NUMERICAL INVESTIGATION OF LIQUID CARRYOVER IN T-JUNCTION WITH DIFFERENT DIAMETER RATIOS

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ABSTRACT

T-junction is commonly used in distributing two-phase flow in a piping system, especially in oil and gas industries. In offshore Malaysia, T-junction is installed at the production header as a compact separator to tap produced gas from reservoir as fuel gas for power generation. However, the splitting nature of two-phase flow with significant differential density at the junction is a major challenge. Excessive liquid carryover in T-junction present a serious operational issue because it trips the whole production platform. The primary objective of the present study is to investigate the liquid carryover due to formation of slug, subsequently its separation efficiency at different diameter ratio. The analysis was carried out on a model with 0.0254 m (1 inch) diameter horizontal main arm and a vertically upward side arm using Volume of Fluid Method from Fluent 16.1. Three different side to main arm diameter ratio of 1.0, 0.5 and 0.3 were investigated with different gas and liquid superficial velocities. The inlet boundary is a prescribed mass flow rate and atmospheric pressure is assumed at the two outlets of the T-junction. Pressure velocity coupling was achieved by using the SIMPLE coupling scheme. The results showed that, when the flow regime in the main arm is slug flow, a combination of high liquid superficial velocity and very small diameter ratio leads to higher liquid holdup frequency or liquid carryover.

Keywords: T-junction; liquid-gas separation; separation efficiency

INTRODUCTION

T-junction is an appendage of small diameter pipe, which is attached to the main pipe to tap the fluid source from the main stream. T-junction consists of three main components, namely main arm, run arm and branch (or side) arm as shown in Figure 1.

This T-junction configuration is often seen in the offshore production platform where the T-junction is used to tap gas directly from the production header. The tapped gas is channel downstream as fuel gas for power generation or source gas for other purposes. When a two phase mixture flows pass a T-junction, lighter phase will incline to enter the branch arm while the heavier phase tends to continue flowing into the run arm. The higher the density difference between the two-phase, the better is the phase separation. Liquid carryover occurred when gas phase takes off to the branch arm reaching a certain limit, creating sufficient suction pressure to draw heavier liquid phase into the branch arm. Liquid carryover is a frequent problem that occurs in a T-junction whereby an excessive amount of liquid is take off into the gas stream and channeled into downstream equipment which is not designed to handle liquid. Consequently, platform trips and production has to halt to drain out the excessive liquid. An example of this is the asset

D35 power failure in Jan 2016 for two days in Sarawak, causing a loss of RM1.2 million.

The deceivingly simple T-junction with a simple geometry is an unbelievably complicated topic [1]. The geometry alone consists of eight different parameters that could have many combinations. Compounding to the complexity are flow parameters such as flow rate and operating pressure etc., and fluid properties such as density, viscosity and surface tension. Interestingly, there is very limited research which focuses on the flow regime behavior before the two-phase flow reach the T-junction and its separation thereafter. The objective of the present paper is to investigate the effect of T-junction's diameter ratio on liquid carryover, when the inlet flow regime is slug flow.

LITERATURE REVIEW

For a horizontal main pipe, with a side arm pointing at 12 o'clock position, there are a number of possible approaches suggested to increase the phase separation performance. The initial focus for studying the phase separation at T-junctions with a reduced side-arm diameter was for industrial situations, where the branch arm of a piping system is made smaller than the main pipe ($D_3 < D_1$, $D_1 = D_2$), see Figure 2. Reduced diameter T-junction referred to the diameter ratio of the branch arm to the main arm. Diameter of main arm and run arm are usually kept the same.

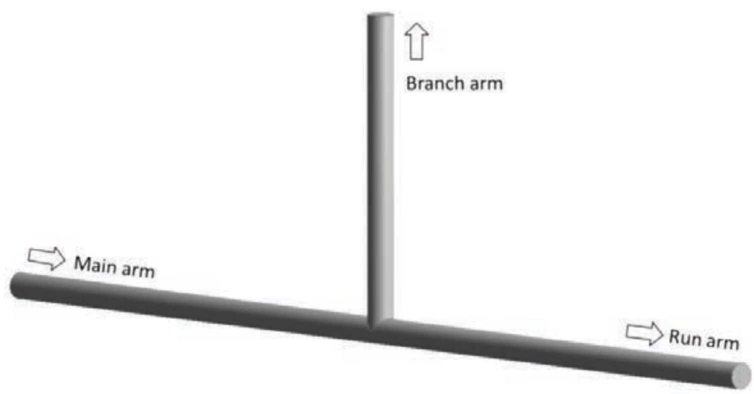


Figure 1 Components of T-junction showing the main, branch and run arms

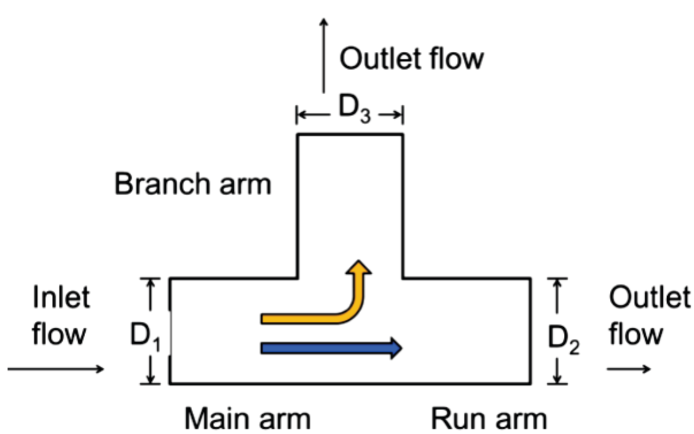


Figure 2 Configuration of regular and reduced T-junction

Typically, it is found that less liquid is taken off, for a fixed gas take-off, when the diameter of the side-arm is reduced. A reduction in the branch arm diameter will have two distinct effects, namely, the pressure drop and the entrance cross-sectional area available for liquid take off. It is well known that the distribution of the phases at a T-junction depends not only on the geometry and approaching flow pattern, but also rely on the two downstream pressures and the pressure drop across the T-junction. Pressure drop measurements around a T-junction generally show a loss between the inlet and side-arm, but a pressure recovery into the run arm as shown in Figure 3. This recovery is attributed to an affect similar to that of Bernoulli for single phase flows, produced as a result of the decrease in the mixture velocity in the run arm [2]. The branch with lower pressure, has a dominating influence on the flowing fluids, thus more fluid will be diverted into the branch [3]. However, it needs to note that this is the conclusion reached when the side arm is pointing at 6 o'clock. Under the dominance of gravity, the liquid will be accelerated, leading to pressure drop. When the side arm is pointing at 12 o'clock, the liquid take-off in the side arm is flowing against the gravity. In other words, the force by the liquid to climb up the side arm is its own momentum force minus the gravity force. Here, the momentum transfer by the gas phase is important if liquid is to take-off in the side arm. Figure 4 showed the experimental results by Hart et al. [5] for horizontal upward pointing T-junction. Notice that the pressure behavior between Figure 3 and 4 are completely different. However, certain common features are recognizable; (a) the run arm is experiencing a higher pressure than the main/branch arm; and (b) the branch arm has a lower pressure gradient than the main arm.

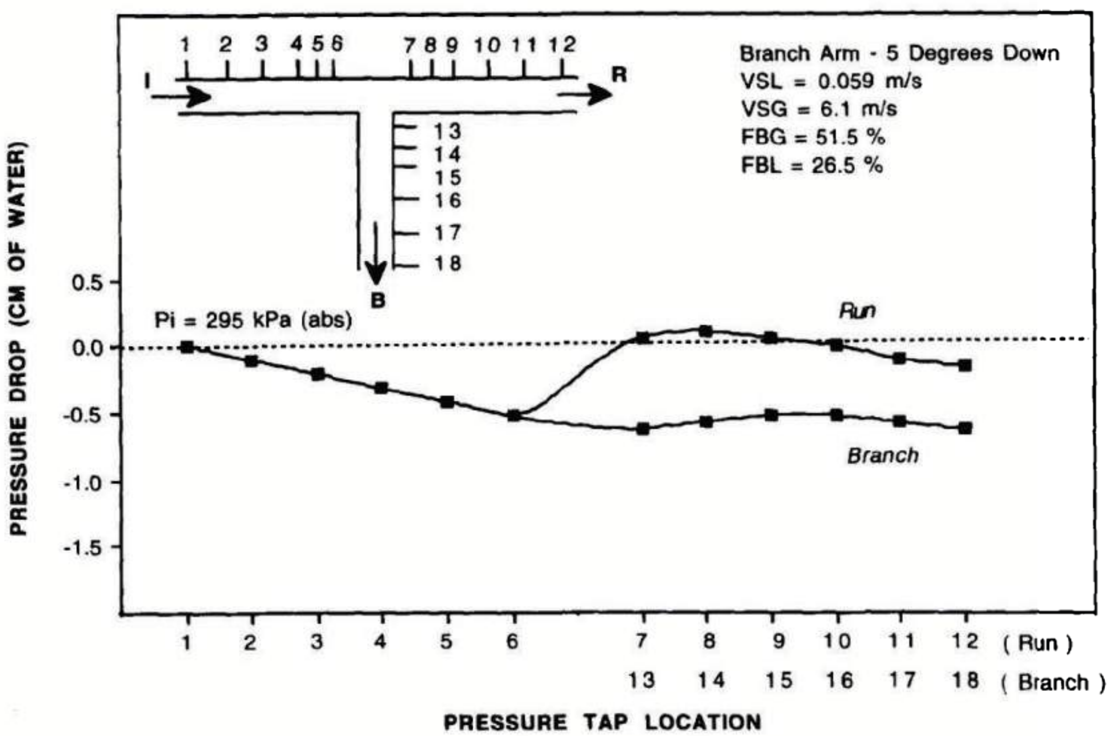


Figure 3 A typical pressure distribution at the tee [4]

