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Branching of two-phase flow from a vertical header to horizontal parallel channels †

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Abstract

The objective of the present experimental work is to investigate the two-phase flow distribution from a vertical main to parallel horizontal branches. Both the main and the branches have rectangular cross-sections simulating the header and the channels of the compact heat exchangers for air-conditioning systems. The cross section of the main is 8 mm × 8 mm while that of the parallel branches is 8 mm × 1 mm. Here, the second (downstream) junction was taken as the reference. The effect of the distance between the branches was mainly examined by changing it from 9 mm to 49 mm for the given flow conditions at the inlet of the downstream junction. Air and water were used as the test fluids. The superficial velocity ranges of air and water at the test section inlet were 13.2 – 21.4 m/s and 0.08 – 0.28 m/s, respectively. When the branch spacing becomes smaller, the fraction of liquid separation through the downstream branch decreases. The trend remains the same over the entire range of the present experiment, i.e., for different values of quality and the mass flow rate at the inlet of the downstream junction. Based on the correlation for single T-junctions, a modified correlation was proposed to take into account the effect of the branch distance in predicting the fraction of liquid separation. The correlation represents the experimental results within the accuracy of ±15 %.

Keywords: Annular flow; Parallel branches; Two-phase flow distribution; Prediction model

1. Introduction

Flow distribution from a header to parallel channels is becoming of interest in predicting heat transfer performance of compact heat exchangers. This is because flow distribution to the channels is not uniform and, occasionally, there is little flow through some of them. Especially with a two-phase flow, the situation becomes even worse. Related to this problem, Wu and Webb [1] estimated the performance of a brazed aluminum evaporator with three refrigerant passes. There, 24 horizontal flat tubes (1.8 mm × 26 mm) with 12 sub-channels (1.8 mm × 1.8 mm) were connected in parallel to the rectangular horizontal header (26 mm × 26 mm). R-404A entered the header and flowed through the tubes. Their estimated results over-predicted the performance of the three-pass evaporator by 8%, which was considered to be due to the flow maldistribution. Thus, they emphasized the header and pass (channel) arrangements should be designed to minimize the flow mal-distribution.

Fig. 1 shows a tube array of a compact heat exchanger. Osakabe et al. [2] considered the header-tube assembly simply as an accumulation of single T-junctions. This may be acceptable in their case because the distance between the tubes was large (130 mm) compared to the header (40 mm × 40 mm) and/or tube (D = 10 mm) sizes (hydraulic diameters), and the flow interaction between the junctions could be minor. In other words, the flow behavior at one junction had no influence on that at the next junction. On the other hand, for most of the compact heat exchangers, the distance between the parallel channels is comparable to or even small than the header size (hydraulic diameter).

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Thus, the flow interaction between the junctions has to be taken into account carefully. This effect becomes more prominent if the distance between the channels becomes closer. In addition, the hydraulic diameters of the channels of compact heat exchangers are much smaller than the cases with conventional-size heat exchangers, and dependence of two-phase flow behavior on the channel size should be taken into account.

Concerned with the flow distribution at small single T-junctions, Stacey et al. [3] and Lee and Lee [4] have performed experimental works. Stacey et al. [3] used a horizontal T-junction of the tubes with both diameters being 5 mm. Lee and Lee [4] tested three different sizes of horizontal branches (8 mm × 8 mm, 8 mm × 4 mm and 8 mm × 1 mm) with the cross-section of the vertical main being fixed to 8 mm × 8 mm. Both of them reported that the behavior of flow separation in small T-junctions appeared different from that in the large T-junctions, and Lee and Lee [4] proposed a simple model to predict the fraction of flow separation.

As for the flow distribution of single-phase fluid from a main tube to parallel branches, according to Azzopardi [5], if the distance between the junctions is less than three main-tube diameters, the flow interaction is expected. However, he noted that no such information was available for the two-phase flow cases.

Therefore, in the present study, as an extension work of Lee and Lee [4] with single T-junctions, the two-phase flow distribution from a vertical main (header) to parallel horizontal branches was examined through a series of experiments. Fig. 1 illustrates the header-channel configuration tested in the present study. Both the branches and the main have rectangular cross sections simulating the header and the channels of compact heat exchangers for air-conditioning systems. The experimental conditions were limited to the annular two-phase flow regime in the main.

