Air water flow through horizontal Tee junction

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1 ABSTRACT

This experiment examines the effect of superficial phase velocity and T-junction diameters on the on the phase distribution across the T- junction. Due to time constraints and the unavailability of some of the required apparatus, only the effect on fractional liquid take off was examined.

For the experiment a 51mm T-junction was used. This diameter was selected as other work was found on various smaller and larger T-junctions and not so much for this size. It was later found that a 51mm T-junction was used by Shoham et al. (1987) in his experiment.

For the experiment superficial liquid and gas velocity ranged between 0.05-0.1m/s and 5.5-27.7m/s respectively. For these velocities the flow pattern would range between intermittent and annular. From the data collected it was seen that the phase superficial velocities had little effect on the liquid fraction take off. For the geometrical model prediction splits it can be seen that there are some similar trends in the data with some deviation. Insufficient data was collected to make a more accurate quantitative analysis.

With the glass T- junction with reduced entrance and exit diameters, the air flow velocities were the same but water flow velocities ranged from 0.05-0.32m/s. It was seen that for this T-junction highest fractional take off was seen at a liquid velocity of 0.255m/s and lowest take off at 0.095m/s over the range of air velocities. On the other hand it was also seen that air flow velocities had little change over the tested range of velocities.

For similar flow conditions it was seen that a higher liquid fractional take off was obtained with the PVC T-junction than with the glass set up that had reduced diamters.

2 INTRODUCTION

The flow patterns produced by a single phase flowing thorough a pipe system is quite simple when compared that of a two phase flow. Flow regimes for a two phase flow system vary widely depending on the superficial velocities of each phase and the orientation of the pipe system. As a result of the interaction between the phases and the flow regime, it is seen that flow across a T-junction does not necessarily result in an equal distribution of phases in each of its arms. Knowing the phase distribution is necessary in many industrial areas and as a result it would be the objective of this project to test the effect of two phase flow across a horizontal T-junction.

The experiment would investigate how the superficial gas and liquid velocities affect the fractional take off of phases into the branch arm of the T-junction. In this experiment a 2 inch diameter PVC Tee would be used and data would be compared to T-junctions of different diameters. In addition another T-junction (glass) would be used that has a diameter of 1.5 inches but which is reduced in all arms to ½ inch. There would also be a comparison of the experimental data to predicted values using an existing geometrical model for phase distribution.

3 LITERATURE REVIEW

Before going into the research topic under question all the parameters, variables and fluid dynamics must be researched and explained to obtain a better understanding of the research question at hand.

3.1 Flow Patterns

The fluid dynamics that are of interest in this study would be the turbulent or laminar properties or the fluid flow. These properties affect the manner in which the two phases would interact and would thus affect the two phase flow patterns. The type of flow is generally characterised by its dimensionless Reynolds number.

3.1.1 Laminar Flow

Laminar flow is defined by parallel layers without any disruption of eddies occurring between the layers. It is associated with low fluid velocities and is characterised by it low Reynolds number (<2040).

3.1.2 Turbulent Flow

Turbulent flow is the opposite of laminar flow characterised by having a chaotic pattern (Wikipedia). These disruptions in the flow layers have high Reynolds numbers (>2040).