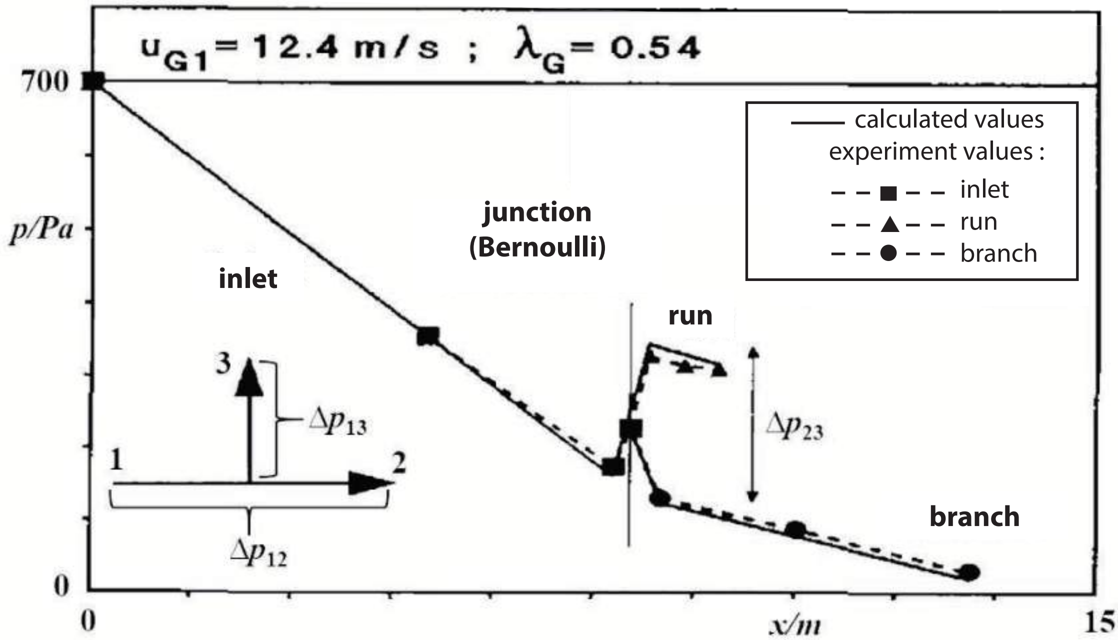
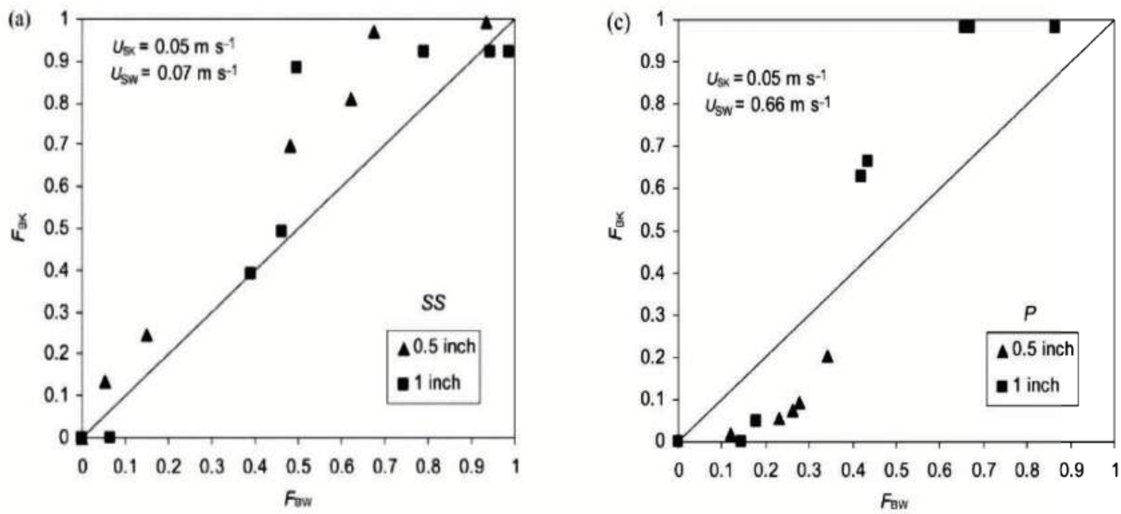


Figure 4 Pressure distribution of single phase air flow through regular T junction [5]

Penmatcha et al. [4] stated that the pressure rise in the run arm is due to the Bernoulli effects. A lower pressure gradient in the branch arm provides the momentum change for the fluids moving from the inlet into the branch arm. The effect caused by a reduction in side-arm diameter, as first suggested by Azzopardi [6], would be to reduce the axial distance available for phase take-off to occur. This reduces the liquid travel time, the time available for the liquid to flow into the side-arm instead of flowing straight into the run. As such there is less chance of the liquid that is dragged towards the side-arm by the gas leaving in the smaller opening has it hits the pipe wall instead and continues along the pipe into the run. Hence, more liquid bypasses the branch, so for a given gas take-off, the corresponding liquid take-off should be less than for a regular T-junction. The final effect on the phase separation produced by a reduction in the side-arm would appear to be a combination of the two factors above coupled with the flow pattern approaching the junction. The main difference between the reduced tees and regular tees can be observed in the branch pressure contour distribution. For the same instance of inlet flow condition, there is a higher pressure drop in the branch of reduced tee compared to the regular tee. This is due to the higher gas phase velocities occurring in the reduced side arm for the same branch gas phase fraction intake. Pandey et al [7] carried out experiment to verify the effect of side arm diameter ratio on phase split for stratified flow and plug flow. Experiments have been performed with kerosene and water in a reduced diameter T-junction whose branch arm is 0.0127 m in diameter while the main and run arms are 0.0254 m (diameter ratio: 0.50) and compared with phase split result obtained from a regular T-junction. There is an increased in the fractional liquid take off with a decrease in the branch arm diameter. Comparison of results shown in Figure 5(a) and 5(b) shows negligible impact of diameter ratio in stratified-smooth flow while there is more kerosene take off in the regular T compared to a reduced T for stratified-wavy conditions.

Azzopardi [9] studied the scale effect of branch arm to main arm diameter ratio on phase split of liquid-gas flow at T-junction for annular and stratified flow. The data were taken at 2 scales: a small scale T-junction with main arm diameter of 0.038 m and side arm bore of 0.038, 0.025m and 0.0127m; a large scale T-junction with main arm diameter of 0.125m and side arm bore of 0.125m and 0.076m. The medium used was air and water.

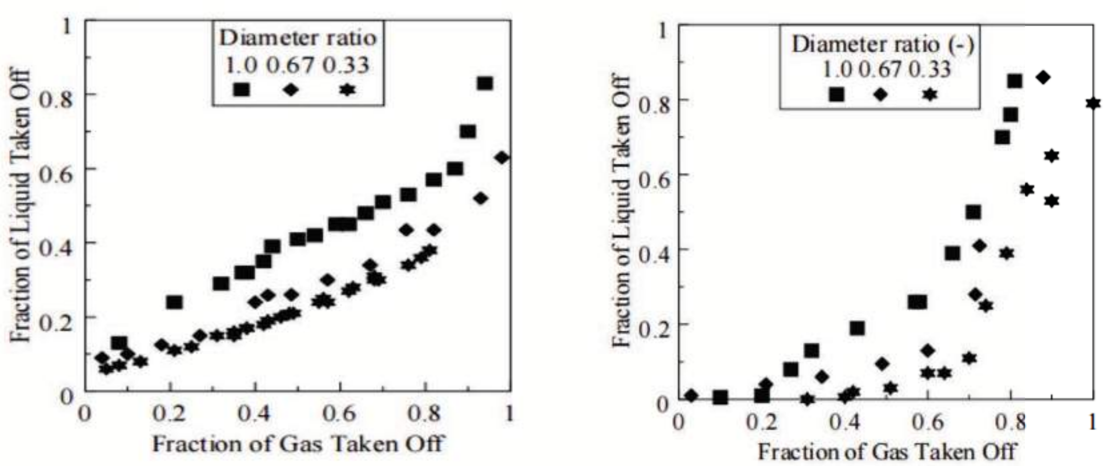
For the small scale T-junction, data plotted in Figure 6 (a) and 6(b) shows that decreasing the diameter ratio of a T-junction leads to lower liquid take off for both stratified and annular flow. For the larger scale T-junction in Figure 7(a) and 7(b), the conclusion is also valid. The effect of diameter ratio is most significant at lower gas rates while least at lower liquid and high gas flow rate conditions. Marti and Shoham [9] carried out experiment to compare the reduced and regular tee data for horizontal branch arm. Main arm diameter of 0.051 m was paired with side arm of 0.051 m (regular T) and 0.0255 m (reduced Tee). Figure 8 showed that application of reduced tee results in lower branch liquid intake compared to regular tee.



(a) stratified smooth flow

(b) plug flow

Figure 5 Effect of branch arm diameter of flow split for (a) stratified and (b) plug flow [7].



(a) Stratified flow,
$v_g = 18.6$ m/s, $v_l = 0.067$ m/s

(b) Annular flow,
$v_g = 8.3$ m/s, $v_l = 0.056$ m/s

Figure 6 Effect of diameter ratio on phase split in small scale T-junction for (a) stratified flow and (b) annular flow [8]

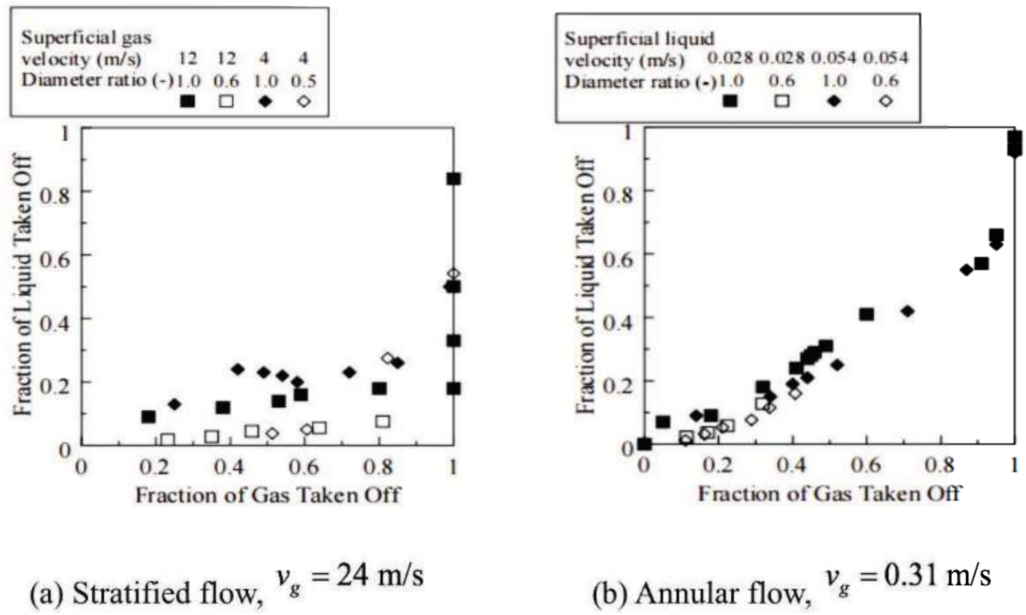


Figure 7 The correlation between diameter ratio on phase split in large scale T-junction (a) stratified and (b) annular flow [8].