This is because the two-phase flow pattern in compact heat exchangers is mostly annular. Then the measured data were compared to those of Lee and Lee [4] to check the effect of the distance between branches on the dividing two-phase flow, and a prediction model that the effect of the channel spacing can be taken into account was proposed.

2. Experimental setup

Fig. 2 illustrates the experimental setup. Air and water were used as the test fluids. Water was supplied from a reservoir pressurized with the building air, and water flow rate was controlled and measured by a calibrated rotameter. Air-flow rate was also measured by another calibrated rotameter. As shown in Fig. 2(a), water and air were introduced to the test section (the dotted portion in the figure) through a mixer (⑤) that consists of concentric tubes; air was passing through the inner tube while water was flowing through the outer tube (Fig. 2(b)). Therefore, an annular flow was

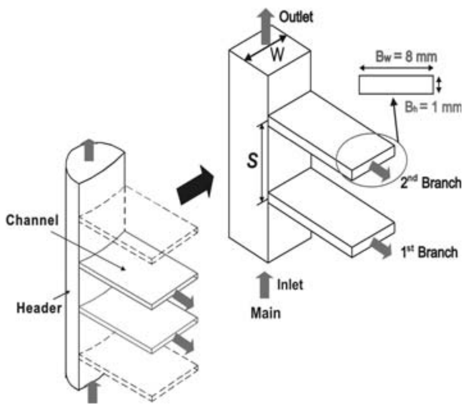
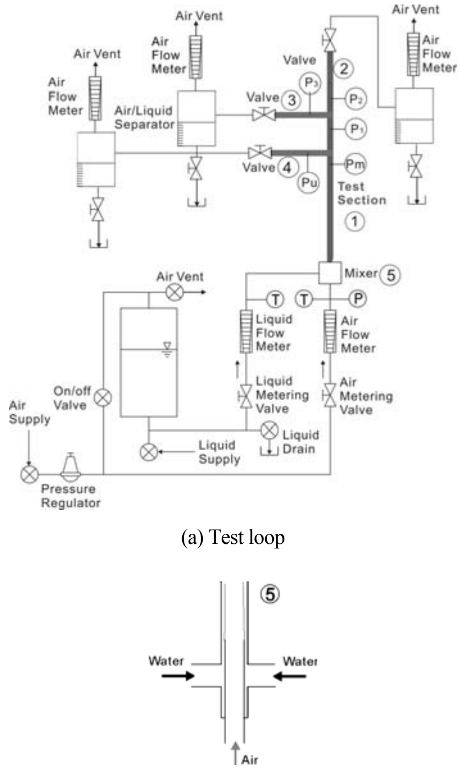


Fig. 1. Channel array of a compact heat exchanger.



(a) Test loop

(b) Mixer

Fig. 2. Experimental setup.

formed at the entrance of the test section. The test section is made of transparent acrylic plates for flow visualization. It consists of a 1 m-length vertical main (①), 600 mm-length run (②), and two 300 mm-length horizontal parallel branches (③, ④). The cross section of the vertical main is 8 mm × 8 mm while that of the parallel branches is 8 mm × 1 mm. Here, the effect of the distance between branches (S) was mainly examined by changing it from 9 mm to 49 mm as shown in Fig. 1.

In the present work, the second T-junction was chosen as the reference (point B in Fig. 3) because the flow disturbance propagates mostly in the downward direction and the backward flow disturbance (from the second T-junction to the first one) was considered insignificant. For given flow rates of air and water at the second inlet (i.e., for given values of W_1 and x_1), the valves at the downstream of the branches and the run were adjusted simultaneously to maintain the second junction pressure (i.e., P_1 at distance l = 4 mm upstream of the second junction point (B)) to be constant at 100 ± 5 kPa. Also, the pressures at the downstream of the both branches (P_3 and P_u at distance n = 39 mm from each junction point (A, B)) were set to be the same, ranging from 95 kPa up to slightly less than P_1 depending on the flow rates through them. The pressures were measured with differential pressure transducers (Validyne, P300D).

Thereby, for each inlet flow condition at the upstream (W_1, x_1), the flow rates through the branch (W_3, x_3) and the run (W_2, x_2) could be controlled with the valves at the downstream locations. The signals from the pressure transducers are amplified and sampled by using the data acquisition system (Data Translation, DT3001PGL) with the sampling rate of 200 Hz.