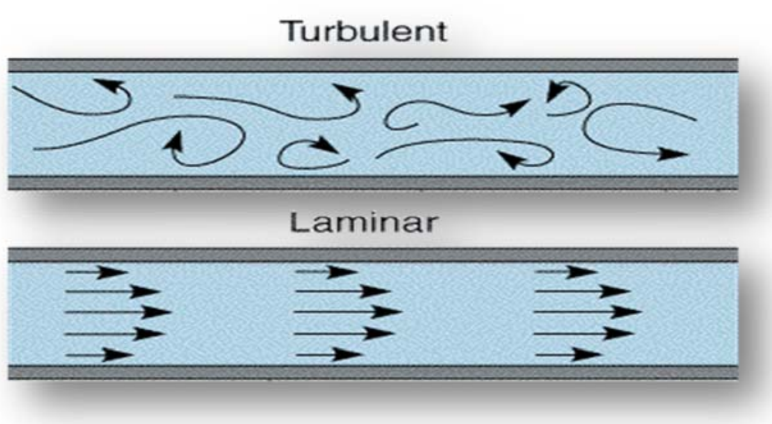


Figure 1: Comparison of Turbulent and Laminar Flow

3.2 Two Phase Flow

Two phase flow involves the presence of two different phases (gas and solid, gas and liquid of liquid and solid) in a single system. It can also be used to describe the combined flow of immiscible liquids such as oil and water.

Generally it is defined as one phase transported within another where the phases are not chemically related and where each phase occupies it own volumetric fraction and the sum of both being 1. (Wikipedia)

3.2.1 Two Phase Flow Patterns

The flow patterns that are present in a co-current two phase flow system is dependant on the Reynolds number, whether the flow is laminar or turbulent, and the orientation of the system, vertically or horizontally oriented systems.

3.2.1.1 Vertically Oriented Tubes

The flow patterns that are in the vertical tubes are (Wolverine 2007, 12-1,12-2)::

- Bubbly Flow- Numerous, discrete nearly spherical gas bubbles dispersed in the liquid phase that have a much smaller diameter than the tube itself.
- Slug Flow- Increased gas void fraction causes the bubbles to come closer together and collide and coalesce to form larger bubbles with a similar size to the tube diameter. They have a bullet like shape.
- Churn Flow- This is a result of turbulent flow patterns and is an intermediate between slug and annular flow regimes.
- Annular Flow- When the gas flow has a sufficiently high velocity to become dominant over gravity, it expels the liquid from the centre of the tube making it flow as a thin film along the sides of the tube while the gas flows continuously up the centre.
- Wispy Annular Flow- Increased flow rates causes water droplets to form clouds or wisps in the central vapour core.
- Mist Flow- This can be seen to be the opposite of bubbly flow. The high gas velocities shears the liquid from the walls of the tube and entraps it as droplets in the continuous gas phase.

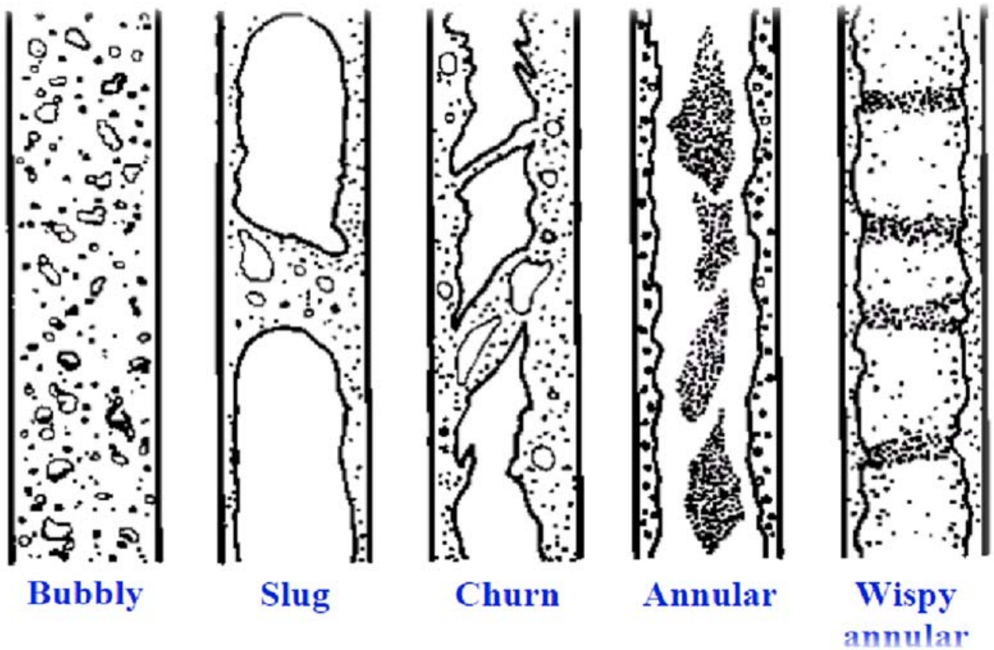


Figure 2: Two Phase Flow Patterns in Vertical Tubes

3.2.1.2 Horizontally Oriented Tubes

Flow patterns seen in horizontal tubes are (Wolverine 2007, 12-3,12-4):