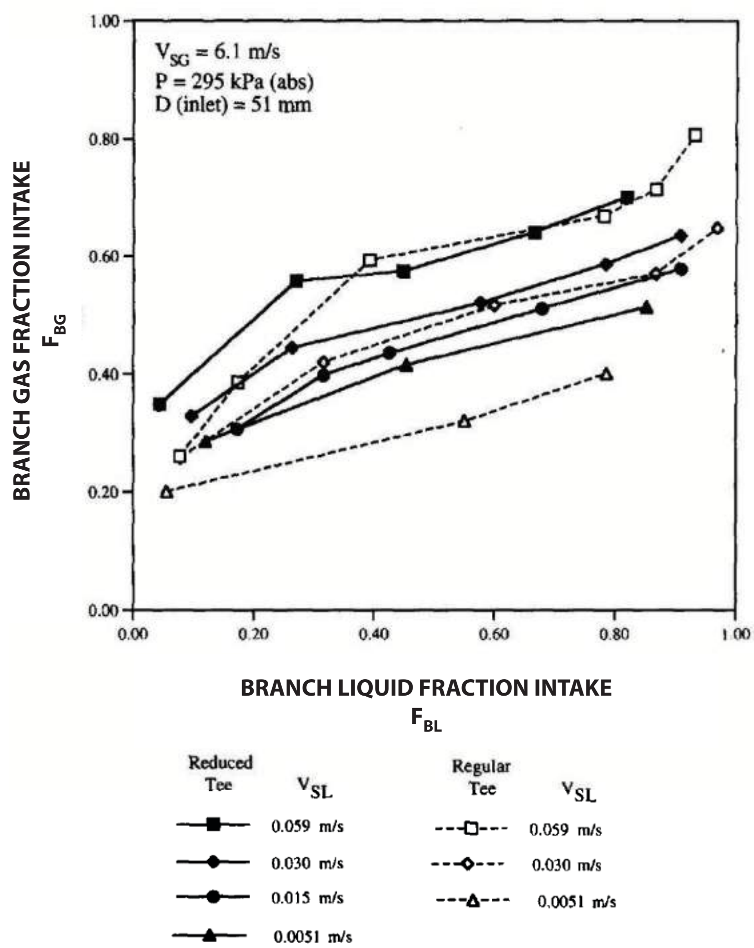


Figure 8 Comparison of reduced tee data and regular tee data for horizontal branch arm [9]

Figure 8 also suggests that at higher side arm extractions, reduced T-junction delivered more liquid carryover as compared to regular T-junction. This was due to the accelerated gas velocities in the reduced T-junction forcing a greater proportion of the liquid phase to be drawn off its axial course and into the side arm. However, at very low gas fraction intakes, less liquid was diverted for reduced T-junctions than for regular T-junctions as the pressure drop at the T-junction, due to increased gas velocity in the reduced diameter side arm, was not yet significant enough to compensate for the dominating axial inertia forces within the liquid phase. Furthermore, the effect of reduced tee is more pronounce in lower superficial liquid velocity.

METHODOLOGY

Governing Equations

Unlike the approach followed in [10 - 12, 13] by the same group of authors, this paper used Volume of Fluid (VOF) Method to simulate the T-junction liquid carryover. The reason for using VOF Method is because the authors found that the Eulerian Multiphase Model was unable to mimic the required flow regime. Even though the mass fluxes were input into the Eulerian Multiphase Model from the Baker's flow regime map [14] as inlet boundary conditions, and the results validated with experiments, the flow regime contour cannot be reproduced. Consequently, this lack of flow regime visual evidence from the numerical model forced the authors to look for alternatives for T-junction investigation. Consequently, instead of two momentum equations representing gas and liquid phase, respectively, the VOF Model only has one momentum equation to represent the entire gas-liquid mixture. The mixture mass conservation equation and the momentum for the mixture are given by

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{U}) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho \mathbf{U}) + \nabla.(\rho \mathbf{U}\mathbf{U}) = -\nabla \rho + \nabla.[\mu(\nabla \mathbf{U} + \nabla \mathbf{U}^T)] + \rho \mathrm{g} + \mathrm{F} \qquad (2)$$

respectively, where ρ is the mixture density, $\mathbf{U}$ is the mixture velocity, ρ is the mixture pressure, μ is the mixture viscosity, $\mathbf{g}$ is the gravity acceleration and $\mathbf{F}$ is the body force vector. Equations (1) and (2) need to be complemented by the α-phase continuity equation from VOF given by

$$\frac{\partial \alpha_g}{\partial t} + \mathbf{U}.\nabla \alpha g = 0 \qquad (3)$$

where α_g is the volume fraction of gas. Equation (3) is subjected to the constrain

$$\alpha_g + \alpha_l = 1 \qquad (4)$$

where the subscripts l and g refer to liquid and gas. The mixture density and viscosity can be calculated as

$$\rho = \alpha_l \rho_l + \alpha_g \rho_g \qquad (5)$$

$$\mu = \alpha_l \mu_l + \alpha_g \mu_g \qquad (6)$$

In the present approach, gas phase is assigned as primary phase. The volume fraction of each phase is assigned as initial condition. We note the difference between the mixture model and VOF model here. In the VOF model, the individual phase is non-penetrating and there is no mass transfer between phases.

Pipe Geometry and Mesh Independent Study

The schematic model of T-junction was modeled in ANSYS workbench with the dimension as shown in Figure 9. The T junction was tessellated with Assembly Meshing Cutcell method with tetrahedral volume elements throughout the T junction. In this meshing method, a volume is divided into predominantly hexahedral cells, resulting in better mesh quality in comparison to tetrahedral mesh. Through repetitive tuning, mesh skewness as low as 0.02 and aspect ratio of 1.05, as described in Fluent 16.1 manual as good quality mesh, can be achieved. Mesh independency tests were carried out to determine the solution convergence behavior and to determine the minimum mesh density requirement.

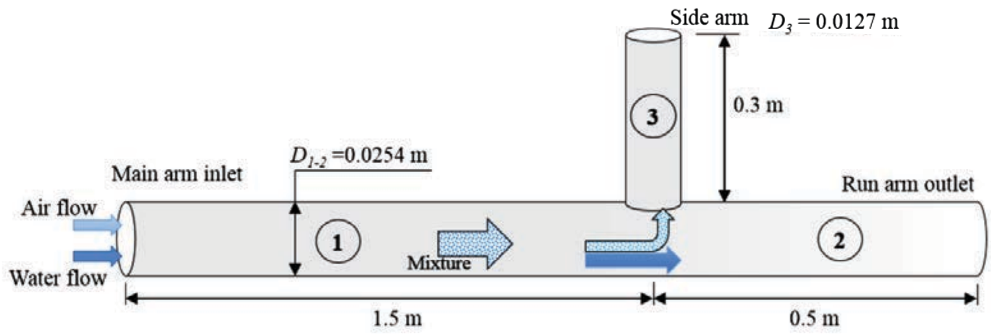


Figure 9 Schematic and dimension of T-junction used for simulation

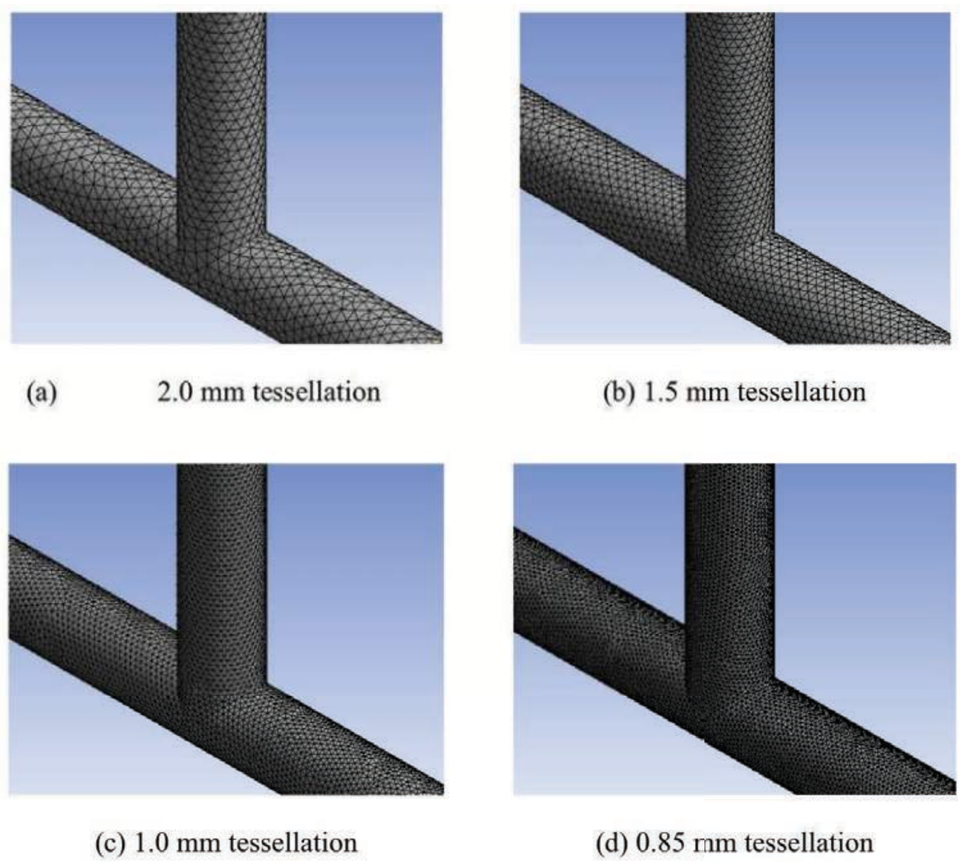


Figure 10 Different model tessellation showing element sizes of (a) 2.0 mm; (b) 1.5 mm; (c) 1.0 mm and (d) 0.85 mm.

