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Experimental investigation of two-phase separation in a horizontal T-junction with vertical branch arm

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ABSTRACT

T-junctions are commonly used in offshore platforms and process industry. When two-phase flow passes through T-junction, separation of two-phases takes place. This separation of two-phase flow through T-junction produces high liquid carry-over in the branch arm, causing breakdown of downstream equipment. In this experimental study, phase separation data have been obtained for air-water mixture flow through dividing T-junction with a pipe diameter of 74 mm and the branch arm is positioned vertically upward. T-junctions with diameter ratios of 1, 0.67, 0.5, and 0.27 were tested in the slug flow regime. The superficial velocities of air (J_{G1}) were varied 0.20 - 1.16 m/s and inlet water superficial velocities (J_{L1}) were varied 0.40-0.53 m/s. The extraction ratio between branch arm and main arm (W_3/W_1) was varied between 0 to 1. It was observed that the phase separation efficiency of T-junction depends upon the diameter ratio, upstream superficial velocities of both phases - air and water. Finally, the experimental data have been compared against the predicted results obtained from the numerical correlations.

Keywords: Gas-liquid separation; T-junction; slug flow; diameter ratio effect; superficial phases' velocities.

INTRODUCTION

T-junctions are frequently used in the two-phase gas-liquid distribution system as phase separators and flow dividers. Their application exists in process industry, oil and gas, and off-shore platforms [1, 2]. During gas-liquid flow through T-junction, uneven phase distribution occurs. Each time volume of individual phases diverted into the branch arm is different; sometimes, the branch receives the gas-liquid rich stream, and another time it receives gas-rich stream during which liquid flows un-diverted into run arm [3–5]. This uneven and volatile nature of splitting in T-junction is because of the involvement of a large number of geometrical parameters that govern the splitting phenomenon. These parameters include D_1, D_2, D_3 diameter of main arm, run arm, and branch arm, L_1, L2, L_3 length of main arm, run arm and branch arm, α angle of branch arm from the main arm, and β Angle of branch arm from horizontal plane. Figure 1 illustrates the simple geometry of a T-junction.

Besides geometry, the mass flow rates of the phases, pressure drop between main and run arm ΔP_{12}, pressure drop between main arm and branch arm ΔP_{13} across T-junction, and physical properties also influence the phase separation phenomenon [6–8].

The uneven splitting of the gas-liquid phases across T-junction causes the problem for the downstream keeping the performance and efficiency in a declining trend. As in the case of evaporators, uneven distribution of phases in gas-liquid flow across T-junction will leave some branches to dry out and causing them to underperform in terms of reduced heat transfer [9–11]. However, this uneven distribution of the phases made the T-junction possible to be used as a partial phase separator [12]. The T-junction has the edge over the conventional phase separators because firstly, it can be introduced where space is limited for instance in off-shore applications where the inclusion of T-junction before main separator enables the partial phase separation to occur in which majority of gas volume can be separated and redirected. This decreases the load from the main separators and also reduces the area it occupies on the platform. Secondly, in the handling of combustible fluids as the residence time is low. Thus inventory of flammable liquids will be meager [13, 14].

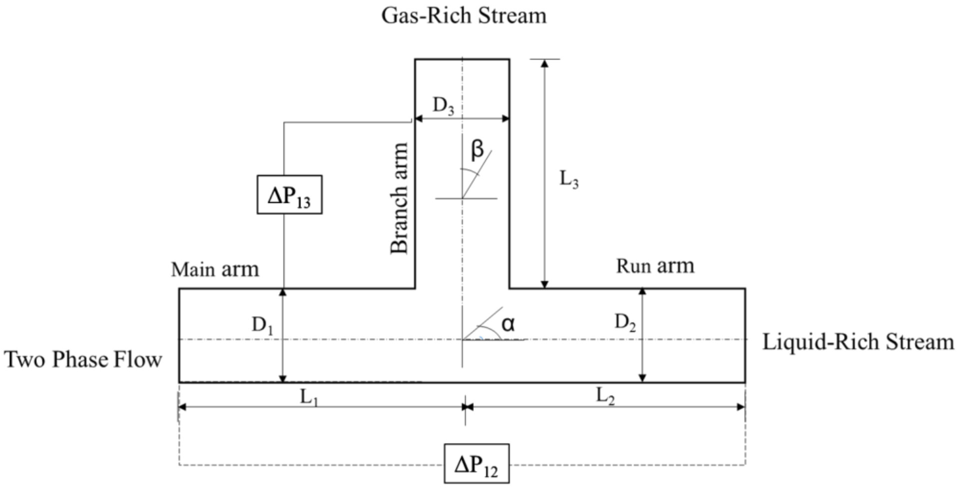

Figure 1. Geometry of the T-junction.

Azzopardi [15] studied the effect of branch arm diameter ratio in a T-junction. The diameter ratio was 1, 0.67, and 0.33. It was reported that reducing the diameter ratio, the preference of the gas phase to flow into the branch arm increased, and liquid phase flows straight into the run arm. It was also observed that reduction in the branch arm diameter produced pressure drop causing the gas phase to pour into the branch arm and also reduced the axial distance available for the liquid take off in the branch arm. Similar observations were made by Peng [16], Baker [17], Pao et al. [18].