- Bubbly Flow- This flow regime typically takes place at high mass flow rates and is characterised by a dispersion of bubbles in the liquid with a high concentration at the surface due to their buoyancy.
- Stratified Flow- At low liquid and gas velocities there is a distinct separation of the phases. The liquid travels at the bottom of the tube while the liquid at the top.
- Stratified-wavy Flow- As the gas velocity increases it causes waves at the interphase of the phases. The waves do not reach the top of the tube but climb on the sides of the tubes leaving behind a liquid film.
- Intermittent Flow- This is caused by further increase in gas velocity resulting in the formation of waves of varying amplitudes, some of which reach the top of the tube. These waves may contain entrapped bubbles. This type of regime is a combination of Plug and Slug Flows.

  - Plug Flow- Liquid plugs are separated by elongated bubbles. Their diameters are such that the liquid flow remains continuous at the bottom of the tubes, below the bubbles.
  - Slug Flow- Increased gas velocities causes the elongated bubbles to increase in diameter to match that of the tube and result in liquid slugs in between the bubbles.
- Annular Flow- Similarly with vertical flow the gas flows in the core of the tube forcing the liquid to the perimeter of the tube. Small amplitude waves occur at the phase interphase causing small droplets of water to be dispersed in the vapour core. At high gas fractions the liquid film may cover only part of the tube perimeter (lower part) and would thus be classified as Stratified-wavy Flow.
- Mist Flow- This flow regime is the same as described with vertical tubes.

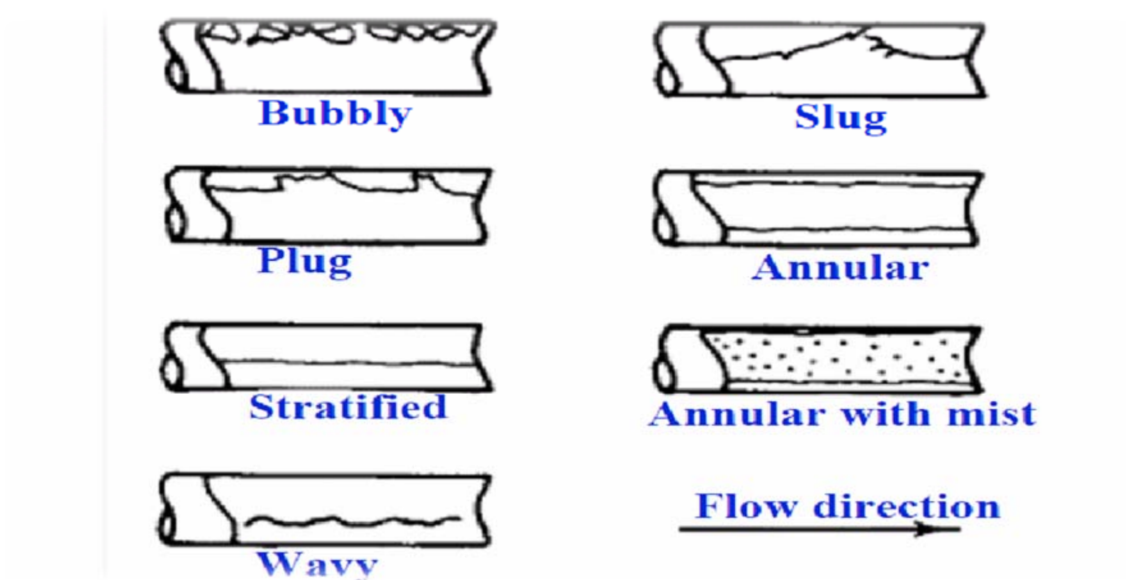


Figure 3: Two Phase Flow Patterns in Horizontal Tubes

Using the following flow regime map can use the mass velocities of the different phases to determine the flow patterns inside the system.