Figure 10 showed a snapshot of different volume tessellation with prescribed maximum element sizes. Notice that in the current model, uniform tetrahedral meshing has been adopted instead of the geometry adaptive meshing. This is because the present investigation is not only focused on the T-junction but also the slug flow behavior in the main arm and liquid carryover flow in the side arm.

Two parameters, namely the branch arm suction pressure and mixture flow rate were used as convergent criteria. Figure 11 showed the semi-log plot of number of elements versus branch arm pressure and mixture flow rate. Based on the mesh dependency test, the suction pressure at the branch arm converges towards 64 kPa while branch mixture mass flow rate converges towards 0.13 kg/s when the element number reaches around 265,000 or element size of 0.9 mm. In other words, increasing the number of elements beyond this threshold will not improve the accuracy of the model further. Due to the nature of solution being unsteady, one complete simulation takes about 5 days on 16 GB RAM, 64bit Intel Core i7-6700 CPU at 3.40 GHz.

Initial and Boundary Condition, Solution Procedure and Convergence Criteria

The initial condition of the model is setup such that gas-liquid occupied 50-50 by volume in the main and run arm. The branch and run arm outlets were prescribed atmospheric pressure, p = 0. For the inlet boundary condition at the main arm, there are two options with which boundary conditions can be applied, namely the mixture velocity and the mass flow rate. In the present paper, the mass flow rate of each phase is prescribed.

For discretization, the PRESTO (pressure staggering options) scheme was applied for pressure interpolation. A combination of the PISO (pressure implicit with splitting of operators) algorithm for pressure–velocity coupling and the second order upwind calculation scheme for the determination of volume fraction and momentum were used to perform the calculations [14].

Gas was chosen as primary phase and liquid as secondary phase. The surface tension was set a constant value, for air-water of σW = 0.072 N/m. Gas-liquid two-phase flow is the dynamic flow behavior, therefore, all cases of numerical simulation for unsteady state calculation were carried out with a time step of 0.001s. The residual value of the calculated variables for the mass, velocity components and volume fraction of two-phase are contributed to the convergence criterion. When the scaled residuals of the different variables are lowered by four orders of magnitude, the numerical calculations were considered converged in this work.

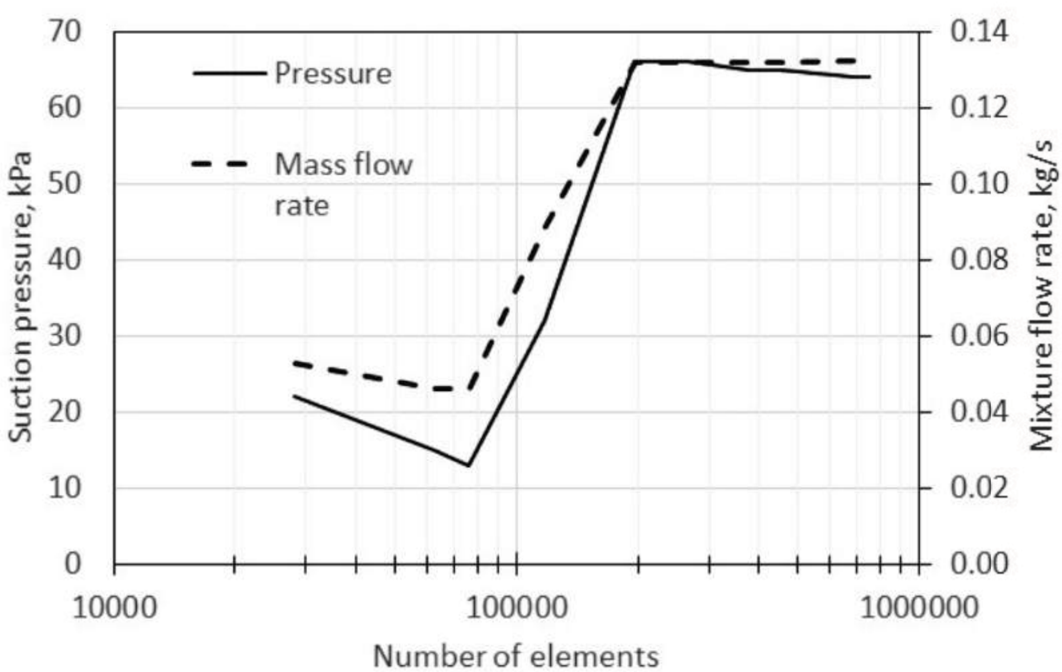


Figure 11 Number of elements versus branch pressure and mass flow rate for solution convergent study

RESULTS AND DISCUSSION

Validation of Flow Regime with Baker's Map

The first validation involved selecting several data points from the Baker chart [13] and numerically input the mass fluxes as inlet boundary conditions to investigate if the corresponding flow regimes could be reproduced. From here onwards, unless otherwise stated, Baker chart refers to Baker [13]. The generated flow regime contours were then investigated in-depth by comparison with numerically simulated flow regime contours from other researcher.

The case selected is the model from [15], for a 7 m long horizontal tube with 0.08 m diameter. Five flow regimes were compared which are stratified, wavy, slug, plug and bubbly flow. The input parameters for the inlet boundary conditions are shown in Table 1 and the corresponding points is shown in the Baker's chart in Figure 12.

Table 1 Operating conditions for the simulations of water-air flow

Flow Regime	G/λ (kg/m²s)	G (kg/m²s)	Lλψ/G	L (kg/m²s)
Stratified	2	2	2	4
Stratified wavy	27	27	0.2	5.4
Slug	4	4	100	400
Plug	0.2	0.2	6000	1200
Bubbly	41	41	1000	41000

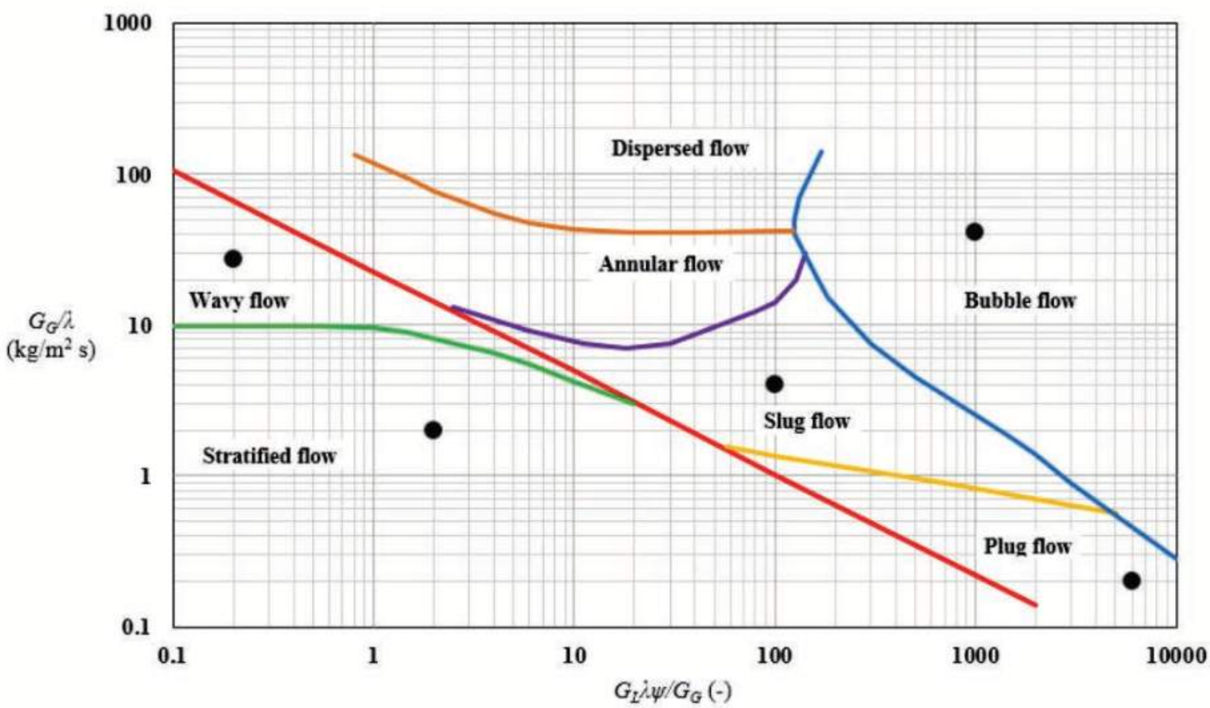


Figure 12 Data points selected from the Baker's chart [13] for validation

The water density is assigned a constant value of 998.2 kg/m^3, air density 1.225 kg/m^3, viscosity of water 0.001003 Pa-s, surface tension 0.0719404 N/m.

flow in a horizontal pipe. The air is dispersed evenly throughout the fluid due to rigorous mixing between the two phase.