Shoham et al. [19] experimented with the air-water two-phase flow in a regular T-junction with an internal diameter of 0.051 m. The experiments were performed by varying inlet superficial gas and liquid velocity in stratified, stratified-wavy, and annular flow regimes. It was concluded that at the fixed superficial gas velocity, the preference of liquid to enter into the branch arm decreased as superficial liquid velocity increased and liquid preference into the branch increased as superficial liquid velocity decreased. This was due to the increase in momentum of the liquid phase. At higher velocity liquid has higher momentum and passed the junction un-diverted straight into the run arm, and at a lower velocity, it has lower momentum and easily turns into the branch arm. Similar observations were made by Walters [20] and Yang et al. [21].

Rubel et al. [22] Performed steam-water experiments in regular T-junction for stratified, stratified-wavy and semi-annular flow. It was reported that an increase in superficial gas velocity (J_{G1}) the degree of phase separation decreased in semi-annular flow but increased in stratified flow. Reimann et al. [23] presented air-water experiments at different orientations of T-junction. The results demonstrated that as the inlet superficial gas velocity increased, phase separation decreased with the increase of liquid carry-over in the branch arm. This is in accordance with the results reported by Ballyk and Shoukri [24], Buel et al. [25] and Tran et al. [13]. Most of the available literature is on the stratified, stratified wavy and annular flow, but less of the work has been done slug flow.

The aim of the experimental study is to perform a parametric study of phase separation behavior across T-junction in slug flow. The effect of diameter ratios and phases' superficial velocities have been examined.

TEST RIG ARRANGEMENT

The two-phase air-water flow loop is illustrated in Figure 2. The test section consists of air and water feeding lines, mixing section, T-junction, branch separator tank, liquid holdup tank, and liquid supply tank. T-junctions used in this experimental study are made up of acrylic pipes welded plastically to each other. The main purpose of using acrylic pipes was to gain the optical clarity of the phase separation mechanism inside the T-junctions.

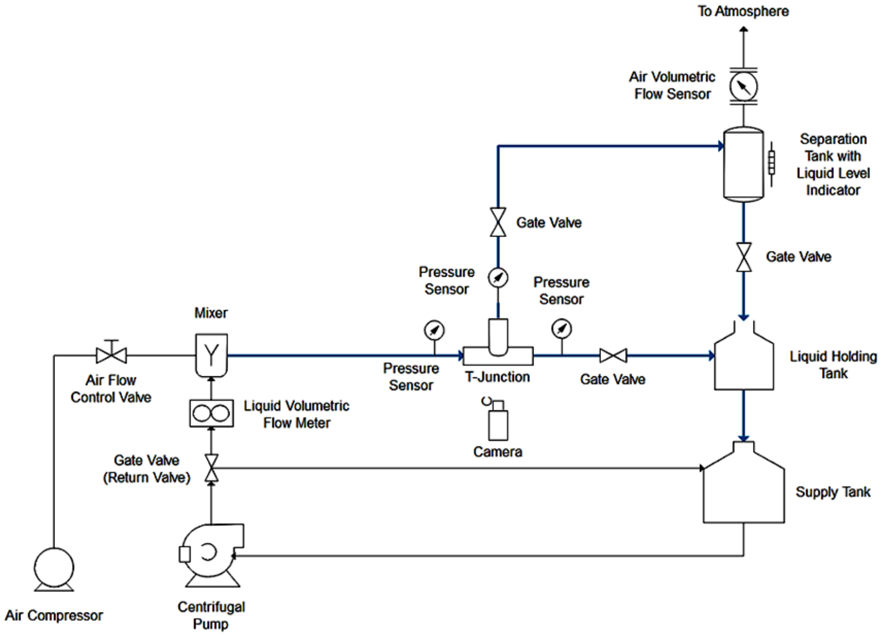

Figure 2. Experimental flow loop [26].

Air and water were supplied to the mixer through different feed lines. A five horsepower two-stage SWAN air compressor capable of delivering air at 0.9 m^3/s and 8 bar pressure, was used to feed air into the system. The flow rate was controlled via a gate valve installed at the air inlet section of the mixer. A three-phase (415 V, 50 HZ) TECO centrifugal pump was used to introduce water inside the mixture. Correct water pressure and flow rate were maintained via an inlet control valve and bypass valve. The centrifugal pump was capable of delivering water at a maximum flow rate of 0.0167 m^3/s, with 8-10 m of pressure head. The flow rates of air and water were measured by NEW-Flow made calibrated rotameters installed in the inlet section. The calibration of the rotameters was within +4% of the manufacturer's value.

The test section was provided with 82 times pipe diameter flow development length. The flow then entered into the T-junction having horizontal main and run arm and vertical upward branch arm. The length of each arm of the T-junction was of 1 m. The fluid stream flowed around 2.5 m before diverting into the branch separator tank. Air and water were separated in the branch separator tank by the action of gravity. Air measured by flow sensor SA5000 and the water was measured by collecting it for a specific time in the separator tank. After the measurement, water was returned to the supply tank via a liquid holdup tank. The fluid flow discharging from run arm flowed further around 3 m and collected into the supply tank. The supply tank was kept at atmospheric pressure, water was collected and supplied back to the system, and the air was vented into the atmosphere. The pressure transmitters WIKA A-10 were installed at an inlet and both outlets of T-junction. The function of these transmitters was to measure gauge pressure in order to find out the pressure profile across the T-junction. The pressure transmitters have the range of 0-1000 psi with <0.5% BFSL non-linearity.

Sony α6000 high-speed compact mirrorless camera with a superfast hybrid autofocus system was used to record the process of phase separation in the test section. The camera has a 24.3-megapixel sensor resolution. It has the capacity to record 6000 x 4000 image quality and 1920 x 1080 60 fps video quality.