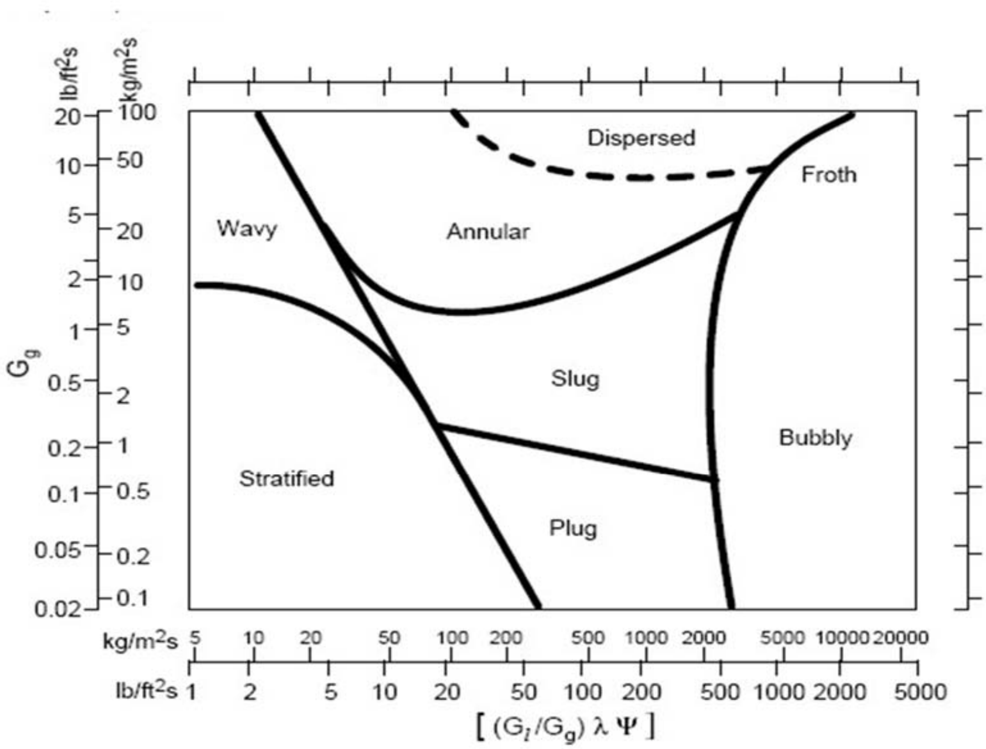


Figure 4: Baker's Two Phase Flow Pattern Map for Horizontal Tubes

3.3 Flow Across T-Junction

A two phase flow regime through a T-junction is seen to have an unequal distribution of phases between the branch and run arm outlets. The study of this phenomenon is of significant technical concern. It can result in major operational and control problems in numerous industrial uses that include the process, power and gas production industries. A positive application of this phenomenon is in the production of compact and relatively inexpensive partial separators for a two phase mixture. (Azzopardi, 1993, G. Das et al., 2005)

Many experimental investigations and theoretical analysis have been conducted into this phenomenon of phase splits across a T-junction and many reviews have been published. All variables and parameters, flow patterns, temperature, pressure, phase velocities orientation, junction diameter, have been manipulated in an attempt to produce models for the prediction of flow splits at the T-junction.

