Phase Split Characteristics of Slug and Annular Flow in A Dividing Micro-T-junction^{*}

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ABSTRACT

The characteristics of slug and annular gas–liquid two-phase flow when moving through a rectangular micro-channel dividing T-junction were investigated with experiments focusing on the relationships between the phase split and the two-phase superficial velocity, liquid surface tension, and liquid effective viscosity. The effects of the pipe sizes and pipe cross section shapes on phase split were compared and analyzed. Phase split was tested using a $100 \times 800 \mu\text{m}$ rectangular dividing micro-T-junction. Air was used as the gas medium and the liquid mediums were water, 0.01% SDS solution, 0.5% SDS solution, 0.1wt%PAAm, 0.25wt%PAAm, and 0.5wt%PAAm. Results showed that whether the inlet flow pattern was slug or annular flow, the liquid taken off from side branch at the dividing T-junction decreases with an increase in liquid superficial velocity and that there is little effect of inlet gas flow rate on the liquid taken off. It was also found that the liquid taken off from side branch decreases with a decrease in liquid surface tension and increases with an increase in liquid effective viscosity. When results were compared to those from studies using channels of other diameters, it was seen that the phase split of the slug flow was similar at different sized dividing T-junction, while the phase split of annular flow varied at different pipe sizes. It was also seen that the phase split characteristics of a dividing micro-T-junction are dependent on the aspect ratios of the channel's cross section. A predictive model of phase split characteristics studied in this investigation was formulated with the regression analysis of the experimental data and verified by calculations showing little error.

Keywords: micro-T-junction; slug flow; annular flow; phase splitting

1. Introduction

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During gas–liquid two-phase flow through a T-junction, a component used in almost all pipeline systems, the liquid and the gas move through the side branch and main branch at different levels, creating a phenomenon called current bias or phase split. T-junction phase split in gas-liquid two-phase flow was first observed and studied in the 1960s in oil exploration and nuclear power. Research on the phenomenon hoped to prevent damage to downstream equipment when a T-junction was used as a simple fluid divider. Researchers also hoped to provide an effective means to use a junction as a partial phase separator. These goals make it essential to understand and predict the flow behavior of a mixture at the junction when using different equipment and facing fluctuating operating conditions [1]. However, the characteristics of flow pattern and heat transfer in microchannels have are significantly different from the flow phenomenon of small channels or conventional channels because the influence of the fluid viscous force and inertia force caused by surface tension are more prominent. The gravity and channel orientation can have a big impact in larger channels, but the effects are negligible at a micro-scale. These flow and force factors show how existing models of two-phase flow cannot be directly applied to two-phase microfluidic devices; hence, many experiments have been carried out by researchers to obtain a better understanding of flow patterns and resultant heat transfer in microfluidic devices.

At present, experimental studies have revealed that factors such as inlet velocity, pipe size, and liquid viscosity can all significantly influence T-junction phase split of gas-liquid two-phase flow. The fluid dynamics and the distribution of gas and liquid vary at different flow patterns, making them one of the most important factors in determining the characteristics of the phase split [2-5]. Thus far, scholars have tested the effects of many flow patterns on phase split. Mak *et al.* [6] studied the effects of using a 5 mm pipe diameter on a T-junction. The results showed that the influence of the inlet velocity of gas on the phase split is small. The conclusions reached by Fukano *et al.*[7] are almost the same. However, experiments conducted by Azzopardi *et al.* [8] revealed that the amount of liquid moving down the side branch increases with a decline in inlet velocity of gas. The results suggested that reduced entrained liquid and increased liquid film flow resulting from the decline in gas velocity were related to increases in the levels of liquid traveling down the side branch. Given that the entrained effect in a small channel is low, inlet gas velocity does not affect the liquid taken off from the side branch. In addition, the liquid in the side branch increases with the decrease in liquid velocity, consistent with the conclusions drawn in Azzopardi's experiment. The entrained liquid can be significantly reduced when the liquid velocity is reduced, leading to increases in liquid film flow and liquid in the side branch. Azzi *et al.* [9] and Mak *et al.* [6] found that pipe size does not affect phase split of slug flow in a T-junction. Azzi *et al.* also found through derivation that the ratio of the length of liquid slug to the whole length of slug flow is not related to pipe size, which is another indicator that pipe size does not affect phase split of slug flow. Stacey *et al.* [10] found that in annular flow, liquid in the side branch of a T-junction increases with decreased pipe size due to how liquid shares space with gas in annular flow at these pipe sizes. Das *et al.* [11] found that pipe diameter has no effect on the phase split of stratified flow, but that liquid viscosity has a significant influence. Hong [12] experimented on the phase split of a two-phase flow of air and

non-Newtonian fluid in a 9.525 mm T-junction. Wang *et al.* [13] used a 0.5 mm T-micro-pipe and saw liquid in the side branch increase with increased liquid viscosity. It was proposed that because internal friction resistance increases, the inertia force of liquid is abated, causing liquid levels in the side branch to grow. He *et al.* [14] compared the square cross section of a 500 μm T-junction with a circular cross section and saw that the square T-junction has more liquid taken off at slug flow and slug-annular flow. It happened more slowly at annular flow, with more gas taken off in a square T-junction due to the cross-section effect. Khandelwal *et al.* [15] studied the laminar flow of non-Newtonian shear-thinning fluids in a T-junction and found that with the corresponding power-law index, the length of the recirculation zone increases in the side branch with increasing R_e . Liang *et al.* [16] found that equal distribution of gas-liquid two-phase flow can be achieved and the fractions of gas and liquid taken off are independent of gas and liquid superficial velocities, flow patterns and nozzle positions.