GRAPH INTEGRATION ANALYSIS

The phase separation efficiency was analyzed by the numerical integration method. The method was used to calculate the value of the area under the curve for each experiment. Figure 5 and Figure 6 shows fraction of air taken off vs. fraction of water taken off in the branch arm. It only provides the information mainly for the critical gas take-off (gas threshold) and maximum liquid carry-over. Numerical integration of the Newton-Cotes Method of improved Trapezoidal Rule was performed to calculate the area under a curve.By integrating these graphs, the value of area under the curve will be obtained that is the actual representation of the separation efficiency of T-junction. The method calculates the area under a curve by using available points in the data, as shown in Figure 3.

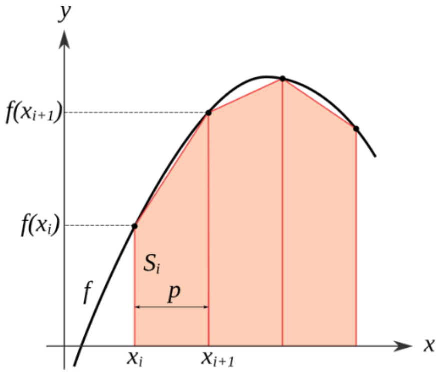

Figure 3. Newton-Cotes trapezoidal rule integration.

In Figure 3, *p* shows distance between two intervals, S_i denotes area under curve, X_i and X_{i+1} shows interval at distance of *i* and *i+1*.

DATA RANGE

The superficial velocities of gas, superficial velocities of liquid, and diameter of T-junction were varied in this experimental investigation. The superficial gas velocity (J_{G1}) and superficial liquid velocity (J_{L1}) were varied 0.20-1.16 m/s and 0.40-0.53 m/s respectively. The diameter ratios selected were 1, 0.67, 0.52, and 0.27 and are shown in Table 1.

Table 1. Inlet flow conditions in slug flow.

Velocity Combination (VC)	**J_{G1} (m/s)**	**J_{L1} (m/s)**	**Velocity Ratio (VR)**
1	0.2	0.4	0.48
2	0.2	0.53	0.36
3	1.16	0.4	2.94
4	1.16	0.53	2.17

It was visually observed that the flow regime approaching to the T-junction was slug flow as it was be seen through transparent pipes. The inlet flow velocities of both phases, air-water were then plotted on Taitel and Dukler map [27] to ascertain the flow patterns observed during the experiments, as shown in Figure 4. It was found that the flow regime observed visually and that predicted by Taitel and Duckler were in good agreement with each other.

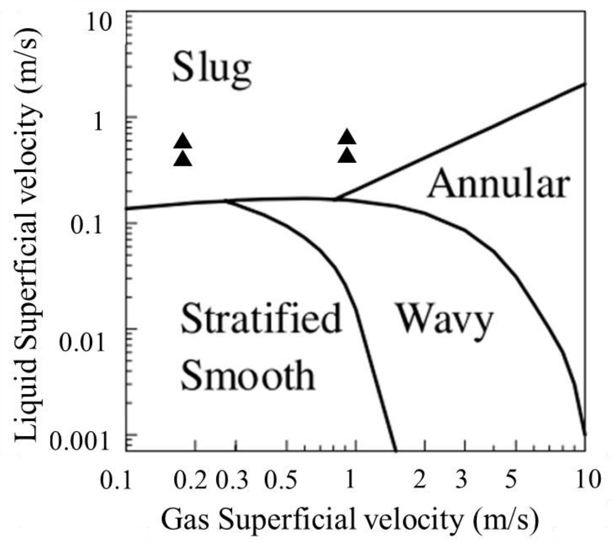

Figure 4. Taitel and Dukler Flow [27] pattern map showing the (▲) inlet conditions at which data was taken on 74 mm pipe diameter.

RESULTS AND DISCUSSIONS

Diameter Ratio of the Branch Arm

The phase separation behavior of T-junction was investigated in regular and reduced T-junctions. The investigation of the data shows that the phase separation efficiency of the T-junction depends upon the diameter ratio. The liquid carry-over in regular T-junction was higher compared to the reduced T-junction, and there was a systematic decline in the liquid carry over as the diameter of the branch arm decreased. It can be seen in Figure 5, that maximum liquid carry-over decreased into the branch arm as the diameter ratio was progressively reduced. In Figure 5(a), for T-junction with a diameter ratio of 1.0, the liquid carry-over was around 88% in the branch arm, that means when all the gas phase was extracted into the branch arm 88% of the liquid also goes with it. The liquid carry-over reduced to 62% in T-junction with 0.67 diameter ratio.

Furthermore, reducing the diameter ratio to 0.5 and 0.27, liquid carry-over reduced to 37% and 25% respectively. This systematic decrease in the liquid carry over with a decrease in the diameter ratio was because of the axial distance available for the liquid to take off in the branch arm decreases and is accordance with the findings reported by Wren et al. [28]. In large diameter ratios of the branch arm, the distance available for the liquid to divert into the branch was higher. Thus liquid — having higher axial momentum had enough time to be influenced; it got diverted and extracted into the branch arm. However, as the diameter ratio decreased this axial distance and the time to divert into the side decreased. In diameter ratio of 0.27, the distance was very small; hence, most of the liquid bypassed the opening of the branch arm, and very less liquid was diverted into the branch arm.