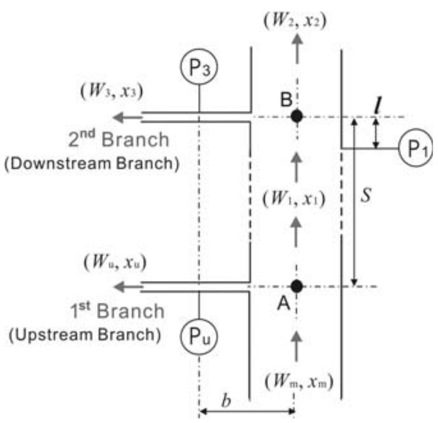


Fig. 3. Variables used in this study.

Air/water mixture passing through the branches finally flowed into the corresponding air/liquid separators. The air flow rates through each branch were measured by using the calibrated rotameters installed at the air vents of the air/liquid separators. The water flow rates were estimated from the volume of water collected at the bottom outlet of each separator for a given period of time.

Superficial velocity ranges of air and water at the test section inlet were 13.2 – 21.4 m/s and 0.08 – 0.28 m/s, respectively. The annular flow pattern could be maintained at the test section inlet in those flow ranges. The flow pattern was visualized and also confirmed with the flow pattern map of Troniewski and Ulbrich [6] that had been constructed to identify flow pattern in vertical rectangular channels with the hydraulic diameters ranging from 7.4 mm to 13.3 mm.

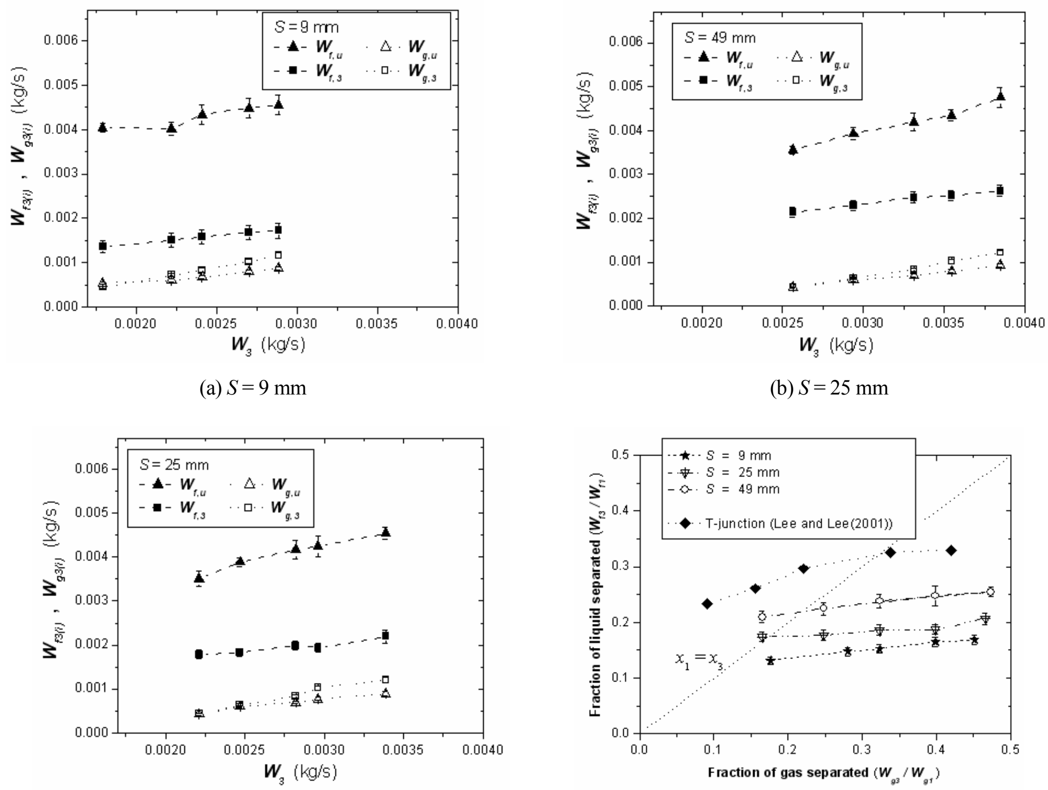
The uncertainty analysis was performed according to the method proposed by Kline [7]. The estimated uncertainties of the liquid and gas flow rates and the pressure measurement were ± 2%, ± 3% and ± 2%, respectively.