Das et al. (2005) conducted experiments for a water and air mixture utilizing a 0.005m T-junction with stratified flow. Experimental data was collected for superficial gas velocities of 2.5ms^{-1}, 3.5ms^{-1} and 5ms^{-1}, water superficial velocities of 0.055ms^{-1} and 0.0097ms^{-1}, and pressures of 131kPa and 191kPa. Their results indicated that liquid fraction in the run arm is increased with high gas and low liquid superficial velocities. Their results are in correspondence with results of experiments conducted with Shoham et al. (1987) and Hong (1978), both of whom used larger diameter T-junctions.

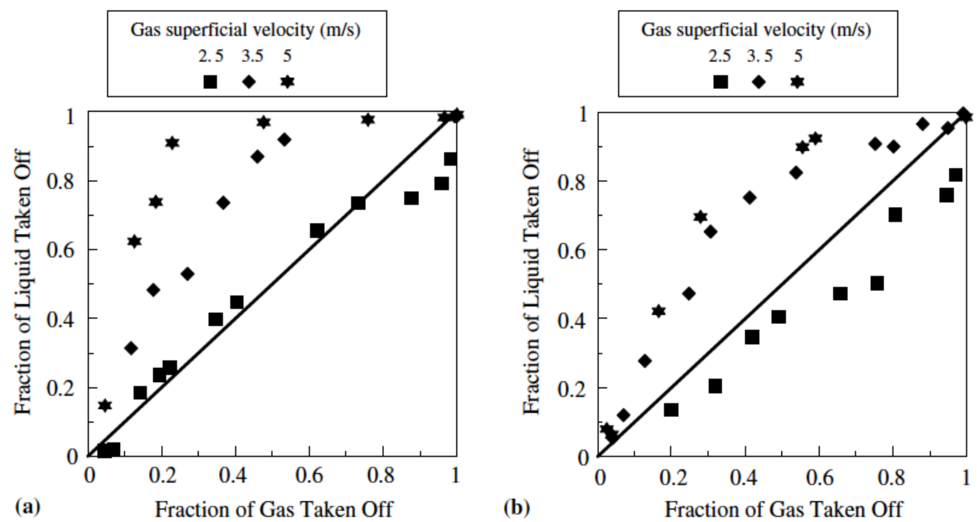


Figure 5: Results obtained by Das et al. for the effect of superficial gas velocity on liquid velocities (a) 0.0055ms-1 (b) 0.0097ms-1

They were also able to conclude that high pressure results in a high liquid fraction in the branch arm at higher gas velocities.

Pandey et al. (2006) experiments utilized superficial flow rates covering a wide range between 0.05ms^{-1} and 2ms^{-1}. They also attempted to determine the effect of changing diameter on flow splits by utilizing a T-junction with main and run arm diameter of 0.0254m and a branch arm diameter of 0.0127m. Two different phase combination were used, air/water and water/kerosene. The results they obtained were close to the values obtained from the prediction model put forward by Shoham et al. (1987).

Stacey et al. (1999) produced a paper to compare the phase distribution across a 0.005m T-junction for the purpose of comparison with data that was available for larger diameter T-junctions. The ranges of the gas and liquid superficial velocities were 46-60m/s and 15-20m/s respectively. Choice of these flow rates were intended to produce an annular flow regime. The result of his experiment illustrated that decreasing pipe diameter increases the fractional take off of the liquid for similar inlet gas velocity.

3.3.1 Shoham et al. Prediction Model

The experiment conducted by Shoham et al. (1987) utilized a T-junction of diameter 50mm. His experiment was conducted over specific flow regimes that included stratified smooth, stratified wavy and annular flow patterns. For these flow patterns liquid flow velocities were selected between 0.0029 and 0.59m/s. Gas superficial velocities were chosen as 2.5, 6.1 and 26m/s so as to range between the three flow patterns.

He found that for stratified smooth and stratified wavy that there was a threshold branch gas fraction intake necessary for diversion of liquid into the branch arm. It is seen that at low liquid flow rates at 0.0029m/s that total diversion of liquid to the branch arm is obtained at 60% gas take off. As the liquid velocity increases, that has a reduced effect on the movement of liquid to the branch arm.