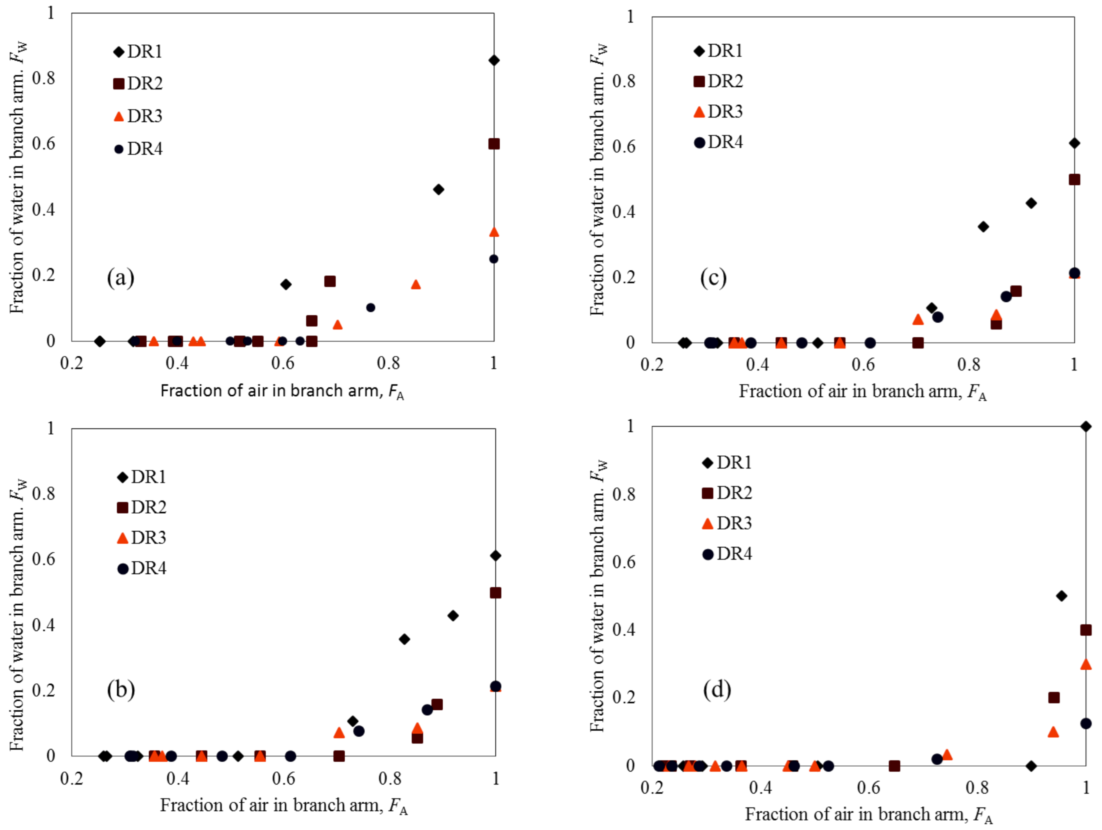

Figure 5. Phase separation behavior across different diameter ratios DR=1, DR=0.67, DR=0.52, DR=0.27 (a) J_{G1}=0.2 m/s, J_{L1}=0.4 m/s (b) J_{G1}=0.2 m/s, J_{L1}=0.54 m/s (c) J_{G1}=1.2 m/s, J_{L1}=0.4 m/s (d) J_{G1}=1.2 m/s, J_{L1}=0.54 m/s.

Upstream Superficial Velocities of Phases

The phase splitting behavior of each T-junction is plotted based on different superficial velocities of gas and liquid phase in Figure 6. It was observed from Figure 6, the increase in the superficial velocity of the gas phase J_{G1} increased the liquid carry-over in the branch arm and an increase in the superficial velocity of the liquid phase J_{L1} decreased the liquid carry-over.