This study aims to provide additional research on the phase split in rectangular dividing micro-T-junctions. Most gas-liquid two-phase flow experiments have used conventional micro-tubes because of limitations of visualization and fabrication, but there are more variables with conventional micro-tubes than there are with rectangular ones.

In this study, a PMMA rectangular micro-channel was constructed using MEMS (Micro-Electro-Mechanical System) fabrication techniques allowing phase split to be observed in a well-controlled environment. The effect of basic factors on phase split, including the inlet flow pattern, two-phase superficial velocity and liquid surface tension, liquid viscosity were studied, as well as the effect of pipe size and aspect ratios of pipe cross sections were compared and analyzed. A predictive model of phase split characteristics studied in this investigation was formulated with the regression analysis of the experimental data and verified by calculations showing little error. Data and conclusions obtained in this study hope to contribute to the establishment of the theory of phase split in micro-channels, and also provide theoretical guidance and technical support to allow suitable heat and mass transfer in micro-channels.

2. Experimental setup

The dividing micro-T-junction used in this experiment is shown in Fig. 1. The material used in the experimental section is PMMA, and the channel cross section is rectangular and measures $100 \times 800 \mu\text{m}$. The length of the entrance for the gas and liquid is 1 cm, the mixed section is 2 cm, and the length of the main and side branches are both 1 cm.

The experiment's system, shown in Fig. 2, used a SDS-MP09 micro-channel injection pump for the water and gas with a FA2004A electronic balance measuring the liquid flow of the branch pipe, micro pressure transducer for measuring the pressure in the micro-channel and a D-600MD digital mass flow controller measuring the gas.

The two-phase flow images were digitally recorded using a SpeedCam Visario system, which is a charge-coupled device camera system developed by Weinberger (Switzerland). This system has a maximum

resolution of 1536 pixels $\times$ 1024 pixels and a frame frequency of 10000 frames/s. However, given that a high-resolution camera has high light-source requirements, this experiment adopted a resolution of 512 $\times$ 192 pixels and a frame frequency of 1000 frame/s.

Fig.1 Dividing Micro-T-junction

The gas used in this experiment is air, and the liquids are pure water, 0.01% SDS solution, 0.5% SDS solution, 0.10wt% PAAm solution, 0.25wt% PAAm solution, and 0.50wt% PAAm solution. The properties of the fluids are listed in Table 1. The surface tension of fluid and the liquid-liquid interfacial tension were measured by using the surface tension instrument in the Pendant Drop method. The fluid viscosity of fluid was measured in a rheometer. All tests were conducted at 25 ± 0.5 °C and atmospheric pressure.

Table 1 Properties of the fluids used in the gas-liquid two-phase flow experiments (standard state)

Working fluid	Density, $\rho/\text{kg} \cdot \text{m}^{-3} \times 10^3$	Surface tension, $\sigma/\text{mN} \cdot \text{m}^{-1}$	Consistency index, $k/\text{Pa} \cdot \text{s}^n$	Flow Index, n
pure water	1.000	72.00	1.000	1.000
0.01%SDS solution	1.000	48.60	1.000	1.000
0.50%SDS solution	1.000	33.12	1.000	1.000
0.10wt%PAAm	1.000	71.20	0.3237	0.4853
0.25wt%PAAm	1.000	70.50	1.056	0.4097
0.50wt%PAAm	1.000	69.80	2.632	0.3610

The liquid and gas were pumped by the micro-channel injection pump, metered, and introduced into a mixer. The flow rates of the gas and liquid were also controlled by the micro-channel injection pump. Within the micro-channel, the pressure was measured by pressure transducer, when the gas and liquid mixing surpassed 20 mm, they were redistributed at the T node. This process was recorded by the high-speed camera.

In order to measure how much liquid can be taken off the side branch, the division of the gas flow was controlled by coordinately adjusting electromagnetic valves in the mass flow controller on the two outlet pipes. This means that the fraction of gas taken off is adjustable. For each case, we could get gas and liquid removed as needed for better run conditions. After redistribution, the two-phase fluid flowed through two length-adjustable

flexible tubes with inner diameter of 500 μm into two separators which were made by cylindrical vessels. The liquid was then diverted to a graduated vessel. A high-precision electronic balance was used to measure the liquid velocity after separation, and the total mass was measured within 3 min. The gas separated from the two separators flowed through the digital mass flow controller, which measures the gas velocity. A bubble flowmeter designed by Azzi *et al.* [9] was used for further measurement and monitoring in this experiment. This bubble flowmeter was a modified burette, whose tap had been replaced by a rubber bulb partially filled with soapy water. The gas entered just above the rubber bulb. When we squeezed the rubber bulb, it produced a bubble that occupied the entire cross-section of the channel. The bubble was pushed up by the gas flow. According to the time taken for the bubble and the distances of the bubble moving up, the gas flow rate can be determined. In each trial, the mass balance between the inlet and outlet was checked to assure that there was no leakage in the whole experimental section.