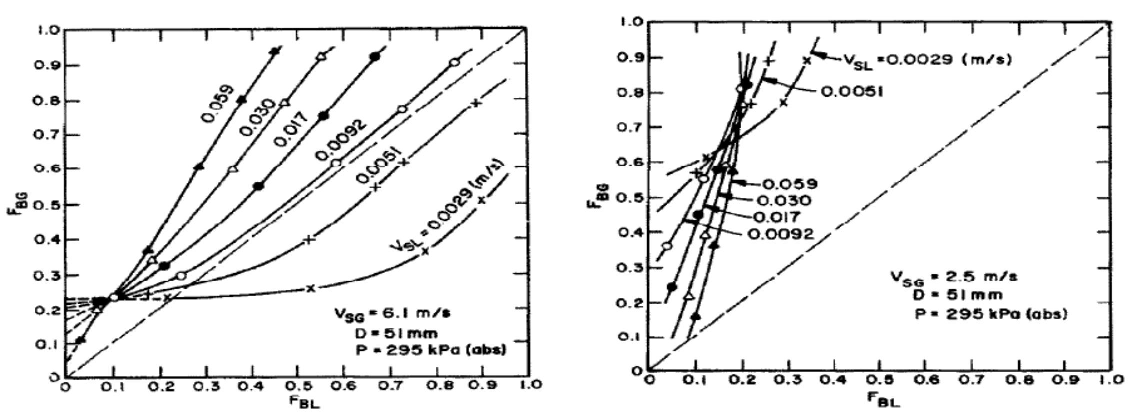


Figure 6: Phase split data obtained by Shoham et al. 1987 for stratified smooth (right) and stratified wavy (left) flow regimes

For annular flow he found that liquid flows preferentially to the branch arm. For all vales of liquid velocity it was found possible to divert all the liquid to the branch arm.

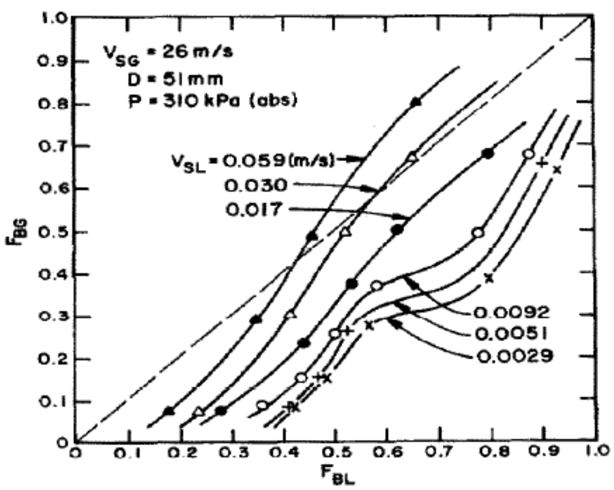


Figure 7: Phase split data obtained by Shoham et al. 1987 for annular flow regime.

From his conducted experiments Dr. Shoham was able to develop a flow pattern specific model to predict flow splitting.