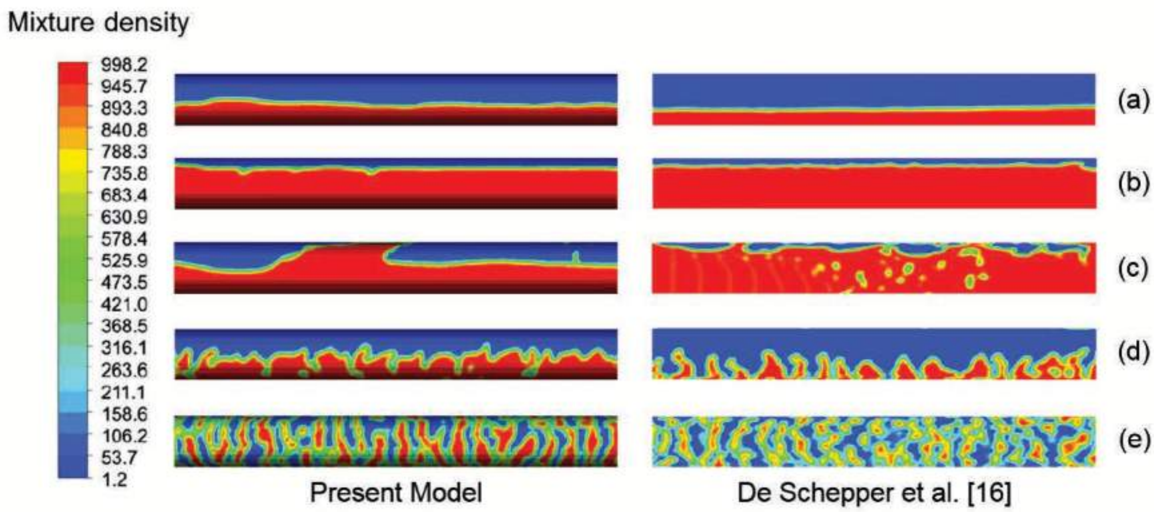


Figure 13 Comparison of density contour of current model with De Schepper et al. [16] for (a) stratified, (b) stratified wavy, (c) slug, (d) plug, (e) bubbly flow

Figure 13(a) shows the mixture density contour for stratified flow. Stratified flow occurs when there is a distinct and calm interface between air and water. It occurs when air and water velocity is typically low and thus the gravity is the major influence that settle down the water phase. However, as the air velocity increases, small waves start to formed. At this time, two forces are acting on the wave crest in the opposite directions which is gravity and Bernoulli force. Gravity force acts similar to stratified flow while Bernoulli force caused by increasing air velocity above the wave will cause pressure drop to increase the crest height, forming wavy flow, Figure 13(b). Figure 13(c) and 13(d) shows the results for slug and plug flow, both of which are termed intermittent flow regime that usually happen at higher gas velocities and moderate liquid velocities. The main initiation for occurrence of slug and plug flow is due to perturbation between the interface of air and water. The perturbation may come from turbulence flow or may originate from stratify wavy flow. Bubbles will rise to the top part of the pipe and accumulated into elongated bubbles due to buoyancy forces. It is clear that the current model of slug flow pattern is more realistic. Figure 13(e) illustrates bubbly

Validation of Slug Flow with Experiment

The second validation model for horizontal two phase slug flow was taken from experimental result of Christophe et al. [16], who conducted experiment in transparent rectangular conduit of 4 m long, 100 mm height and 30 mm width. The slug flow measurement of 5 s was taken with 5 m/s superficial inlet air velocity and 1 m/s superficial water inlet velocity. In the present validation, the inlet boundary conditions for the CFD model were still using the mass flow rate. In order to achieve the superficial velocities described by the experiments, a cross sectional plane very near to the inlet was cut out and the averaged superficial velocities of each phase was adjusted on that plane to be as close as possible to the experimental values by tuning the mass flow rate. In the original paper, the images were supplied without time stamp and the exact location of the superficial velocities was not entirely clear. Figure 14 showed the side to side comparison of the present simulation model at 1.92 s, 1.96 s and 2.06 s respectively. There are some discrepancies which could be attributed to the inaccurate boundary conditions, particularly at the downstream of the conduit. Nevertheless, the present model is able to mimic the two-phase slug flow captured by experiment.

Validation of T-junction Separation with Experiment

Wren [3] performed experiments on air and water flow separation in a large diameter T-junction. The conduit in his experiment was 8 m long with a diameter of 0.127 m. The vertical T-junction with 1.5 m height, and 0.0762 m was positioned in the middle of the conduit. The diameter ratio of branch to main arm is 0.6. Due to long computational time to obtain each data point, only inlet air superficial velocity of 12 m/s and inlet water superficial velocity of 0.0283 m/s was selected for verification.

Based on Figure 15, it is seen that in order for liquid carryover to occur, the gas velocity need to be sufficiently high to overcome the liquid phase inertia and gravity forces. As pointed out by Wren [3], reducing branch arm diameter will cause an increase in air velocity in the branch arm, leading to a pressure drop. With the branch arm in suction pressure, liquid will be sucked up into the branch arm, aided by the back pressure from the run arm. The amount of liquid carryover is negligible unless a gas takes off reach its critical value.

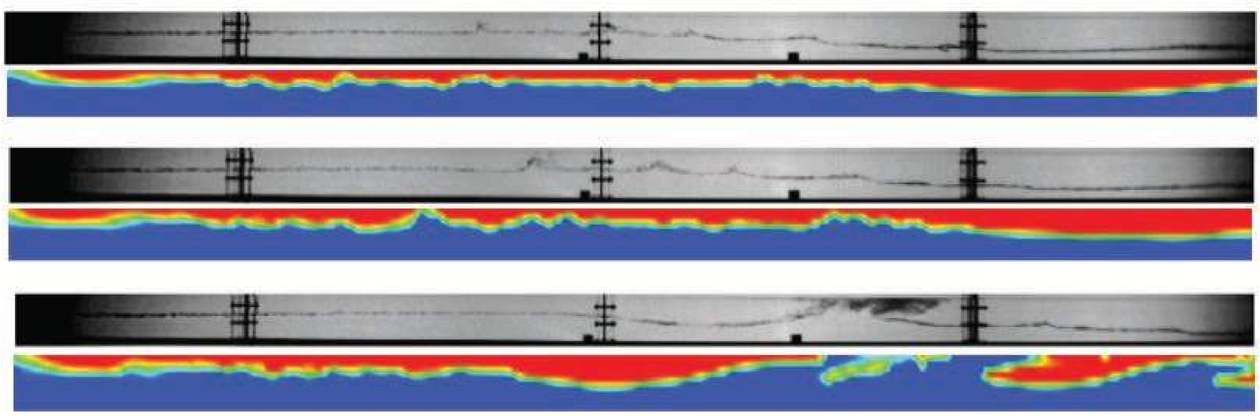


Figure 14 Comparison of experimental image of Christophe et al. [16] and the present simulation model

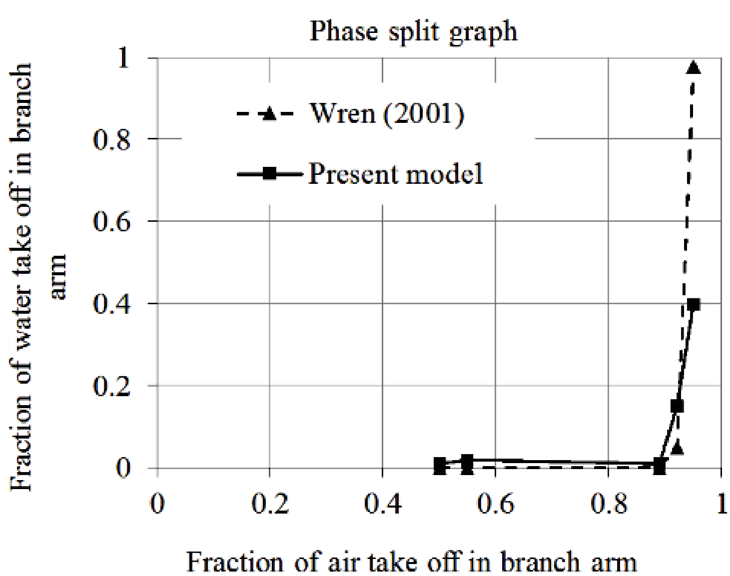


Figure 15 Phase split chart at a reduced T-junction with a vertically upwards branch arm

Parametric Analyses of T-junction Separation with Reduced Branch Arm Diameter and Slug Flow

In order to understand the behavior of liquid carryover due to diameter ratios under slug flow condition, parametric study was conducted in regular and reduced T-junction. The horizontal main arm was 1.5 m long with vertical branch pointing at 12 o'clock located 1 m away from the inlet. The height of the branch arm is 0.3 m. The main and run arms were 0.0254 m (1 inch) in diameter and was kept constant. Three different branch arm diameter with the same height of 0.3 m were used, resulting in branch to main arm diameter ratio of 0.3, 0.5 and 1.0. The schematic model is shown in Figure 16.

The air and water mass flow rate (kg/s) were carefully calibrated so that (a) the inlet flow generated the required slug in the main arm and; (b) its resulting superficial velocity allows easy comparison of results in order to draw meaningful conclusion. After some tedious trial and error experiments, air and water velocities were set at 1 m/s and 2 m/s for each phase in a combinatorial fashion, making up 4 combination of velocities with identifiable high and low values. Table 2 listed the corresponding inlet air and water mass flow rate and the associated superficial velocities for the parametric study. This resulted in 12 simulations (4 variation of superficial velocities for each diameter ratios). The liquid holdup and its frequency at the outlet of side arm as shown in Fig 16, were recorded from 0 to 5 seconds. In the present, it is important to define the liquid holdup as

$$H_L = \frac{A_L}{A} \tag{7}$$

where A_L is the cross-sectional area occupied by the liquid and A is the total cross-sectional area of the pipe.

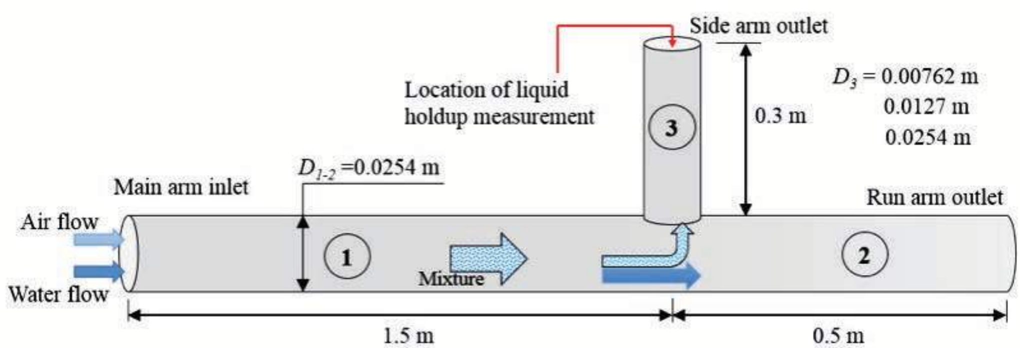


Figure 16 Schematic diagram of the T-junction for parametric study

Table 2 Air and water mass flow rate for parametric study

	Superficial velocity	
Mass flow rate	1 m/s	2 m/s
Air flow rate (kg/s)	0.000621	0.001241
Water flow rate (kg/s)	0.506	1.012

Before detail discussion about the results, the mechanism of liquid carryover in branch arm under approaching slug flow regime in the main arm are shown in Figure 17, 18, 19 and 20 in order to illustrate the physical meaning of this parametric study and at the same time, to appreciate the difficulty in carrying out the 'proper' simulation.