The following formulas were used to calculate the amounts of gas and liquid moving through the channels:

$$F_G = \frac{M_{3G}}{M_{1G}} = \frac{M_{3G}}{M_{3G} + M_{2G}} \quad (1)$$

$$F_L = \frac{M_{3L}}{M_{1L}} = \frac{M_{3L}}{M_{3L} + M_{2L}} \quad (2)$$

where F_G represents gas taken off, F_L represents liquid taken off, M_{3G} represents gas mass flow rate of the side branch, M_{1G} represents gas mass flow rate of the inlet, M_{2G} represents gas mass flow rate of the main branch, M_{3L} represents liquid mass flow rate of the side branch, M_{1L} represents liquid mass flow rate of the inlet, M_{2L} represents liquid mass flow rate of the main branch.

In the experiment, the range of inlet gas superficial velocities, j_G , was 0.01–19 m/s, and the inlet liquid superficial velocity, j_L , was 0.01–0.9 m/s. j_G and j_L were calculated as follows:

$$j_G = \frac{\rho'_G V'_G}{\rho_G A} \quad (3)$$

$$j_L = \frac{\rho'_L V'_L}{\rho_L A} \quad (4)$$

where V'_G and V'_L represent the inlet volume flow of gas and liquid under the standard state, respectively. The inlet volume flow of gas and liquid can be set by the micro-channel injection pump, ρ'_G and ρ'_L , respectively. The density of gas and liquid under the standard state, ρ_G and ρ_L represent the density of gas and liquid under the operating temperature and pressure, respectively. A is the channel cross-sectional area. The operating temperature was 25 ± 0.5 °C and the operating pressure was read from the pressure transducer.

Mass balances were carried out between the inlet and outlet flows. The percent of mass difference between the inlet and outlet were within $\pm 1\%$ for the liquid and $\pm 3\%$ for the gas. Measurements exceeding these percentages

were discarded. In order to show the reproducibility of data, each tested was conducted twice under identical inlet conditions. The accuracy of the control and measurement devices were as follows: tensiometer $\pm 0.1\%$; viscometer $\pm 1.0\%$; electronic balances (0–120 g) $\pm 0.01\%$; bubble meters $\pm 1.0\%$; mass flow controller (0–500 ml/min) $\pm 1.0\%$ F.S; syringe pump $\pm 3.0\%$ F.S.

Fig. 2 Schematic diagram of the experiment's apparatus

3. Result and discussion

3.1 Flow pattern observed

The high-speed camera captured typical slug and annular flow patterns, as shown in Fig. 3 and Fig. 4. To show these patterns matched the flow pattern map from similar studies Chung and Kawaji [17] conducted using a 0.53 mm micro-channel, phase split data points were selected and annotated on the flow pattern map, as shown in Fig. 5.

Fig. 3 Slug flow ($j_G = 0.5\text{m/s}$, $j_L = 0.35\text{m/s}$)

Fig. 4 Annular flow($j_G=16.5\text{m/s}$, $j_L=0.02\text{m/s}$)

Fig. 5 Flow conditions plotted on the flow pattern map

3.2 Effect of basic factors on phase split

3.2.1 Effect of basic factors on phase split of slug flow

1) Effect of superficial liquid velocity on phase split

The graphs in Figs. 6–7 show the amount of phase split taken off as a ratio of the side branch phase flow mass to the main branch phase flow mass. The data was plotted as the amount of gas taken off against the corresponding amount of liquid. In these figures, the diagonal lines show the two-phase medium uniform distribution. Data points near the line indicate even distribution, whereas data points far from the line show uneven distribution. Points under the line indicate more gas moving down the side branch pipe, whereas points above the line show where there was more liquid in the side branch pipe. The curves are the distribution trend of the fraction of both liquid and gas taken off. These curves are the fitting curves of the experimental data.

Fig. 6 (a) shows that the superficial gas velocity remained constant at 0.5 m/s, whereas the superficial liquid velocity increased from 0.1 m/s to 0.35 m/s. In Fig. 6 (b), the superficial gas velocity remained constant at 1.0 m/s, whereas the superficial liquid velocity increased from 0.1 m/s to 0.16 m/s. The data is concentrated evenly under

the distribution line, showing more gas was present in the side branch pipe. The fraction of liquid taken off decreased with the increase in superficial liquid velocity. When the superficial liquid velocity decreased, the kinetic energy ρu^2 (ρ is fluid density, u is fluid velocity) of the slug flow liquid column fell off further with the decrease of liquid velocity. That caused the kinetic energy of the bubble to be too low to overcome the surface tension and burst when the gas slug arrived at the junction. At the junction, the bubble lost the support of the wall, more liquid flowed into the side branch pipe, and the fraction of liquid taken off increased by the effect of capillary number. In addition, the length of the bubble decreased with the increase of superficial liquid velocity. According to the work by Link *et al.* [18], the shorter the bubble length is, the more difficult it is to burst. Thus, the shorter bubble is easier to turn into the side branch pipe with higher pressure gradient.

Fig. 6 Effect of liquid velocity on phase split of slug flow

2) Effect of superficial gas velocity on phase split

The superficial liquid velocity remained constant at 0.16 m/s, as shown in Fig. 7 (a), whereas the superficial gas velocity increased from 0.2 m/s to 1 m/s. The superficial liquid velocity remained constant at 0.1 m/s, as shown in Fig. 7 (b), whereas the superficial gas velocity increased from 0.2 m/s to 1 m/s. Because the liquid phase density is much larger than that of the gas phase density, the kinetic energy of the liquid slug is much larger than the kinetic energy of the gas slug. The increase in superficial gas velocity had limited effect on the kinetic energy of the liquid slug with the fraction of the liquid taken off changing only slightly, which is consistent with results obtained by Wren *et al.* [19] and others.