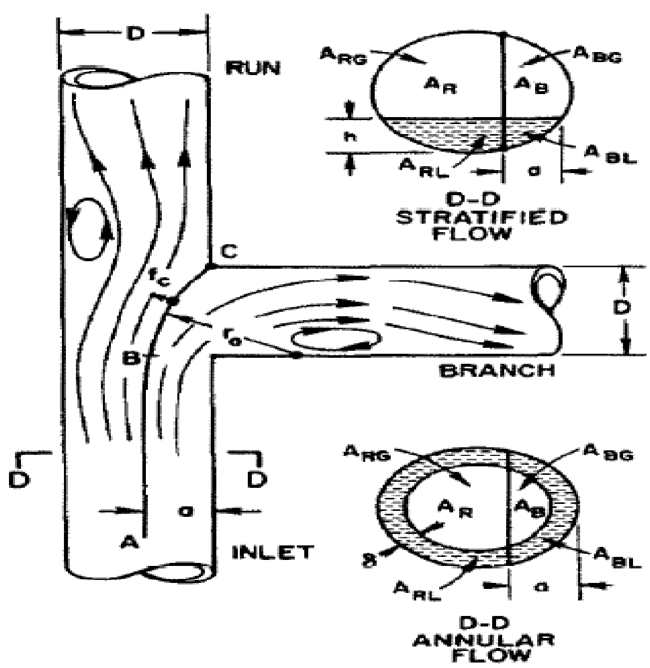


Figure 8: Schematic Flow Description in Horizontal T-junction. Shoham et al. 1987

In the schematic diagram of the flow it is inferred that the stream line A-B-C divides the cross sectional areas into two sections. The geometrical model is based on the assumptions that the liquid fraction in A_B above is directed to the branch arm and that the fraction in A_R is directed to the run arm and that there is uniform mass flux distribution. The rule of splits are given by the relationships:

$$F_{BL} = \frac{A_{BL}}{A_{BL} + A_{RL}} = \frac{A_{BL}}{A_L} \qquad \text{Equation 1.}$$

$$F_{BG} = \frac{A_{BG}}{A_{BG} + A_{RG}} = \frac{A_{BG}}{A_G} \qquad \text{Equation 2.}$$

Derivation of these two equations are seen in Appendix 9.1 as taken from Shoham et al. (1987). From the predictions generated by Shoham et al. it is seen that they are in close correspondence with the data collected by experiment.

The geometrical model though is inadequate for the explanation of the splits as it fails to explain preferential liquid movement into the branch arm at high air velocities. It is assumed that this preference is assumed to be the result of the centripetal force action on the curved region B-C. This centripetal force causes a change in the value of distance 'a' as seen in figure 5, which is used to calculate the radius of the curvature B-C and which is in turn used in the determination of the phase split with the geometric model.

$$r_o = \frac{D^2 + a^2}{2a} \qquad \text{Equation 3.}$$

The resulting new 'a' value 'a_L' can be determined by the method as seen in Appendix 9.2. With this new value the phase splits can then be calculated.

3.4 Pipe Length Necessary for Fully Developed Flow

For accurate results of the phase splits, the flow into the T-junction must be fully developed. In order for this to happen there must be a sufficient pipe length between the mixing point of the phases and the T-junction under which splits are measured. The pipe length can be determined from the equation (Wikipedia, 2012):

$$No.of\ Pipe\ Diamters = 4.4DR_e^{\frac{1}{6}}$$ Equation 4.

The Reynolds number used is assumed to be that of the highest air velocity.

$$R_e = \frac{\rho v D}{\mu}$$ Equation 5.

Where,

- R_e – Reynolds number
- ρ- density of fluid
- D- pipe diameter
- μ- fluid viscosity

3.5 Rotameter Calibration

Rotameter calibration theory uses the relationship between the drag force exerted on the float and the velocity head to determine the change in flow rates with height.

$$F_d = m_f g \left(1 - \frac{\rho}{\rho_f}\right) = A_f \rho C_D \frac{u_{max}^2}{2}$$ Equation 6.

Where:

- m_f – mass of float
- g- acceleration due to gravity
- ρ- density of fluid

- ρ_f- density of float
- A_f- projected area of float
- C_D- drag coefficient
- $\frac{u_{max}^2}{2}$ - velocity head

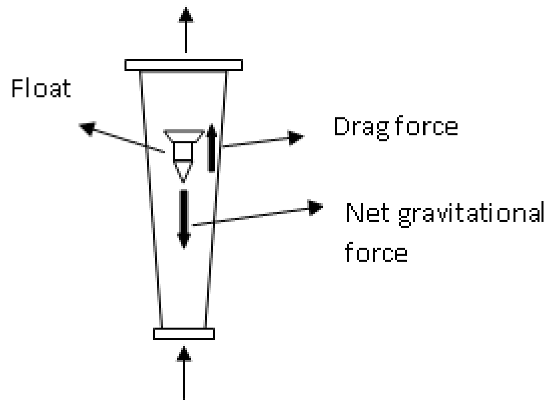


Figure 9: Forces Acting On Float

u_{max}^2 can then be calculated by making it the subject of the formula. This value can then be used to calculate the volumetric flow rate for a given annular diameter i.e. the space between the floats' largest diameter and the walls of the rotameter.