In Figure 17, a slug body about the length of three times the diameter of main arm (3") is approaching the T-junction. The liquid body is fully bridging the upper part of the pipe, with clearly identifiable slug nose and tail, showing that it is a proper 'slug' flow. An air pocket of about the same length (3") is passing through the T-junction. Figure 17 showed that a numerically simulated 'proper' slug body has been formed before it reaches the T-junction. In fact, this is the most difficult and tedious part of the whole parametric study.

In Figure 18, the slug body passed through the T-junction and broken up. Liquid carryover occurred in the branch arm. The liquid jumped into the branch arm to about 0.2 m height, covering almost two third of the height of the branch arm. The contour in Figure 18 captures only the region filled with liquid but droplets of liquid (not clearly visible) flow through the entire length of the branch arm. When the liquid filled up the entire cross-section of the branch arm outlet, liquid holdup = 1.

Figure 19 showed that the tail of the slug body is about to passed through the T-junction. The outlet of the branch arm is now completely filled with water. The air pocket is seen about to pass through the branch arm and portion of air started slipping into the appendage. The bottom of the branch arm is partially filled with air water and partially filled with air. The top section of the branch arm is fully saturated with water.

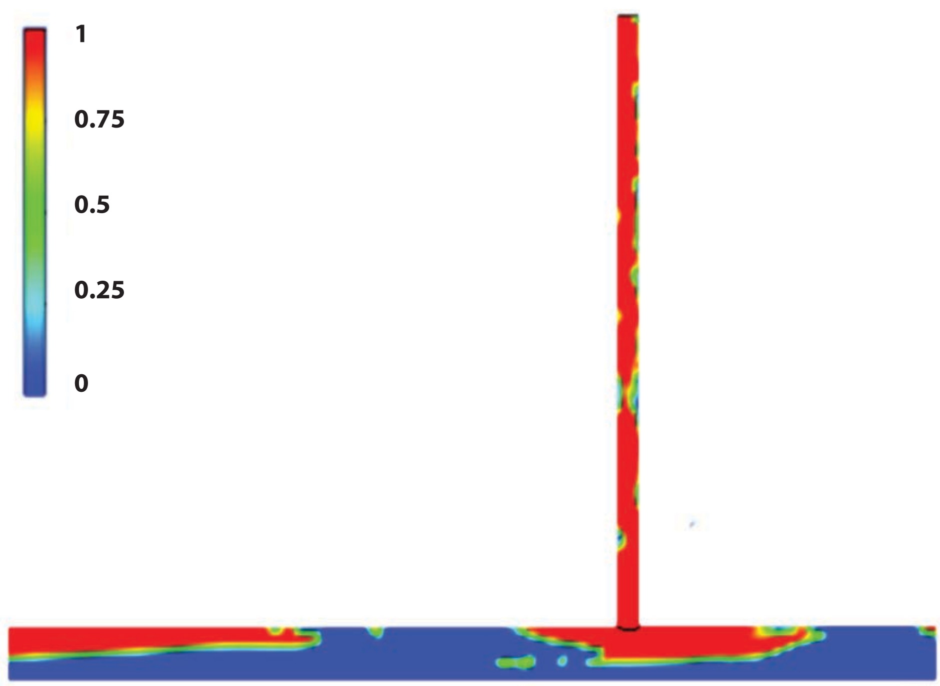


Figure 17 Slug flow approaching the T-junction

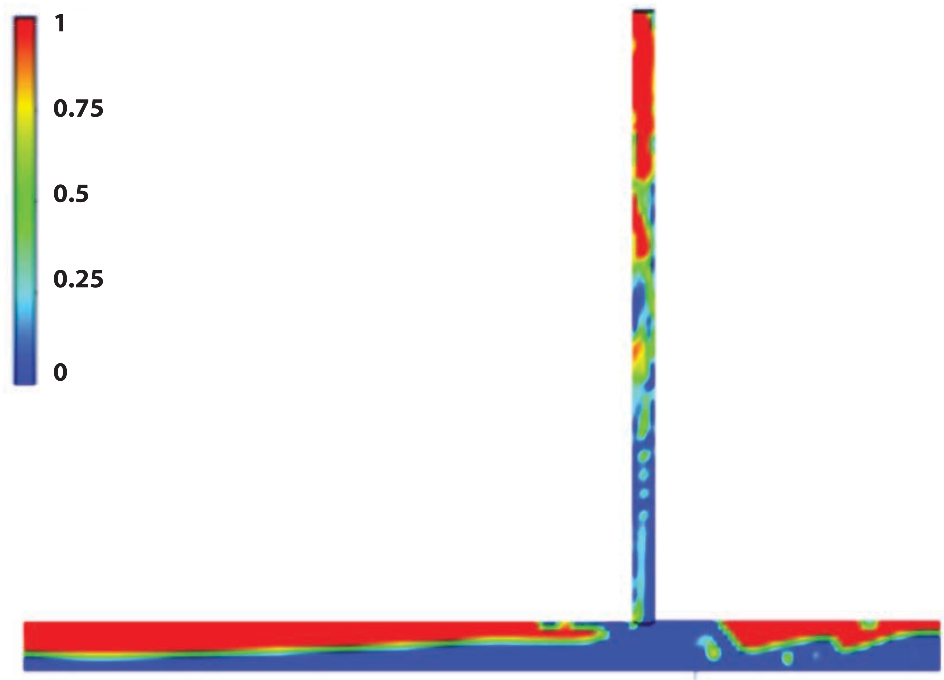


Figure 18 The slug body hit the T-junction and liquid carryover in the branch arm

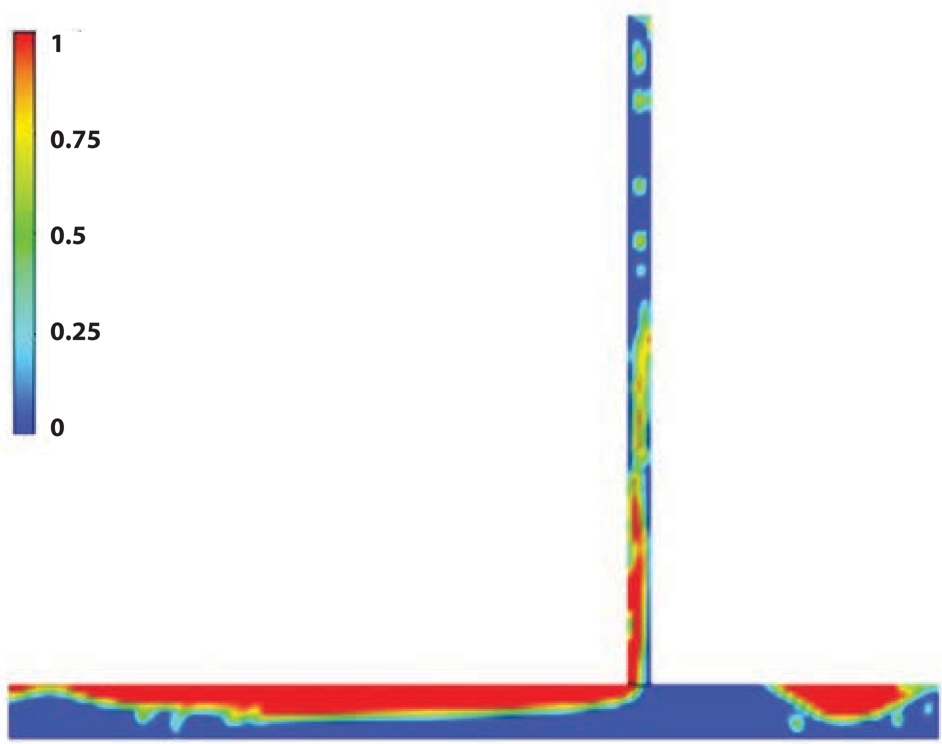


Figure 19 The slug tail about to passed through the T-junction and the liquid falls down under the action of gravity

Figure 20 showed that the slug body completely passed the T-junction. All the holdup water in the branch arm has fallen back into the main arm. The branch arm is now filled up again with air, but traces of water can still be detected. Note that traces of water are detected close to the inner surface of the branch arm. The air velocity has barely enough momentum to drag the water film up into the branch arm.

Once the mechanism of liquid carryover is understood, Figures 21, 22 and 23 showed the recorded liquid holdup, the corresponding input phasic velocities and holdup frequency at the outlet of branch arm from 0 to 5 seconds for diameter ratios 1, 0.5 and 0.3, respectively. When the liquid holdup at the cross-sectional area at branch arm outlet is greater or equals 0.75, it is assumed that carryover occurred and is added to holdup frequency, fh. Therefore, the holdup frequency is assumed to give a rough indication of liquid carryover per unit second.

By comparing Figure 21, 22 and 23 side by side clearly showed that the liquid holdup or frequency is strongly influenced by the diameter ratios and liquid superficial velocity. The holdup frequencies are highest when liquid velocity is 2 m/s and gas velocity is 1 m/s for all three diameter ratios. This can be explained by the fact that every time a liquid slug traverses the junction, a certain amount of liquid jumps up into the side arm. With the increase in liquid superficial velocity, the kinetic energy of the liquid phase is also raised. This cause liquid to jump higher in the side arm. In normal practice, this jumping liquid drops back into the main arm under the influence of gravity at low run arm pressures, after the slug has moved pass the junction. Yet, in present case only a small fraction of it flows backward, while most of it is carried forward, resulting in liquid carryover. This can be attributed to the small side arm height of 0.3 m in current study. Hence, this jumping liquid does not get enough pipe length for falling back. Moreover, as inlet water velocity increases, volume of water available for carryover in the side arm will increase proportionally, resulting in higher liquid carryover.