3. Experimental results

Fig. 4 shows the effect of the branch spacing (S) on the variations of the phase separation to each branch for various flow rates through the second (downstream) branch (W_3) under fixed inlet conditions (W_1 and x_1). As noted earlier, this can be achieved by controlling the valves at the downstream of the branches and the run simultaneously. Here, the open triangles and squares denote the air flow rates through the first and the second branches, and the solid triangles and squares represent the water flow rates through each branch. In general, both the air and liquid flow rates through the branches increase as the total flow rate through the second increases.

Also, the liquid flow rate is always lower at the second branch (W_{f3}) than at the first branch (W_{fu}) by fraction of about 0.5 – 0.7 while the gas flow rates remain approximately the same between two branches, and this trend is more prominent with the closer spacing between the branches.

In other words, the liquid flow rate through the second branch decreases with the closer branch distance. This is because, similar to the results by Lee and Lee [8], it is easy for the annular liquid (especially the portion of the liquid film at the branch-side wall) to flow out upon arrival at the entrance of the first branch,



(a) $S = 9$ mm

(b) $S = 25$ mm

(c) $S = 49$ mm

(d) Phase separation at the downstream junction

Fig. 4. Effect of distance between the channels (S) ($W_1 = 0.0128$ kg/s, $x_1 = 0.2$).

and the rest of the liquid flows through the subsequent branch with the smaller flow rate as it proceeds downstream.

To help understanding the trend of the flow distribution, the flow visualization result using high speed CCD camera (Phantom, Vision Research) with 2000 frames/sec is shown in Fig. 5, and Fig. 6 shows an illustration of the flow configuration. With the smaller branch spacing, there is smaller chance for the disturbed liquid film to be re-distributed to have a uniform thickness. This in turn tells that the quality in the second branch should be much higher than that in the first one, and again, it is prominent with a smaller distance between the branches as shown in Fig. 4(a)-(c).

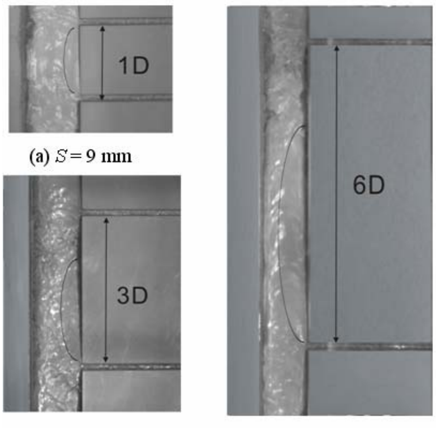
Fig. 4(d) shows the variations of liquid separation fraction (W_{f3}/W_{f1}) against gas separation fraction (W_{g3}/W_{g1}) from the main to the second branch for different branch spacing. The straight line in the figure represents the case with the same fraction of separation at the second T-junction; in other words, the quality at the second branch (and also at the run) is the same with that of the main flow, i.e., $x_1 = x_3$. The graph shows that the liquid separation fraction decreases with the smaller branch spacing, and far more deviates from the single T-junction case reported by Lee and Lee [4].

That is, with the larger branch spacing, the flow distribution at T-junctions can be predicted as single T-junction without any serious error, as easily imagined.

Similar trends were observed with different inlet quality (x_1) and liquid mass flow rate (W_{f1}) conditions.

For example, in Fig. 7(a) and 7(b), the fraction of liquid separation decreases as the distance between the branches becomes closer, regardless of the inlet quality. Another thing to note is that, within the range of the present quality condition (x_1 = 0.15 – 0.25), the liquid separation fraction little changes with quality.

This trend is similar to the results for single T-junctions reported earlier by Lee and Lee [4]. Again, the fraction of the liquid separation becomes smaller with the closer distance between the branches for each liquid flow rate at the inlet, as seen in Figs. 8 (a) and 8 (b).



(a) $S = 9$ mm (b) $S = 25$ mm (c) $S = 49$ mm

Fig. 5. Flow visualization ($W_1 = 0.0128$ kg/s, $x_1 = 0.15$).