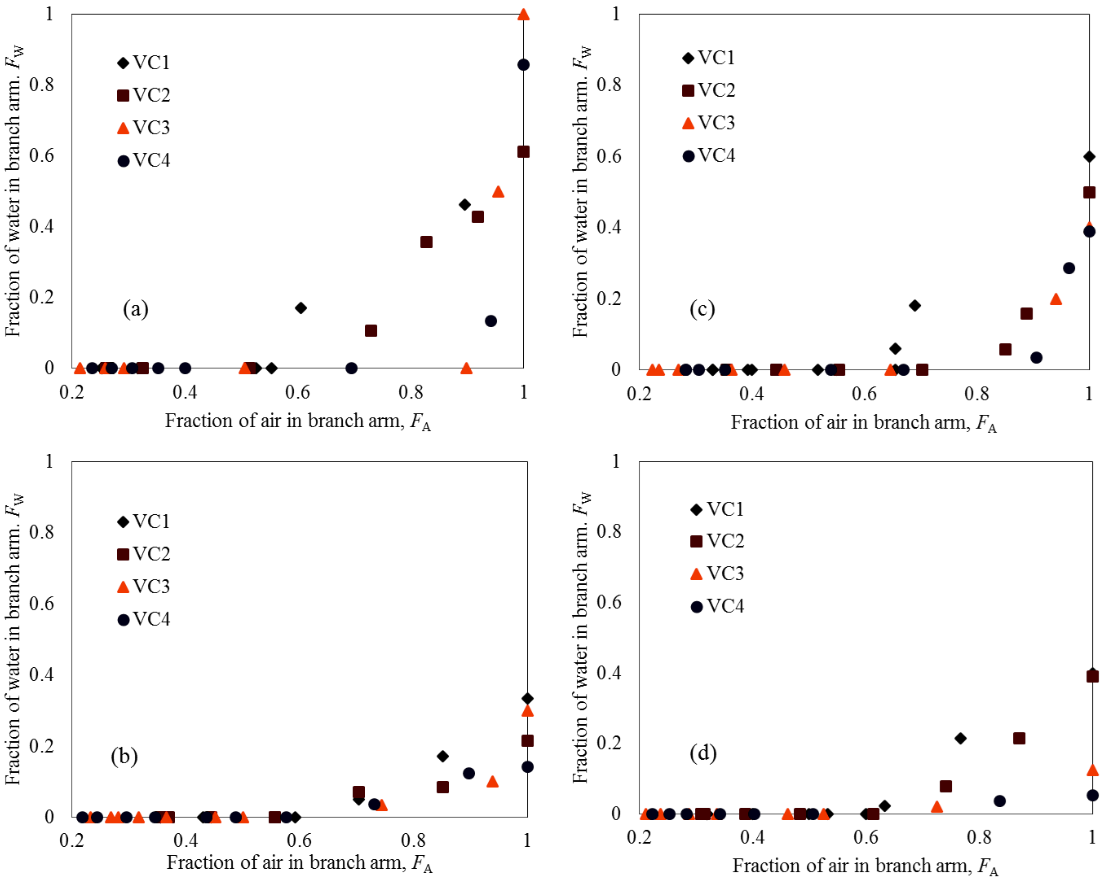

Figure 6. Phase separation behavior across different diameter ratios (a) DR=1, (b) DR=0.67, (c) DR=0.52, (d) DR=0.27.

Figure 6(a) for DR=1 suggest, that keeping the superficial velocity of the liquid J_{L1} constant, if the superficial velocity of the gas J_{G1} is varied from 0.2 m/s (VC1, VC3) to 1.2 m/s (VC3, VC4), higher amount of liquid is sucked into the branch arm. Similar observations were made for T-junction with diameter ratios of 0.67, 0.52, and 0.27. Furthermore, it was noticed that when the superficial velocity of water J_{L1} was varied from 0.4 m/s in (VC1, VC2) to 0.54 in (VC3, VC4), the liquid carry-over decreased. It was because liquid carry-over depends upon the phases' momentum and the pressure drop across the T-junction. According to the findings reported Walters et al. [29], liquid has a higher momentum than gas phase. As the velocity of the liquid phase increased its momentum increased and it has lesser time available to divert into a branch arm. Therefore, less liquid was extracted into the branch arm. As the superficial velocity of gas J_{G1} was increased from 0.2 to 1.2 m/s at fixed 0.4 m/s liquid superficial velocity J_{L1}, it was observed that more liquid was extracted into the branch arm. This was because of the Bernoulli Effect, as the more gas is extracted into the branch arm, it created a pressure drop across the branch arm and main arm, and the pressure drop will increase. This also happened at higher extraction ratios because at higher extraction rate higher volume of gas was extracted into the branch arm, creating suction across the T-junction and higher volume of the liquid will be sucked into the branch arm as the superficial velocity of the gas phase J_{G1} is increased into branch arm. The effect of diameter ratios vs. the area under the curve are plotted in Figure7. It was observed from Figure 7 that if liquid carry-over is small, the area under a curve will have smaller value and vice versa. So, it is concluded that smaller the area under a curve, better is the phase separation across the T-junction and larger the area under curve the higher is the liquid carry-over and thus, shows poor phase separation performance.

Figure 7 clearly shows that as the diameter ratio decreased the area under the curve also decreased; this means that a small amount of liquid was carried into the branch arm. For all the velocity combinations it was observed from Figure 7, that decrease in the diameter ratio depicts the clear trend of a smaller area under a curve. Therefore, the T-junction with the smallest diameter ratio perform better and produce better phase separation. From the experimental data obtained, it was analyzed that gas-liquid phase separation in T-junction and liquid carry-over in the branch arm followed a particular mechanism.

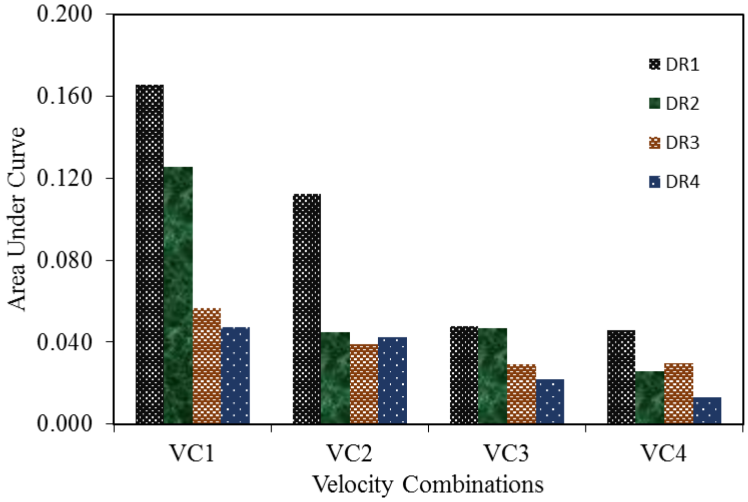

Figure 7. Effect of diameter ratio vs. area under the curve.