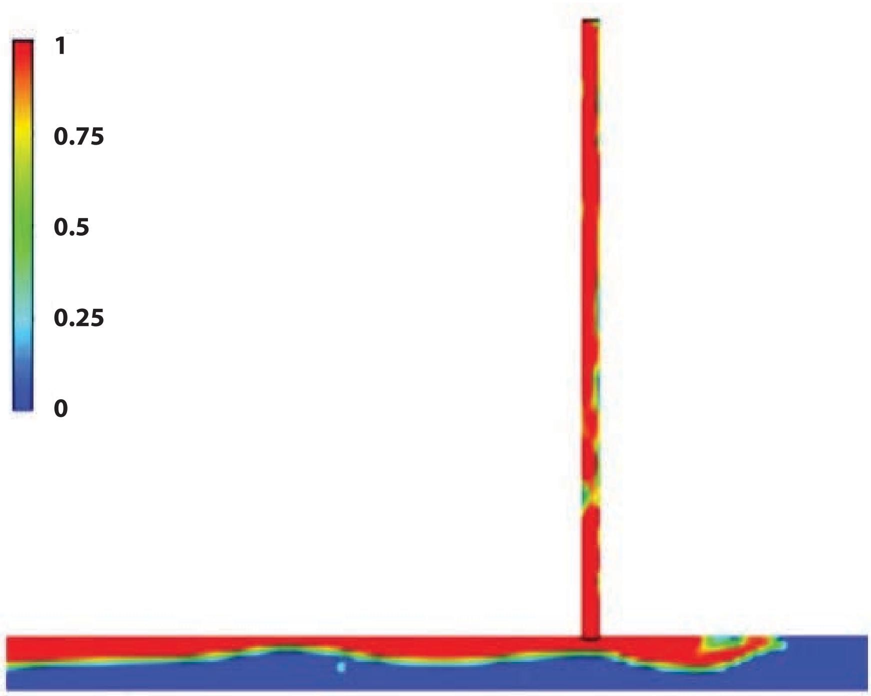


Figure 20 The slug body passed through the T-junction and no liquid carryover

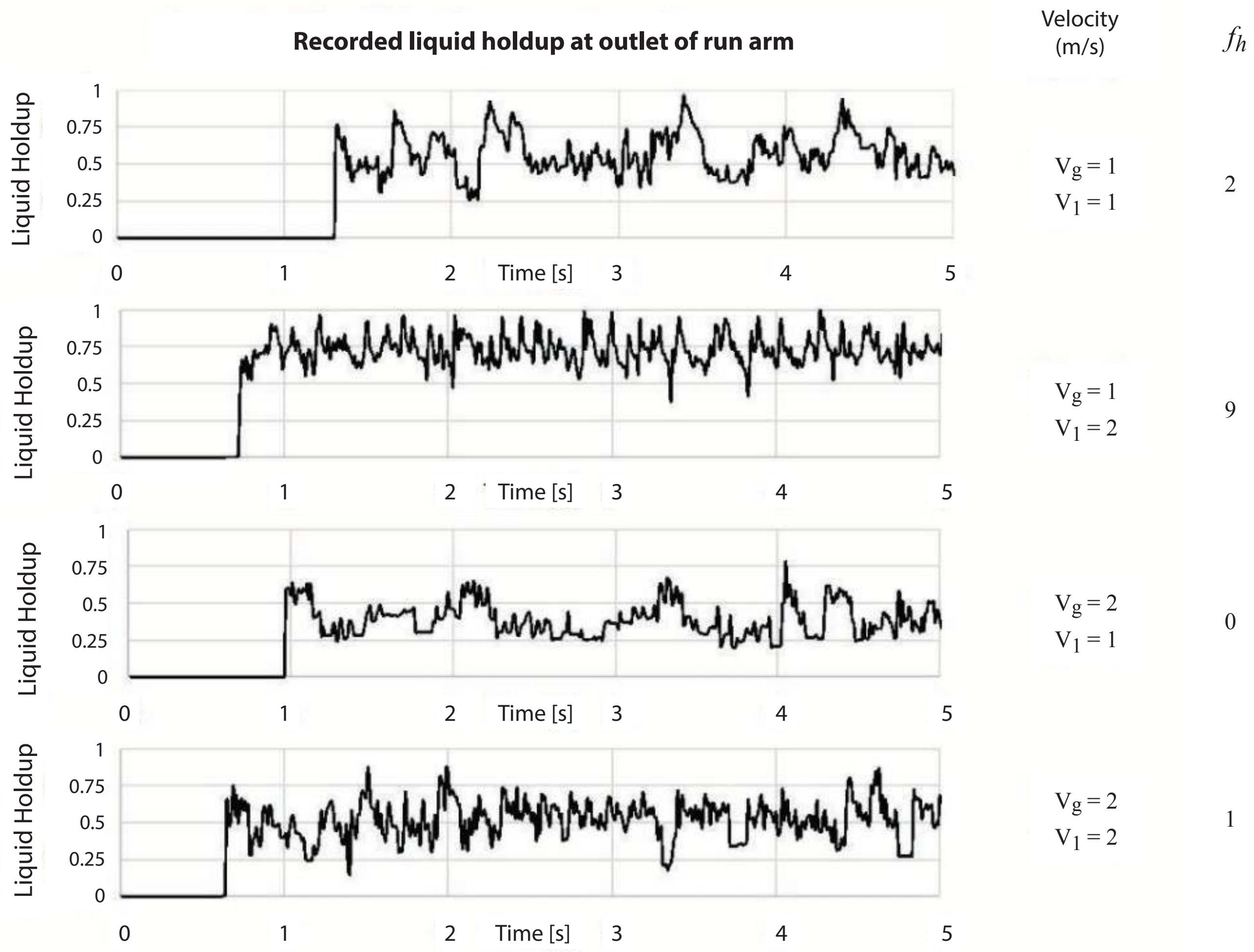


Figure 21 Liquid holdup frequency at outlet of side arm with diameter ratio 1.0

The results also suggested that the smallest diameter ratio have the highest liquid holdup frequency, if one compares fh for all three diameter ratios. While this observation is true for the smallest diameter ratio 0.3, it is impossible at this point to blanketly concluded that liquid holdup frequency is inversely proportional to the diameter ratio. This is because for diameter ratio 0.5, the holdup frequency is not substantially different than diameter ratio 1.0.

At this point, it is important to remember the assumption made in calculating the holdup value at branch arm outlet, i.e. whenever HL ≥ 0.75, liquid carryover is assumed to have taken place. With this assumption and the increases in holdup frequency at 0.3 diameter ratio, it is easily fall into conclusion that smaller diameter ratio T-junction will increase liquid holdup. From literature survey, the Nottingham Group [1, 3, 6, 8] had already pointed out experimentally that smaller diameter ratio T-junction is found to reduce liquid carryover.

The writers are confident that the numerical results were genuine. In order to investigate this further, the holdup distribution versus frequency at the branch arm outlet were plotted in Figure 24 with sampling frequency of 0.01 sec. The four cases A, B, C, D corresponds to the different superficial gas and liquid velocities shown in Figures 21 – 23.

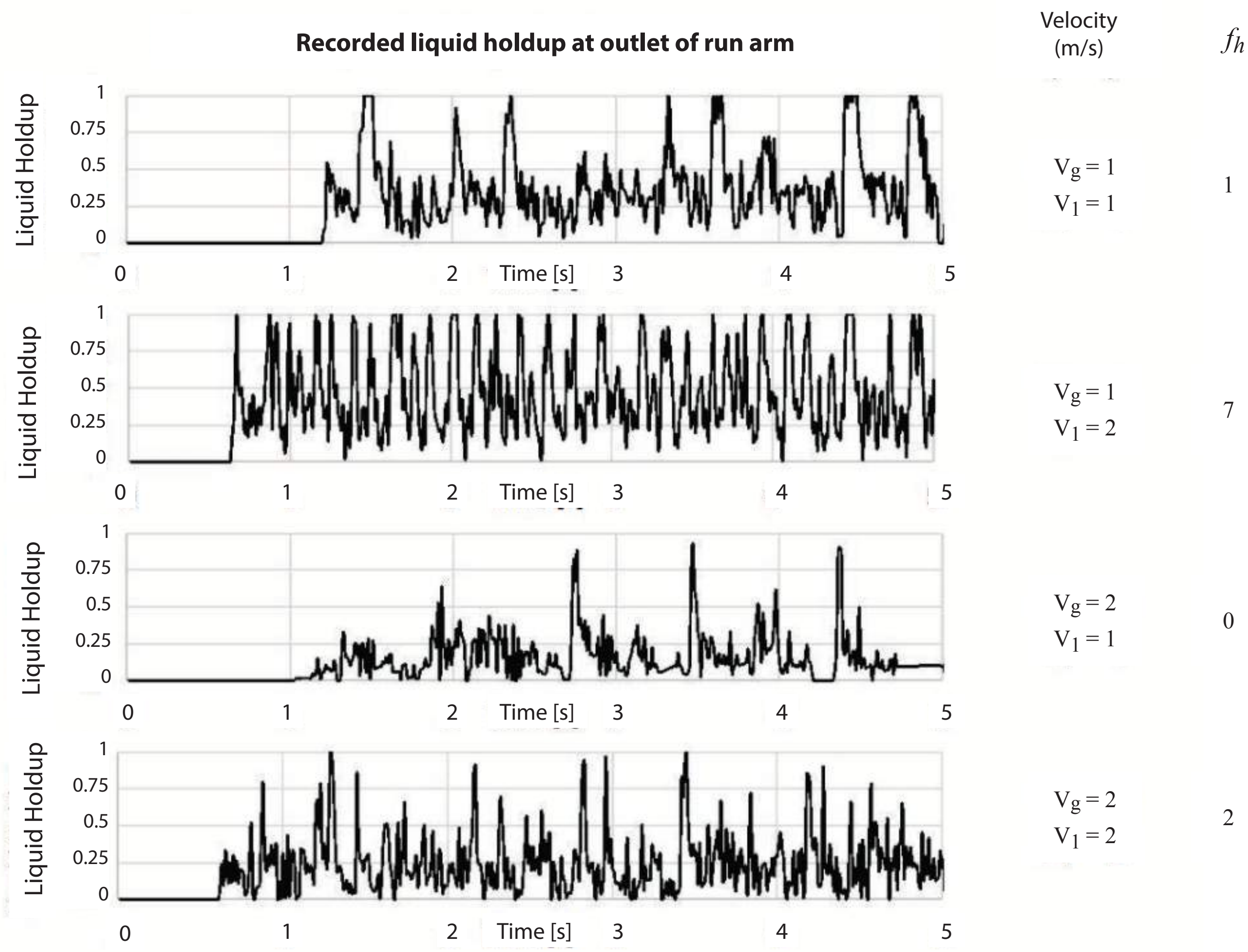


Figure 22 Liquid holdup frequency at outlet of side arm with diameter ratio 0.5

It is clearly evident that Figure 24 agreed with the experimental conclusion from [1, 3, 6, 8], i.e. smaller diameter ratio T-junction has a better separation efficiency, or less liquid carryover. A further careful study reveal that while this is overall true, HL ≥ 0.75, smaller diameter ratio T-junction showed a very high percentile frequency when HL ≤ 0.2 compared to equal diameter T-junction. This is an interesting observation that was never reported in open literature. To come back to the problem of recorded higher holdup frequency in Figures 21 – 23, one reason which came to light after extensive study of these results is that the height of the appendage may also be an important factor in determining the liquid carryover. In the present model, the appendage is only 0.3 m high. It also revealed that holdup frequency cannot be equated to liquid carryover, leading to contradictory conclusion. This is because in numerical simulation, what is recorded is only a temporal HL ≥ 0.75, while in reality, liquid carryover is considered happened even if HL = 0.1 and the effect is cumulative. Hence, further research is required to define liquid carryover mathematically so that it could be numerically investigated.