Fig. 7 Effect of gas velocity on phase split of slug flow

3) Effect of liquid surface tension on phase split

Phase split experiments were also carried out using three liquids with different surface tensions, decreasing from $72 \text{ mN}\cdot\text{m}^{-1}$ to $33.12 \text{ mN}\cdot\text{m}^{-1}$. With a superficial liquid velocity of 0.16 m/s and a superficial gas velocity of 0.5 m/s , the fraction of liquid taken off of a two-phase slug flow pattern decreased with the decrease in surface tension, as shown in Fig. 8. It is because of the breaking up of the gas slug at the junction that it was restrained by the capillary number ($Ca = \mu_L V_L / \sigma$) induced by surface tension. Therefore, with the decrease of surface tension, the capillary number increased making it easier for the gas slug to break up. At this time, the more gas phase is taken off from the side branch.

Fig. 8 Effect of surface tension on phase split of slug flow

Qian *et al.* [20] proposed that the length of gas slug decreases with the decrease in surface tension through numerical simulation. Fig. 9 shows that the separating surface of the gas slug and the liquid column is relatively flat when pure water, which has large surface tension, was used as the liquid phase, but the separating surface is steep

when 0.5% SDS solution, which has small surface tension, was used as the liquid phase. Therefore, the liquid with small surface tension is more likely to be split by gas. The length of the liquid column shortens and the produced frequency speeds up. The liquid with high surface tension clumps together easily, the liquid column lengthens, and the frequency becomes lower. As the length of liquid column and gas slug shortens and the produced frequency speeds up, the relative velocity between the gas and liquid decreases, and the velocity of the liquid slug grows faster.

(a) Liquid phase in pure water (b) Liquid phase in 0.5%SDS solution

Fig. 9 Slug flow at different surface tensions

Waelchli *et al.* [21] proposed that high-speed gas in the two-phase flow accelerates the velocity of the liquid with small surface tension. When the surface tension of the liquid phase is small, then the kinetic energy of the liquid column of the slug flow increases, the share of the liquid into the side branch decreases, and the fraction of liquid taken off decreases.

3.2.2 Effect of basic factors on phase split of annular flow

1) Effect of superficial liquid velocity on phase split

As can be seen in Figs. 10–11, the phase split of annular flow using air and water as working mediums show data points concentrated mainly above the diagonal line, indicating more liquid was taken off in the side branch pipe. The fractions of gas taken off were within a narrow range of 0.25–0.65. Given that the liquid phase of the annular flow are uniformly distributed on the pipe wall and the flow structure is simple and stable, the liquid in the branch pipe is relatively stable, and the fraction of liquid taken off is also relatively concentrated.

As can be seen in Figs. 10 (a) and 10 (b), the fraction of the liquid taken off decreased with increasing superficial liquid velocity. In Fig. 10 (a), the superficial liquid velocity increased from 0.02 m/s to 0.1 m/s, whereas the superficial gas velocity remained at 16.5 m/s. In Fig. 10 (b), the superficial liquid velocity increased from 0.02 m/s to 0.04 m/s, whereas the superficial gas velocity remained at 17.8 m/s.

In annular flow, a continuous gas flow exists at the center of the pipe, and a continuous liquid flow along the pipe wall uniformly distributes in the wall in the form of a liquid film. As the liquid velocity decreased, the kinetic energy of the liquid dropped and the liquid film lost wall support at the T node. Because of the effect of the capillary force, the liquid flow rate of the side branch pipe increased and the fraction of liquid taken off increased.

On the other hand, the thickness of liquid film increased when the liquid velocity increased. The inertia force was more obvious when the thickness of liquid film increased. When analyzing the experimental data, the Reynolds number of liquid film was calculated according to the superficial liquid velocity ($Re_F = w_F d / \mu_F$). When the superficial liquid velocity increased, the Reynolds number of liquid film increased. This means that as the inertia force of liquid film increased, the liquid film trended toward the main branch pipe. This was because the amount of liquid film that broke up at the junction was relatively lower due to the capillary force.

Fig. 10 Effect of liquid velocity on phase split of annular

2) Effect of superficial gas velocity on phase split

As can be seen in Figs. 11 (a) and 11 (b), the fraction of the liquid taken off did not change significantly with an increase in liquid superficial velocity. Fig. 11 (a) shows the superficial gas velocity increased from 12.6 m/s to 17.8 m/s, whereas the superficial liquid velocity remained at 0.04 m/s. In Fig. 11 (b), the superficial gas velocity increased from 12.6 m/s to 17.8 m/s, whereas the superficial liquid velocity remained at 0.02 m/s.

The result is similar to the phase split of gas–liquid two-phase flow in a small 5 mm diameter T-junction reported in a study by Stacey *et al.* [10]. However, the results are different from those found by Azzopardi *et al.* [22] in the phase split of gas–liquid two-phase flow in a large diameter T-junction.

Azzopardi *et al.* [22] showed that the fraction of liquid taken off increases with the decrease in liquid superficial velocity and proposed that reducing inlet gas velocity can reduce the fraction of entrained liquid in the gas phase and increase the thickness of the film hence increasing the fraction of liquid taken off. However, when working with micro-channels, with a small fraction of entrained liquid in the gas phase, even changing the gas velocity only changes the fraction of entrained liquid in the gas phase slightly, and the fraction of entrained liquid in the gas phase basically remains unchanged.