Another interesting observation was made as slug flow is the combination of liquid slug and elongated gas pocket which behaves as a stratified region when this flow approaches at T-junction, the phase split happens as per which part of the stream is opposite to the T-junction. When the gas pocket or stratified region crosses the intersection, the phase separation takes place as the entire flow is stratified. Stratified flow is un-agitated flow in which liquid flows at the bottom section of the pipe and gas flow at the upper section because of gravity.

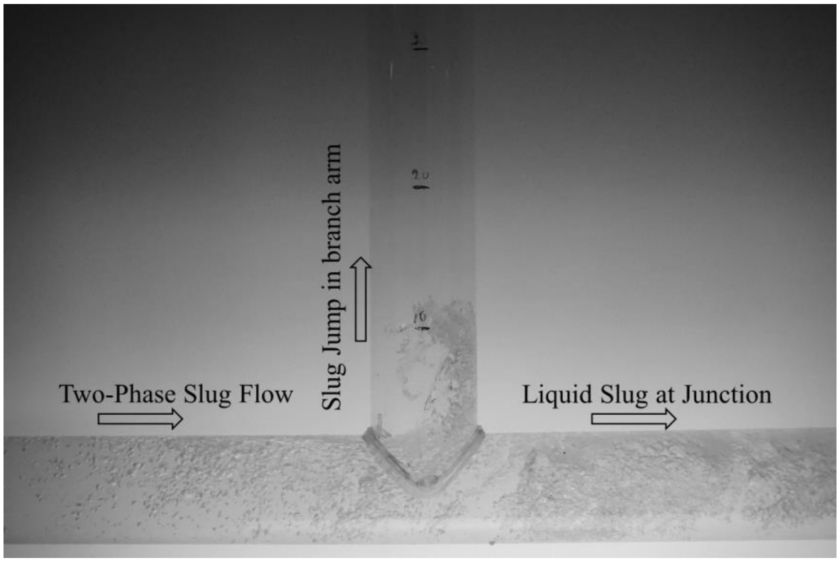

Figure 8. Slug jump in the branch arm in T-junction having DR-01.

However, when liquid slug passed the junction because of having higher momentum compared to the gas phase, the liquid strikes the with a wall of the branch arm and diverted into branch arm and is accordance with the results reported by Saieed [26]. This pouring of liquid into branch arm was motivated by the head of liquid in the main arm. Arirachakaran [30] characterized this flow as “dam break” type flow. However, Saieed [26] describes this phenomenon as slug jump and slug fall back. At low extraction ratios, slug jumps into the branch arm and fall back when the stratified portion is opposite to the junction. The phenomena of slug jump is shown in Figure 8.

It was observed that at lower extraction ratio, the slug diverted into the branch arm fell back into the junction because of action of gravity. Initially, liquid slug did not have enough momentum to cross the branch arm and consequently lost its momentum and fell into the junction as shown in Figure 9 and Figure 10.

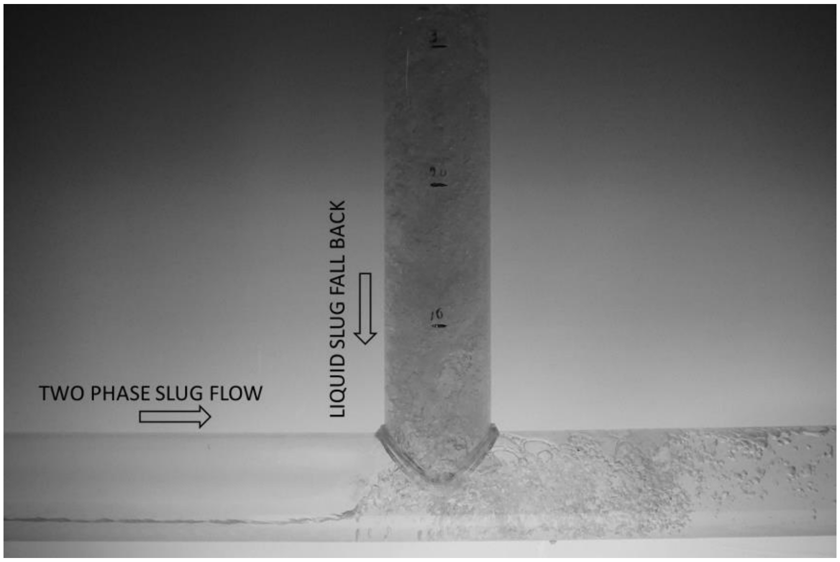

Figure 9. Slug fall back in branch arm in T-junction having DR-01.

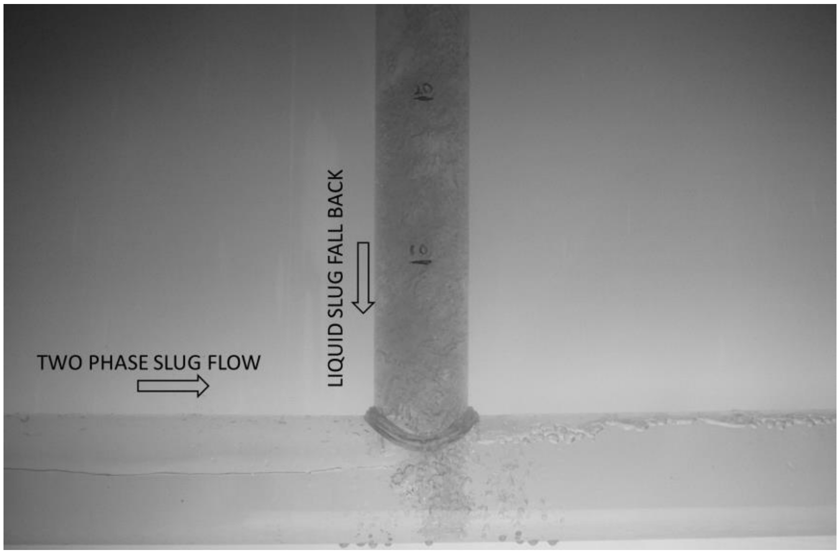

Figure 10. Slug fall back in branch arm in T-junction having DR-0.67.

