hence the lengths of the bubble and the liquid slug) is inversely proportional to the bubble generation frequency, which is controllable by changing the geometrical configuration of the two-phase mixer at the far upstream (Garstecki et al., 2006; Yeom and Lee, 2011). By using this technique, Hong et al. (2010) and Wolden (2012) have shown a strong dependence of the distribution pattern on the upstream bubble length, where the plug flows with shorter bubbles resulted in a higher quality in the branch channel and the flow maldistribution became more prominent. The previous works on the flow distribution at the microscale branching T-junction mostly focused on the time-averaged split ratio (Azzi et al., 2010; Hong et al., 2010; He et al., 2011; Wolden, 2012; Chen et al., 2012, 2013), but it is worth looking into instantaneous behavior of individual bubbles based on the unit-cell approach and linking it to the overall behavior of the flow-distribution phenomena with the emphasis placed on the bubble-length effect. Regarding the bubble breakup at branching T-junction, the underlying physics should be the same with the case of the impacting T-junction and basic forms of Eqs. (1)–(3) may be valid as well. Hence, Wang et al. (2014) adopted those correlations for predicting the critical bubble length at the branching T-junction but with different values of a, b, c and d based on their own measurements, where the correlation of Fu et al. (2011) (Eq. (3)) was considered the best.

Thus, in the present work, the time-averaged split ratio of the two-phase mixture to the branch was measured and the behavior of individual bubbles was visualized for various bubble generation frequencies (i.e., bubble lengths). At the same time, the time evolution of the bubble motion was reproduced numerically and then the effect of the bubble length on the variation of the overall split ratio was examined.

2. Experimental method

An experimental setup for measurement of the split ratio to the branch and for visualization of the bubble motion at the T-junction region is illustrated in Fig. 2. The T-junction was made of acrylic materials for flow visualization, and the main, run and the branch channels had the square cross-section of 0.6×0.6 mm^2. The liquid (water) and gas (air) were introduced to the mixer inlets through separate syringe pumps (CHEMYX, Fusion 200 Infuse/Withdraw) at steady volumetric flow rates of $Q_{f,1}$ and $Q_{g,1}$, respectively; thereby the total volumetric flow rate in the main, Q_1, could be determined. To control the bubble length (i.e., bubble generation frequency) for given flow rates in the main, three different mixers (0.8×0.6 mm^2, 1.0×0.6 mm^2 and 1.2×0.6 mm^2, respectively) were adopted. Once the bubbles are introduced regularly to the main, they are distributed to the run and branch either by breakup