Fig. 11 Effect of gas velocity on phase split of annular

3) Effect of surface tension of liquid on phase split

The characteristics of gas-liquid two phase flow in micro-channels are very different from those in macro-channels. In a micro-channel, shear stress has a significant effect on the two-phase flow interface and gravity and inertia force have small effects. Therefore, liquid surface tension has a significant effect on the liquid distribution of annular flow in a micro-channel.

With pure water, 0.01% SDS solution, and 0.5% SDS solution used as liquid mediums in a gas-liquid two-phase annular flow, where the superficial liquid velocity is 0.04 m/s and the superficial gas velocity is 16.5 m/s, results showed (Fig. 12) that the fraction of liquid taken off at a T-junction decreases with the decrease in surface tension.

A liquid film stop region occurs when the two phases are distributed at a T node, as shown in Fig. 17 [23,24]. When the vortex area speed of liquid flow is reduced and the kinetic energy is consumed, the liquid enters a branch pipe easily. In Fig. 13(a), pure water, with a large surface tension, was chosen as the liquid phase, and the vortex area at T node was large. In Fig. 13(b), using 0.5% SDS solution, with a small surface tension, the vortex area at T node was small. The large vortex area means the film thickness increases. In a correlation (5) proposed by Blangetti *et al.* [25], the shear stress $\tau_{L,G}$ of gas-liquid interface decreases with increasing thickness of liquid film δ . When the shearing force that affects the liquid film weakens, the speed u_L decreases. The kinetic energy of the liquid is reduced, and the liquid in the branch pipe increases. Hence, the fraction of liquid with a large surface tension taken off is large.

$$\tau_{L,G} = -\frac{1}{2} f_G \rho_G (u_g - u_{L,G})^2 + \rho_G |u_g - u_{L,G}| v_{L,G} \quad (5)$$

where ρ_G is the density of gas phase, u_g is the axial average velocity of gas, $u_{L,G}$ is the axial velocity of gas-liquid interface, $v_{L,G}$ is the radial velocity of gas-liquid interface, and f_G is the Fanning friction coefficient applied to the surface of smooth laminar flow. f_G is defined as follows:

$$f_G = \frac{16}{\text{Re}_G} \quad (6)$$

where Re_G is the Reynolds number. Re_G is defined as:

$$\text{Re}_G = \frac{2(R-\delta)\rho_G|\bar{u}_G - u_{L,G}|}{\mu_G} \quad (7)$$

where R is the hydraulic radius of the pipe, δ is the thickness of liquid film, and μ_G is the gas viscosity.

Hence, pure water loses more kinetic energy at the T node, and a greater fraction of liquid is distributed into the branch pipe.

Fig. 12 Effect of surface tension on phase split of annular flow

Fig. 13 Liquid film stop region of annular flow

3.3 Influence of liquid effective viscosity on phase split

To study how liquid effective viscosity influences phase split, we chose Non-Newtonian fluid as the liquid phase. Non-Newtonian fluid does not agree with the experimental laws of Newtonian viscosity. There is no linear relationship between shear stress and shear strain rate in the Non-Newtonian fluid. Non-Newtonian fluids widely

exist in life, and the vast majority of biological fluids are non-Newtonian. But because of the complexity of the two-phase flow, the real viscosity of non-Newtonian fluid is impossible to determine. To solve this problem, Spisak [26] proposed the concept of effective viscosity, defined as follows:

$$\mu_{eff} = k \left(\frac{8j_L}{D_h} \right)^{n-1} \quad (8)$$

where μ_{eff} is effective viscosity, k is consistency index, n is flow Index, j_L is liquid velocity, D_h is Hydraulic diameter.

The specific properties of the Non-Newtonian liquid phase used in this study are shown in Table 1.

3.3.1 Influence of liquid effective viscosity on phase split for slug flow

Fig.14 shows the separation characteristics of the slug flow of PAAm solution at different concentrations at the same superficial velocity. Data points are concentrated evenly under the distribution line, indicating that gas taken off increased in the lateral branch pipe. It also shows that the fraction of liquid taken off increased with an increase in the effective viscosity of the liquid. This is because an increase in viscosity leads to an increase in frictional resistance of the liquid phase, which reduces the velocity of the liquid and its kinetic energy. Waelchli *et al.* [21] have used the PIV to study the velocity distribution of slug flow in a micro-junction and found that the average velocity of the liquid of slug flow is increased when the liquid viscosity is reduced. When the gas-liquid two-phase flow moves through a micro-T-junction, a larger velocity of fluid tends to flow through the main branch pipe because of the effect of the inertia. The inertia of fluid with a smaller velocity is small and this fluid tends to flow into the side branch. Since the larger effective viscosity means the average velocity of fluid is little, the liquid tends to be taken off into the side branch.

Fig. 14 Effect of non-Newtonian fluid phase split of slug flow

3.3.2 Influence of liquid effective viscosity on phase split for annular flow

As can be seen in Fig. 15, data points for the fraction of liquid phase of annular flow taken off by the side branch pipe are mainly concentrated above the diagonal line. This shows that the fraction of liquid taken off increased with the increase of the effective viscosity of the liquid, which is similar to results using slug flow. When liquid film flows to the T node, it loses the support from the channel wall and is affected by the centrifugal force and original inertia. The reduction of pressure when the gas suddenly changes direction at the T node causes the centrifugal force to push liquid into the side branch. When the liquid's effective viscosity increases, the velocity decreases, the effect of inertia decreases, and the share of the liquid's direct access into the main branch is reduced. When the effect of centrifugal force on the liquid is constant, the share of the liquid that flows into the side branch becomes larger, and the fraction of liquid taken off increases.