From the experimental analysis, it was observed that at low extraction, the liquid carried into branch arm was purely from a liquid slug. However, at higher extraction liquid carry-over was two-fold, the liquid carried into branch arm was from liquid slug as well as from the stratified portion as suction created was high enough that liquid at the bottom of a stratified region climbed into the branch arm and is illustrated in Figure 11.

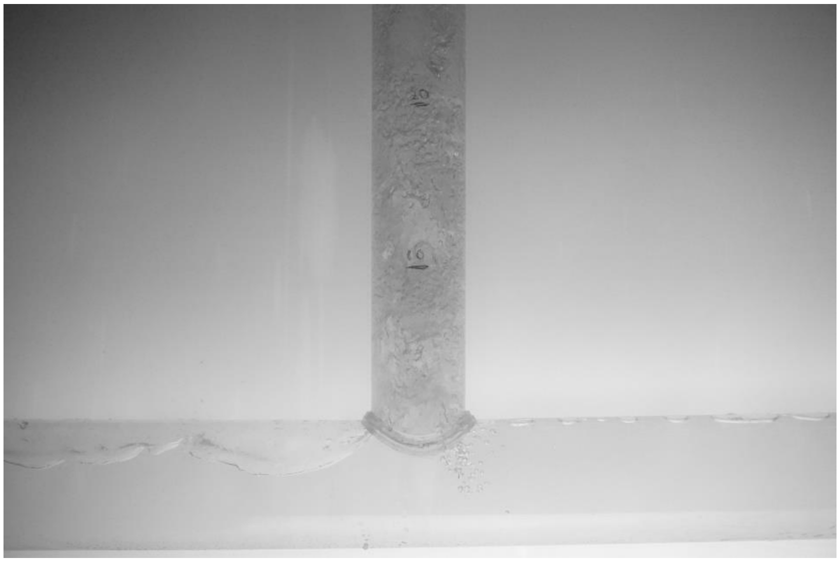

Figure 11. Maximum liquid taken off in branch arm at DR-0.67.

Phase separation behavior of slug flow at a diameter ratio of 0.5 is shown in Figure 12. It was shown that because of reduced diameter in the branch arm, less liquid was carried. This is because less volume is available for a liquid holdup in the branch arm.

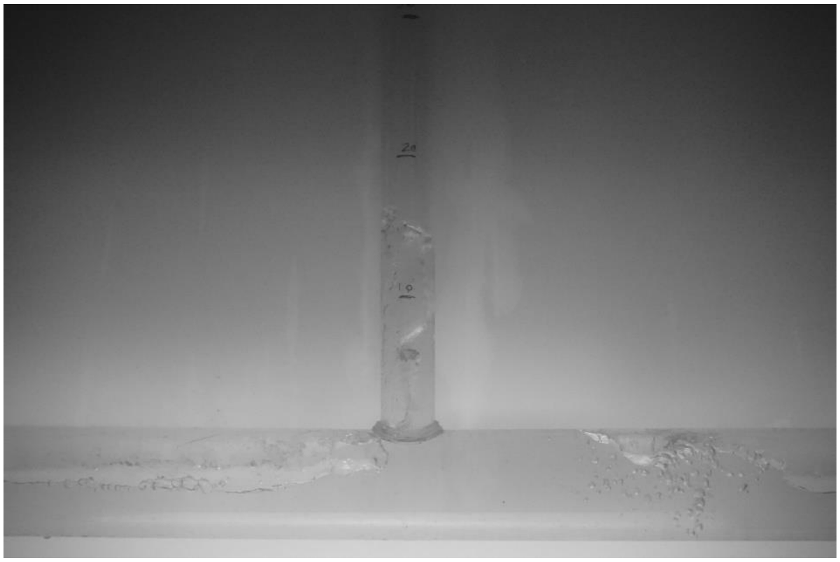

Figure 12. Maximum liquid is taken off in the branch arm in T-junction having DR-0.5.

Statistical Analysis

A statistical measure of experimental data was performed by regression analysis using Eregress software. Predicted values of F_A and F_W were calculated from the empirical model based on the experimental data. Figure 14 depicted the agreement between experimental F_A

and predicted F_A. It was found that almost 99% of predicted data points lie with ±10% error. The value of R^2 obtained was 0.88 that shows that the model fits experimental data.

Figure 15 shows the agreement between experimental FW and predicted FW. Here, it is also found that 98% of the data points lie with ±10%. The value of R^2 obtained was 0.93, and it shows that experimental data fits fairly well in the empirical model obtained by statistical regression analysis.