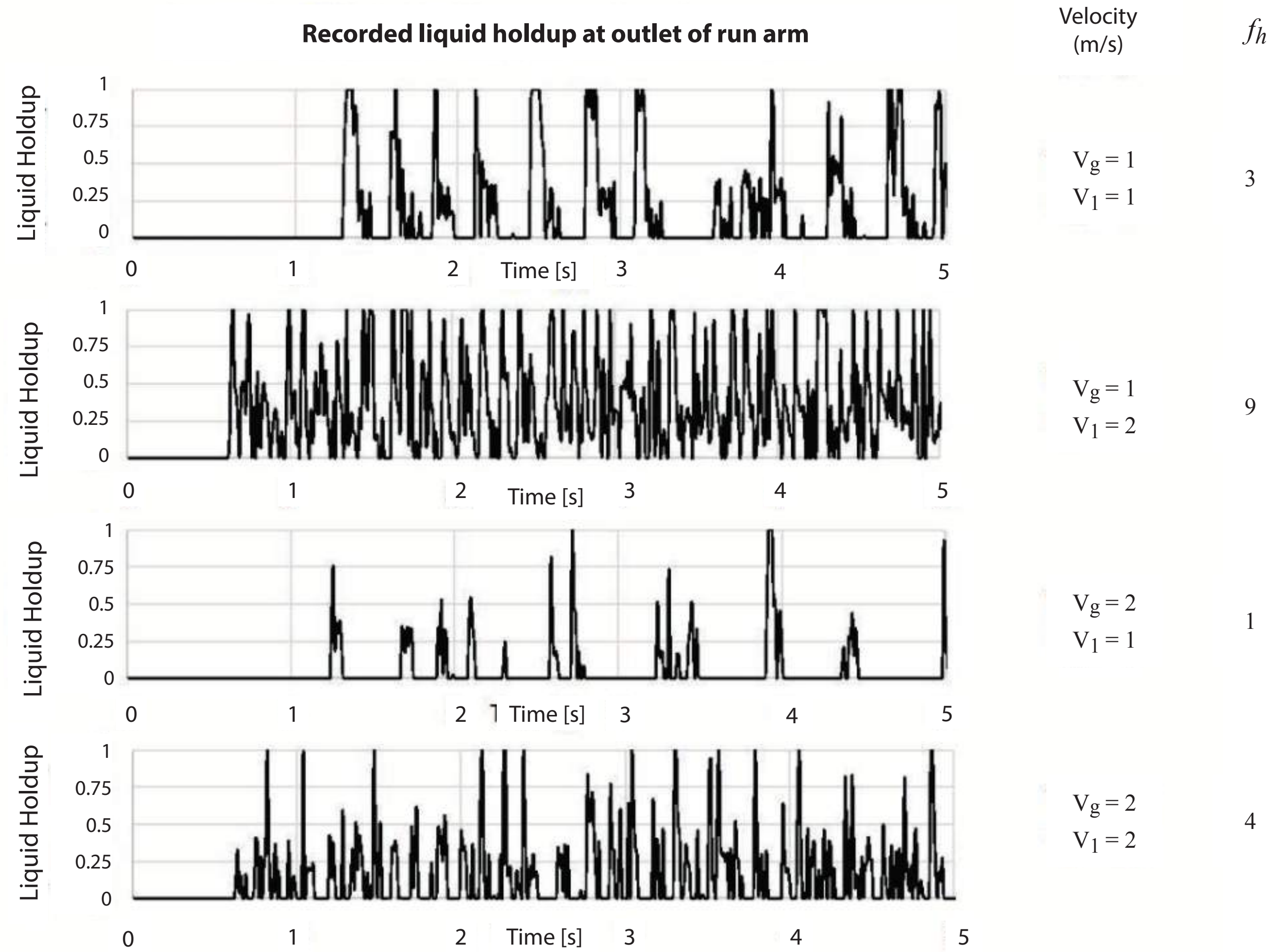


Figure 23 Liquid holdup frequency at outlet of side arm with diameter ratio 0.3

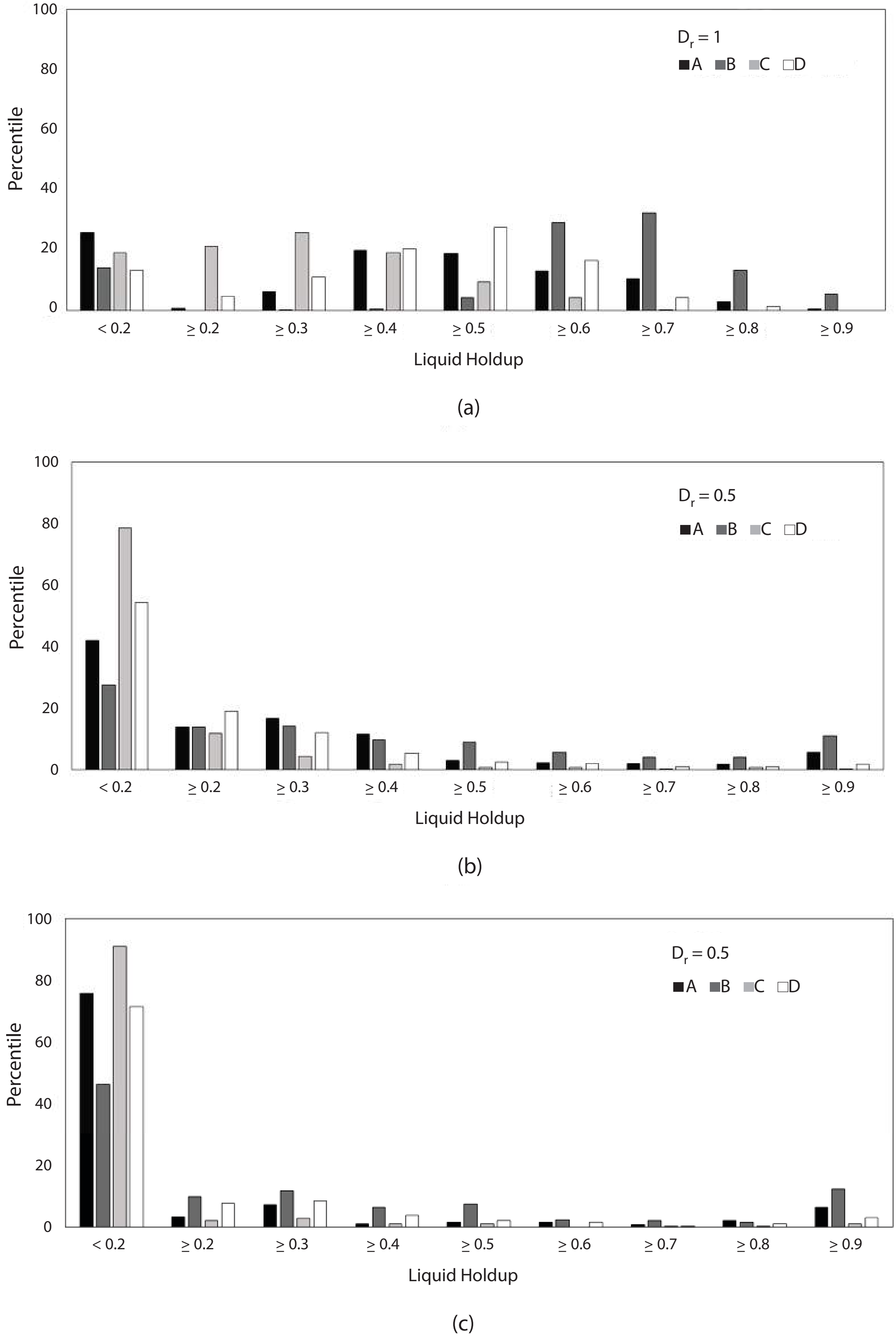


Figure 24 Liquid holdup distribution versus percentile frequency for diameter ratio (a) 1.0; (b) 0.5 and (c) 0.3

CONCLUSION

A numerical study is carried out using FLUENT 16.1 Volume of Fluid Method to investigate the effects of liquid holdup in a T-junction using a different branch to main arm diameter ratios under the influence of different superficial phase velocity. The study focused on slug flow regime in the main pipe and the effect of the slug body on liquid carryover. Unlike our previous work which focus on steady state, this investigation takes into account the fluid dynamics and unsteady nature of slug flow. As far as the authors' knowledge is concerned, we have not come across any research publication that investigated the liquid carryover in T-junction and its associated slug flow in the main pipe, either numerically or experimentally. In this paper, numerical investigation found that liquid holdup in the branch arm decreases with decreasing diameter ratios, consistent with experimental conclusion. The holdup frequency at the outlet of the branch arm cannot be adequately used as a criteria equivalent to liquid carryover, which lead to a contradictory conclusion. It is also coming to light that T-junction's height may play substantial role than previously thought in defining liquid carryover numerically. The experimental investigation of liquid carryover similar to the nature of this paper is underway and the authors should be able to report the findings in the near future.

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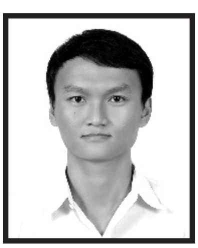

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