Fig. 15 Effect of non-Newtonian fluid phase split of annular flow

3.4 Effect of different sizes of pipe on phase split

3.4.1 Effect of different sizes on phase split for slug flow

Fig. 16 shows a graphical comparison of the phase split in T-junctions of different sizes. This study's data was compared with a study by Arirachakaran *et al.* [27] that used a 50 mm T-junction and a study by Wren *et al.* [19] that used a 5 mm T-junction. This study's data is mostly distributed under the diagonal line, similar to the results of Arirachakaran and Wren. The distribution trend is consistent, indicating that slug flow split is not affected by channel size.

Fig. 16 Comparison between the present data, Arirachakaran (50 mm) data, and Wren (5 mm-diameter pipes) data

The above analysis results can be proved correct by using the formula proposed by Azzi et al. [9], which is written as

$$\frac{L_s}{L_u} = \frac{1.2(1 + j_G/j_L)}{0.0039N} \sqrt{\frac{C_{fg}\rho_G}{C_{fl}\rho_L}} \quad (9)$$

In the equation, L_s and L_u are the length of the liquid slug and the whole length of slug flow. C_{fg} and C_{fl} are the friction loss coefficients of the gas phase and liquid phase, and N is a constant between 8 and 32.

The ratio of the length of liquid slug to the whole length of slug flow is unrelated to the size of the channel, which can be determined by the equation. Therefore, it can be deduced that the size of the channel does not affect the phase split of slug flow.

Fukano *et al.* [28] proposed a correlation (10) that also confirms the above conclusion.

$$\frac{L_s}{L_u} = 0.9826 \frac{j_L}{u_G} \quad (10)$$

3.4.2 Effect of different pipe sizes on phase split for annular flow

The data on annular phase split from this study was compared with data from studies of annular phase split in 5 mm [10], 38 mm [8], 125 mm [4], and 127 mm [24] T-shaped tubes.

Fig. 17 shows that when the superficial liquid velocity is about 0.1 m/s, and the superficial gas velocity is close to 16 m/s, the effect of pipe diameter on annular phase split is significant. The data points are mostly above the diagonal line, showing that the branch pipe contains the most liquid. However, points for conventionally sized tubes are mostly below the diagonal line, meaning that the branch pipe contains the most gas. This suggests that, in annular flow, the fraction of liquid taken off by the side branch pipe increases with a decrease in channel size.

Fig. 17 Comparison of phase split results of T-tube phase separation between different sizes of pipe

Fig.18 Flow pattern schematic of annular flow in conventional pipes

As shown in Fig. 18, part of the liquid carried in annular two-phase flow through conventional-sized pipes is entrained in the gas. With larger diameter sizes, the fraction of entrained droplets carried by high-velocity gas increases. These droplets have high kinetic energy and flow mostly into the main branch of a T-junction. However, entrained droplets are difficult to observe in narrow micro-channels, and the liquid flows mostly in the form of film, as shown in Fig. 9 (b). In a visualization study by Kim *et al.* [29] droplets entrained in gas could not be seen in micro-channels. Kataoka *et al.* [30] proposed the following empirical formula to determine the fraction of entrained droplets in two-phase flow at different pipe sizes:

$$E = \tanh(7.25 \times 10^{-7} We_G^{1.25} Re_L^{0.25}) \quad (11)$$

where Re_L is the Reynolds number of liquid and We_G is the Weber number of gas. Re_L is defined as:

$$Re_L = \frac{\rho_L j_L d}{\mu_L} \quad (12)$$

where ρ_L is the density of liquid, j_L is the superficial liquid velocity, d is the equivalent diameter of pipe, and μ_L is the liquid viscosity.

We_G is defined as follows:

$$We_G = \frac{\rho_G j_G^2 d}{\sigma} \left(\frac{\rho_L - \rho_G}{\rho_G} \right)^{\frac{1}{3}} \quad (13)$$

where ρ_G is the density of gas, j_G is the superficial gas velocity, and σ is the surface tension of liquid.

Based on the formula, the fraction of entrained droplets in annular flow occurring in the micro-channel used under this study's experimental conditions was 0.03%–0.12%.

The values can be ignored. The liquid in the flow takes the form of film and entrained droplets do not exist, leading to a decreased fraction of liquid in the main branch and an increased fraction of liquid taken off through the branch pipe. A comparison, shown in Fig. 19, of phase split results for T-shaped tubes of different sizes, with the superficial liquid velocity at about 0.02 m/s and the superficial gas velocity at about 20 m/s, is consistent with this view.

Fig. 19 Comparison of phase split results between different sizes of T-junction

3.5 Effect of different channel cross sections on phase split

Because gas superficial velocity has little effect on phase split, two-phase flow with the same liquid superficial velocity was used to compare this study's rectangular cross section with the square one used by He *et al.* [14], and the circular one used by Wang *et al.* [13]. The aspect ratios of the channels were 8:1, 1:1, and 1:1, respectively.