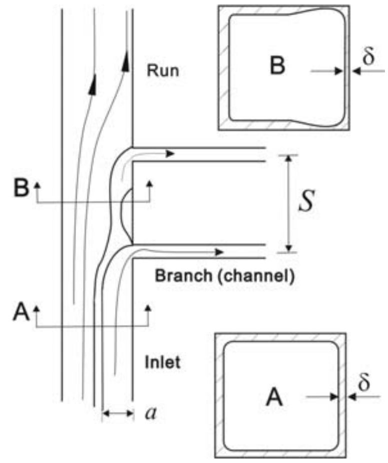
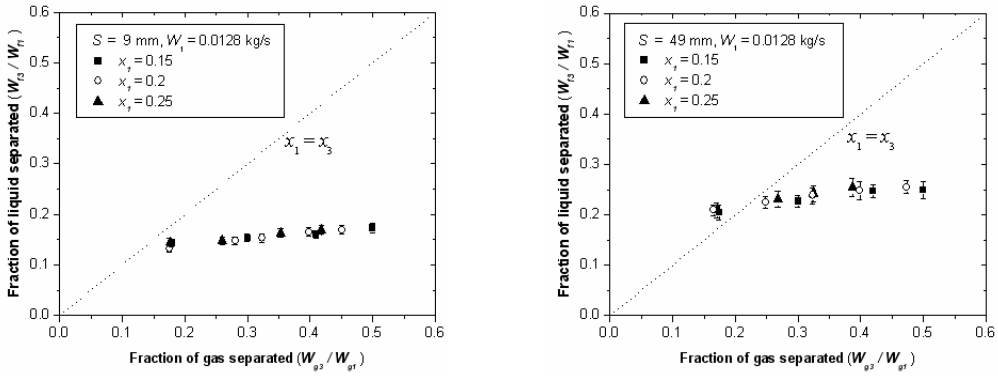
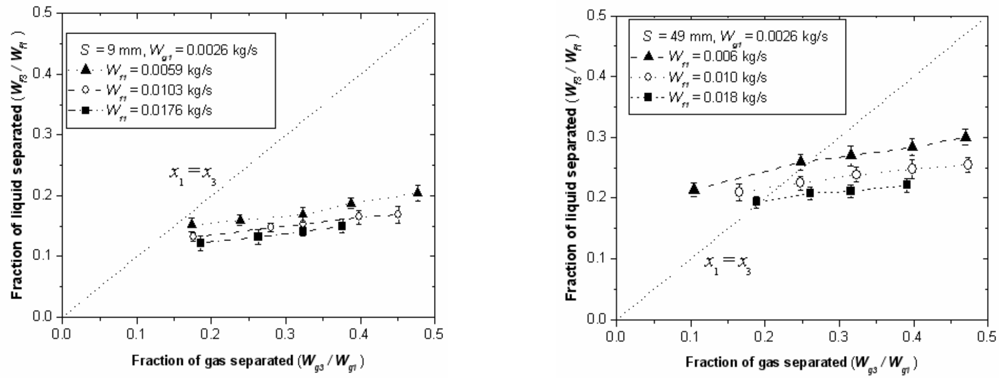


Fig. 6. Schematic flow configuration.



(a) $S = 9$ mm (b) $S = 49$ mm

Fig. 7. Effect of the inlet quality (x_1) ($W_1 = 0.0128$ kg/s, $x_1 = 0.15 - 0.25$).



(a) $S = 9$ mm (b) $S = 49$ mm

Fig. 8. Effect of the liquid mass flow rate (W_{f1}).

Also, the fraction of the liquid separation decreases with the higher liquid flow rate at the inlet; and the trend is similar to the cases of single T-junctions reported by Stacey et al. [3] or Lee and Lee [4]. This is because, due to the larger liquid momentum (inertia) at the inlet, the liquid tends to pass by the junction point to the run.

4. Analysis

4.1 Validation of the measured data

In this section, in order to confirm the validity of the present experimental results, the dividing flow at the first branch is compared to that at the single T-junction, previously reported by Lee and Lee [4].

Prior to their work, there had been several models available to predict the flow separation at dividing T-junctions, such as Azzopardi and Whalley [9], Azzopardi [10], Shoham et al. [11] and Hwang et al. [12], which were basically developed for diameters ranging from 32 mm to 127 mm.