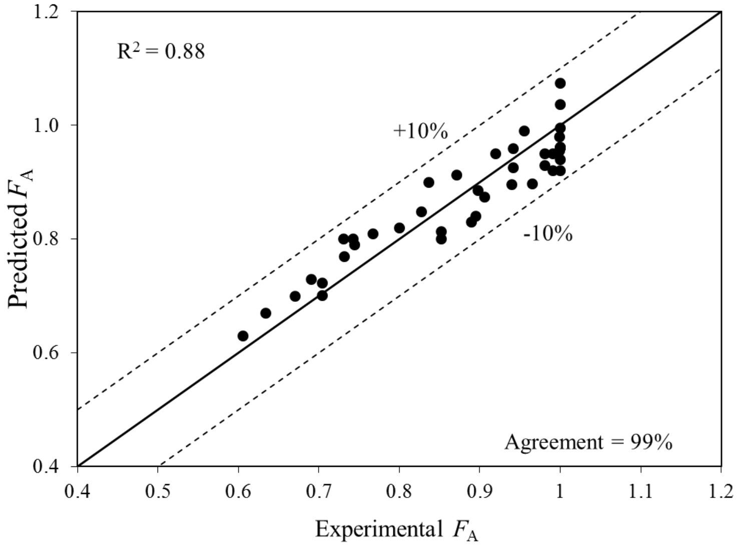

Figure 14. Comparison of experimental and predicted values of F_A in slug flow.

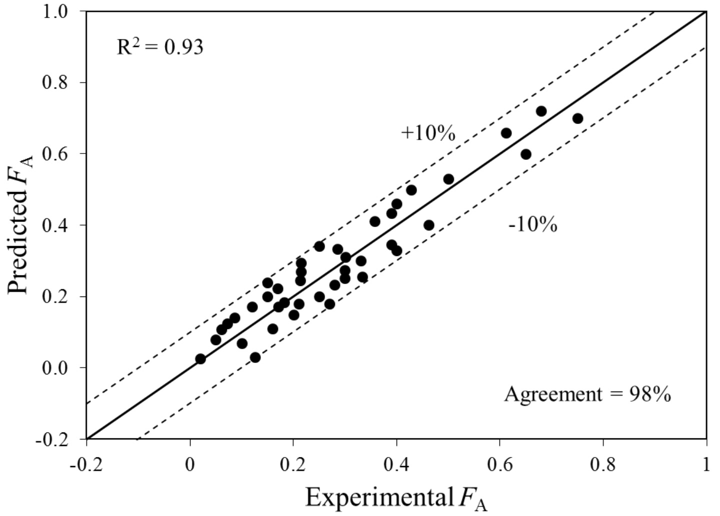

Figure 15. Comparison of experimental and predicted values of F_W in slug flow.

Comparison with Published Data

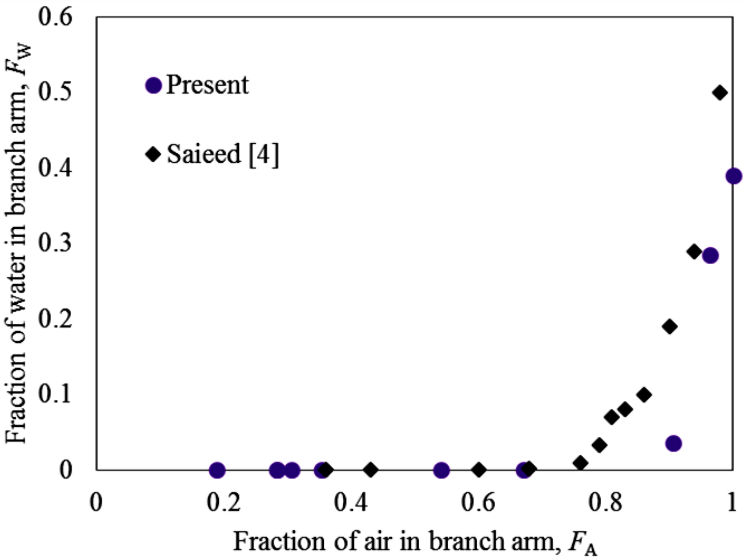

Figure 16. Phase separation data for present study at J_{G1}= 1.2m/s, J_{L1}=0.54 m/s, and Saieed et al. [5] J_{G1}=1.195 m/s, J_{L1}=0.698 m/s at diameter ratio of 0.67.

The present experimental data have been compared with published data of Saieed et al. [5]. Saieed et al. [5] obtained phase separation data for slug flow under different diameter ratios. Figure 16 shows a comparison between the present experimental data and data of Saieed et al. [5] at a diameter ratio of 0.67. In order to compare the data, the velocity ratios of both the studies, pressure, and temperature were kept similar. The experimental results in both the studies match fairly well. Smaller liquid carryover in the present study is because of the height of the branch arm in the T-junction. In the case of Saieed et al. [5], branch arm height was 1 m, but in the present study, it was 1.5 m.

CONCLUSION

The present experimental study investigated the effect of diameter ratio and superficial velocities of the phases to find out the phase separation performance of the horizontal T-junction with a vertical branch arm. It can be concluded from the above discussion that:

1. Diameter ratio plays an important role in the phase across T-junction, decreasing the diameter ratio of the T-junction from 1.0 to 0.27, improvement in the phase separation efficiency of T-junction was recorded in the range 10-50%.
2. The superficial velocity of the liquid has a significant effect, increasing the gas phase velocity from 0.2 m/s to 1.16 m/s the separation efficiency of the T-junction reduced up to 33%. Increase in the superficial velocity of the liquid from 0.4 m/s to 0.53 m/s, improved the phase separation efficiency of T-junction upto 15%.
3. The Phase separation efficiency is inversely proportional to the area under the curve, If the area under the curve is smaller, the separation efficiency of T-junction is higher, and if the area under the curve is higher, the separation efficiency is lower.

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