3.5.1 Effects of different channel cross sections on phase split for slug flow

Fig. 20 shows that differences in phase split of slug flow moving through a cross section are not significant when comparing square to circular shapes. When using both shapes under the same conditions, data points are scattered close to the uniform distribution line. However, when the circular and square cross sections were compared to the rectangular one, the fraction of gas taken off by the branch pipe is between 0.2 and 0.6, with the fraction of the liquid taken off of a rectangular cross section less than that of circular and square ones. This is because the aspect ratio of the circular section and square section are both 1:1, but the aspect ratio of rectangular section is 8:1.

The larger aspect ratio makes the effect of the interior angle of the channel greater. When it moves past the T-node, some of the liquid is taken off in the form of secondary flow. But liquid near the interior angle of the cross section has lower kinetic energy and is subjected to capillary action more easily. Capillary action near the interior

angle makes the liquid film become thinner than the rest of the liquid membrane. The surface tension makes the liquid film near the interior angle have a larger curvature, reducing the fraction of liquid taken off overall by reducing the liquid taken off in the form of secondary flow.

3.5.2 Effect of different channel cross section on phase split for annular flow

Fig. 21 shows that, as in slug flow, there is little difference in the phase split of annular flow when moving through square and circular cross sections. But when the fraction of gas taken off is between 0.5 and 0.9, the fraction of liquid taken off of by a rectangular cross section is less than that in circular and square ones. This is also due to the larger aspect ratio of the rectangular cross section, which, because of capillary action and surface tension, affects the secondary flow of the phase split and causes more liquid to be absorbed near the interior angles. The liquid film flowing into the side branch in the form of secondary flow becomes thinner and the fraction of liquid taken off is reduced.

Fig. 20 Effect of different aspect ratios and channel cross section of slug flow

Fig.21 Effect of different aspect ratios and channel cross section of annular flow

3.6 Predictive model of phase split

Some predictive models have sought to solve the phase split of the gas-liquid two-phase flow in the T-junction, but most models have been created to predict the impacting T-junction such as the model proposed by Chen et al. [31] and Azzopardi et al. [32]. For the prediction model of the dividing T-junction, the application of the model proposed by Seeger et al. [33] was wide enough to predict the behavior of phase split under a variety of flow patterns. The model in [33] established an empirical formula by using a large number of experimental data. As shown in Fig. 22 for comparison of the present experimental data and the results of prediction proposed by Seeger et al., the error is large. The phase split in the present experiment cannot be predicted well by the model in [33]. The reason for this is that the equivalent diameter of the channel is much larger than that in present experiment. As discussed above, the phase split characteristics of annular flow are dependent on pipe size. In addition, the liquid is taken off not only in the form of liquid film but also in the form of droplets. Under the same conditions, the fraction of liquid taken off tends to be larger than that in the micro-channel. So we provided a more accurate prediction of model.

Fig. 22 The error between the predicted data of empirical formula of Seer et al. and the experimental data from present experiment

Because flow pattern affects phase split prediction models, this proposed model is based on slug flow and annular flow patterns. Through the above analysis, we know that the fraction of gas taken off and the fraction of liquid taken off by a T-junction in these types of two-phase flow are affected by gas superficial velocity, liquid superficial velocity, liquid viscosity, surface tension and density of the gas phase and liquid phase, as well as the hydraulic diameter of the pipeline. This paper presents the empirical correlations of the phase split of slug flow and annular flow through regression analysis of the experimental data. This method is based on dimension analysis of physical quantity, using the following specific calculations:

For the slug flow :

$$\begin{aligned}
F_L &= 0.3587 F_G^{0.898} Re_L^{-0.066} We_G^{0.019} Ca^{-0.125} \\
&= 0.3587 F_G^{0.898} \left(\frac{\rho_L V_L D}{\mu_L} \right)^{-0.066} \left(\frac{\rho_G V_G^2 D}{\sigma} \right)^{0.019} \left(\frac{\mu_L V_L}{\sigma} \right)^{-0.125}
\end{aligned} \tag{14}$$

For the annular flow :

$$\begin{aligned}
F_L &= 0.3616 F_G^{0.499} Re_L^{-0.018} We_G^{-0.029} Ca^{-0.064} \\
&= 0.3616 F_G^{0.499} \left(\frac{\rho_L V_L D}{\mu_L} \right)^{-0.018} \left(\frac{\rho_G V_G^2 D}{\sigma} \right)^{-0.029} \left(\frac{\mu_L V_L}{\sigma} \right)^{-0.064}
\end{aligned} \tag{15}$$

Eq. (14), (15) is the proposed empirical formula for predicting the characteristics of two-phase slug flow and annular flow under experimental conditions. In this formula, the Re_L represents the ratio of inertia force and viscous force, with smaller Re_L values indicating that the influence of viscous force is more significant. We_G represents the ratio of the inertia force and the surface tension, with the smaller We_G values showing where surface tension was affected most. Ca represents the ratio of the viscous force and surface tension, where the smaller surface tension values indicate liquid moving into the side branch pipe more easily.

As shown in Fig. 23, the prediction formula for annular flow is more accurate than the formula for slug flow, and coincides better with the experimental data. This is because the gas and liquid columns move alternately in slug flow pattern, leading to strong pulsations that create flow instability. Annular flow is a relatively simple and stable pattern with liquid taken off into the side branch at a relatively stable and concentrated flow. Fig. 24 shows how much the predicted data differs from the experimental data. The amount of error between the two when analyzing slug flow ranges from -20 % ~15 %, but most of the difference is concentrated around 10%. The relative error of annular flow is in the range of -10 % ~5 % .