However, as the junction size becomes smaller, more fraction of liquid is separated into the branch; this is because, according to Stacey et al. [3] and Azzopardi [13], the increase of the liquid fraction separation to the branch for small T-junctions is due to less entrainment of the liquid phase to the core-gas flow in the main.

At the same time, Lee and Lee [4] reported that the previous correlations for the T-junctions were not applicable to the smaller ones.

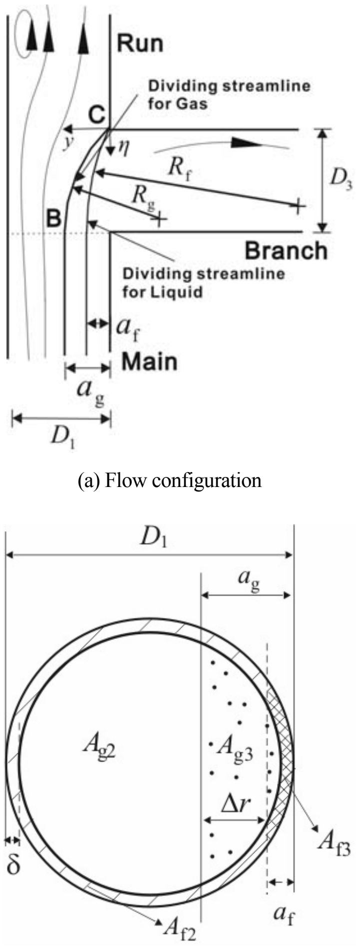
Thus, Lee and Lee [14] have checked the validity of those models for two-phase annular flow at small, dividing T-junctions (less than 10 mm in hydraulic diameter) using the experimental data by Hong [15], Stacey et al.[3] and Lee and Lee [4].

Fig. 9 illustrates the flow configuration considered based on the model by Hwang et al. [12].

In this figure, the dividing streamlines of the liquid and the gas flows are shown with their radii of curvature being R_f and R_g, respectively.

Previously, Azzopardi and Whalley [9] introduced the concept of “zone of influence” and assumed the boundary lines of the liquid and gas flows are the same, i.e., $a_f = a_g$.

Here, when a part of the gas flow is split to the branch, the zone of influence is formed, and accordingly, a portion of the liquid flow that belongs to that zone is also extracted from the main tube. The liquid flow through the branch is mainly from the



(a) Flow configuration

(b) Cross section of main tube

Fig. 9. Illustration of flow distribution based on the model by Hwang et al. [12].

film portion in the main tube rather than from the entrained drop-flow in the core portion because the liquid film has a lower velocity (momentum) than the liquid drops.

Therefore, the proportion of the liquid film entering the branch was considered dependent simply on the gas flow rate flowing into the branch.

Later, Azzopardi [10] modified the model of Azzopardi and Whalley [9] to take account of the effect of the diameter ratio between the branch and the main tube, D_3/D_1.

Based on a similar physical concept, Shoham et al. [11] introduced a flow-pattern-dependent model to extend the applicable range to the larger dividing ratio (take off), W_3/W_1. The model considers the inertial, centrifugal and damping forces on the liquid film having a boundary line, a_f, with no liquid entrainment to the gas stream, and the dividing gas streamline has an arc shape with the radius of curvature R_g.

This model has an advantage of discriminating the liquid boundary line from the gas boundary line, and an appropriate correlation for Δr (= $a_g - a_f$) was proposed.

To estimate the dividing ratio, the liquid film thickness should be given somehow, and Shoham et al. [11] adopted the model by Taitel and Dukler [16] to get this. The model works well for large T-junctions, as tested by Azzopardi [17].

Hwang et al. [12] proposed a model similar to that of Shoham et al. [11], but with a different approach in obtaining the dividing streamlines for the gas and the liquid flows, as illustrated in Fig. 9.

For an annular flow, the accelerational and interfacial drag forces were considered negligible, and only the centrifugal force was considered important.