In addition, the phase split of other studies were respectively tested by the present prediction formula. Put the data from Azzi *et al.* [9] for slug flow and the data from Stacey *et al.* [10] for annular flow into the prediction formulas proposed by this paper. The results are shown in Fig.25. It can be seen from Fig. 25, when the flow pattern was slug flow, the differences between the predicted and experimental values were relatively larger. However, the data distribution was relatively concentrated. There were two main reasons for this appearance: firstly, when the gas phase and liquid phase flowed through the pipe alternately in the slug flow pattern, the stability of the system was more complicated and lower. Secondly, although the diameter of the pipe was similar, the structures of the inlet and outlet were different, which made the work pressure of the experimental section different. The experimental pressure data is 0.13-0.18MPa for slug flow of Azzi *et al.*[9]; the present experimental pressure data is

0.03-0.07MPa. There is slightly more maldistribution at the higher pressure that has been proven by Azzi *et al.*[9]. The difference of the experimental pressure has an effect on the viscous force and the inertia force at the junction. This agrees with the measurements reported by Das *et al.* [11], in that the side branch pipe taken off tends to be richer in the gas phase as pressure increases. However, the predicted values were in agreement with the experimental values in the annular flow. The result showed that the annular flow was less affected by the channel shape and length making the system of annular more stable. Prediction formula of annular flow was relatively accurate.

Fig. 23 Comparison of the predicted data with the experimental data

Fig. 24 The Error between the predicted data and the experimental data from present experiment

Fig. 25 The experimental data of others were verified by the prediction formulas proposed by this paper

4. Conclusions

The purpose of this paper was to study the characteristics of slug and annular gas-liquid two-phase flow when moving through a rectangular micro-channel dividing T-junction. The following conclusions were drawn from the work reported above:

(1) When the inlet flow pattern is two-phase slug flow, the gas taken off is dominant, the liquid taken off is distributed among 0.1-0.9. The liquid taken off by the side branch in a dividing T-junction decreases with an increase in superficial liquid velocity. The inlet gas flow rate has little effect on the liquid taken off. In addition, the liquid taken off decreases with lower liquid surface tension and effective viscosity. When this study's data was compared with data from studies of junctions with other diameters, the phase split characteristics of the slug flow were similar.

(2) When the flow pattern is two-phase annular flow, the liquid taken off is dominant and concentrated in the 0.3-0.65. The liquid taken off at the dividing T-junction decreases with an increase in superficial liquid velocity. The inlet gas flow rate has little effect on the liquid taken off. In addition, the liquid taken off decreases with decreasing liquid surface tension and liquid effective viscosity. When this study's data was compared with data from studies of junctions with other diameters, it can be seen that phase split characteristics of annular flow are dependent on pipe size, the fraction of liquid taken off by the side branch pipe increases with channel size decreasing.

(3) When comparing the effects of differently shaped channel cross sections on phase split, the aspect ratio of the cross section influences results greatly. The aspect ratio was shown to affect the amount of liquid taken off by the side branch in the form of secondary flow, with the fraction of liquid taken off decreasing with an increase of the aspect ratio.

(4) The empirical correlations proposed for predicting the characteristics of two-phase slug flow and annular flow under experimental conditions were determined through regression analysis of the experimental data and verified by calculations showing little error between the forecasting model and the experimental in this paper. In addition, the forecasting model proposed by this paper was used to verify others' experiments. The results showed that for the slug flow, the difference between individual points is large, but the overall trend is consistent; for the annular flow, the predicted values are in agreement with the experimental values and the error is small.

Nomenclature

A	channel cross-sectional area (m^2)
C_{fg}	gas phase friction loss coefficient (m/s)
C_{fl}	liquid phase friction loss coefficient
d	equivalent diameter of the pipe(m)
E	percentage of gas carried droplets of channel
F_L	Fraction of the liquid taken off
F_G	Fraction of the gas taken off
f_G	Fanning friction coefficient
j_G	superficial gas velocity(m/s)
j_L	superficial liquid velocity(m/s)
L_s	length of Liquid slug (m)
L_u	whole length of slug flow (m)
M_{IL}	liquid mass flow rate of inlet
M_{IG}	gas mass flow rate of inlet
M_{2L}	liquid mass flow rate of main branch
M_{2G}	gas mass flow rate of main branch
M_{3L}	liquid mass flow rate of side branch
M_{3G}	gas mass flow rate of side branch
R	channel hydraulic radius (m)
Re_G	Reynolds number of gas
Re_L	Reynolds number of liquid
u_G	gas axial average velocity (m/s)
u_L	liquid velocity (m/s)
$u_{L,G}$	gas-liquid interface axial average speed(m/s)
$v_{L,G}$	gas-liquid interfacial radial average speed(m/s)
V_G	gas volume flow (ml/h)
V_L	liquid volume flow (ml/h)

We_G Weber number of gases

$Wt \%$ weight percentage

Greek symbols

ρ_L liquid density (kg/m^3)

ρ_G gas density (kg/m^3)

δ thickness of liquid film (m)

σ liquid surface tension (N)

$\tau_{L,G}$ gas-liquid interface shear force (N)

μ_L liquid viscosity (Pa•s)

μ_G gas viscosity (Pa•s)

Mathematical symbols

$\text{Tan}(\bullet)$ tangent function

Acronyms

SDS Sodium dodecyl sulfate

PAAm Polyarylanide

PMMA Polymethyl methacrylate

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