Finally, they derived a correlation for R_g / R_f as:

$$\frac{R_g}{R_f} = \frac{\rho_g U_g^2}{\rho_f U_f^2} = \left(\frac{a_f}{D_1}\right)^{n_f} \Bigg/ \left(\frac{a_g}{D_1}\right)^{n_g} \tag{1}$$

where

$$n_k = 5 + 20\exp\{-53(a_k/D_1)\}$$
$$\text{(k = g (gas) or f (liquid))} \tag{2}$$

Again, in this model, the film thickness and entrainment rate should be determined to predict the fraction of the flow split to the branch. Lee and Lee [14] adopted the approach of Whalley [18], where the interfacial friction factor (or roughness correlation, Ambrosini et al. [19]), triangular relationship (Asali et al. [20]), and entrainment correlation (Hewitt and Govan [21]) were considered.

The model of Hwang et al. [12] was considered to represent the measured results by Hong [15], Stacey et al. [3] and Lee and Lee [4] within the range of -10% and +25% as indicated by open symbols in Fig. 10.

In the same figure, the present results (dividing flow at the first branch) were plotted with the solid symbols. This shows the relevance of the present results staying within the same error range.

This is because the streamline shapes are better represented by the Hwang et al.'s model in describing the dividing flow configuration at the junction.

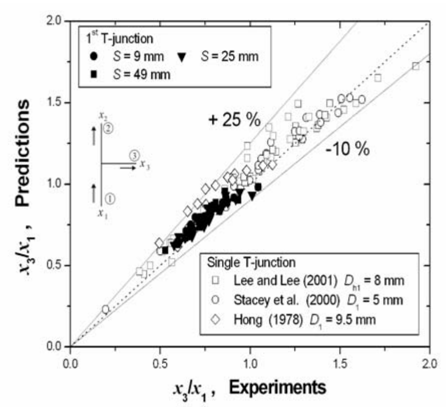


Fig. 10. Prediction of the flow distribution at the upstream branch (channel).

4.2 Prediction of the flow distribution at the downstream T-junction

As noted earlier, the fraction of the liquid separation to the second branch decreases with the smaller branch spacing, and far more deviates from the single T-junction case reported by Lee and Lee [4].

In other words, with large branch spacing, the amount of the flow split can be predicted using the single T-junction model without any serious error, as easily imagined.

Therefore, the effect of the branch spacing can be taken into account in predicting the flow split to the parallel branches by modifying Eq. (2) originally proposed by Hwang et al. [12] as:

$$n_k = C \cdot \left\{5 + 20\exp\left[-53\left(\frac{a_k}{D_1}\right)\right]\right\} \tag{3}$$

where C considers the upstream junction effect .

In this equation, C should be unity when the distance between the branches becomes very large, and should be smaller as the branch distance (S) decreases.

Hence, it may be reasonable to have a form of

$$C = 1 \quad \text{(upstream T- junction)} \tag{4}$$

$$C = \left(1 + 47\frac{B_h}{S}\right)^{-0.43} \quad \text{(downstream T-junction)} \tag{5}$$

obtained through the data regression process.

Eqs. (3)-(5) well represent the measured results for the upstream (Fig. 10) and the downstream junctions (Fig. 11).

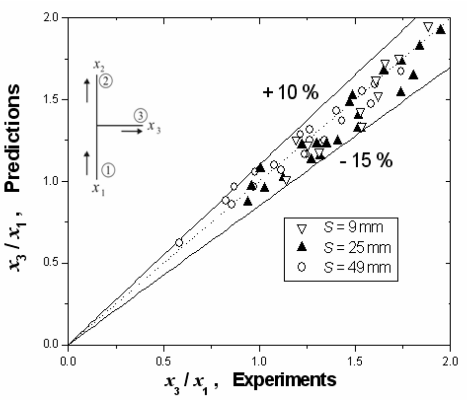


Fig. 11. Prediction of the flow distribution at the branch (channel).

5. Conclusion

With the smaller branch spacing, the liquid flow rate (and hence, the total flow rate) through the downstream branch becomes smaller because the distance between the branches is not large enough for redistribution of the liquid film disturbed by the upstream branch.

Also, a fraction of the liquid separation decreases with the decrease of the branch spacing. The trend remains the same regardless of the inlet quality and the liquid flow rate.

A correlation for the liquid dividing line was proposed to take account of the branch distance effect in predicting the liquid separation fraction within the accuracy of ± 15% by modifying the correlation proposed by Hwang et al. [12].

Acknowledgments

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