$$q = u_{max} \frac{\pi}{4} (D_t^2 - D_f^2) \qquad \text{Equation 7.}$$

Where,

- q- volumetric flow rate
- D_t – tube diameter
- D_f – float diameter

For a tapered rotameter with a base diameter equal to that of the float the relationship between the annular are and height, h, is given by:

$$(D_t^2 - D_f^2) = (D_f + ah)^2 - D_f^2 = 2D_f ah - a^2 h^2 \qquad \text{Equation 8.}$$

Where,

- a- tube taper constant

$$a = 2tan\alpha \qquad \text{Equation 9.}$$

- α- angle of taper of rotameter

4 METHODOLOGY

4.1 Programmes

A Fortran simulation was used to predict the phase distribution at the tested phase flow rates. The Fortran programme simulated the geometrical model of Shoham et al.

4.2 Materials and apparatus

- Rotameters
- 2 inch PVC pipes
- 2 inch PVC elbows and Tees
- Compressed Air Tank
- Water Reservoir
- 2 inch globe and ball valves
- Glass T-junction
- Water Pump

The apparatus was constructed based on the schematic shown below. It was based on similar setups used in past experiments.

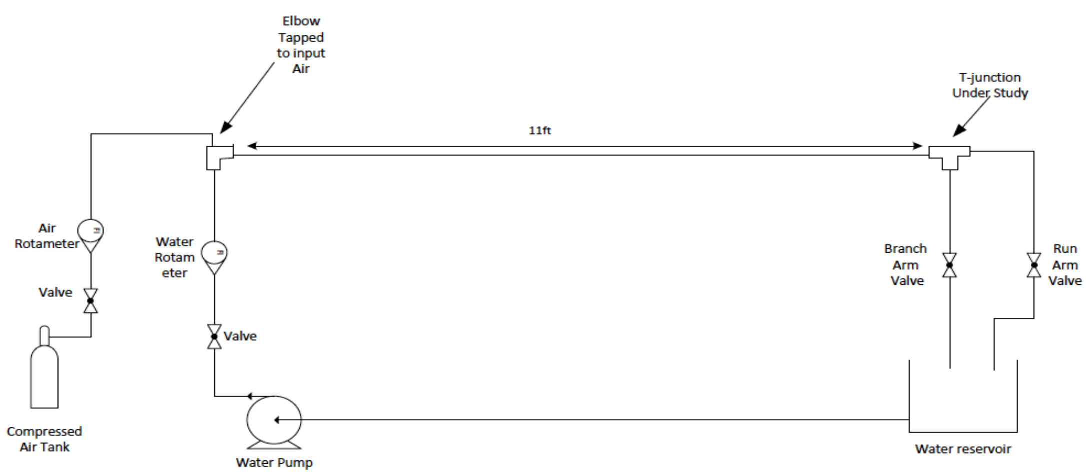


Figure 10: Schematic set up of apparatus

(a)

(b)

(c)

(d)

Figure 11: (a) Overall view of apparatus setup (b) Water reservoir and discharge of run and branch arms (c) modifications made to accommodate for backflow (d) glass T-junction with reduced diameter at entrance and exit arms

The modifications were made since the flow rates of the water were causing backflow at small valve opening fraction. The recycle included was put in to alleviate this problem and it also aided in better control of the flow rates.

In order to attach the glass T-junction to the system flanges were utilized to an adapter in place (figure 11d). The adapter was constructed of a piece of threaded ½ inch steel pipe welded to a circular piece of stainless steel.

A straight run distance of 12ft was used between the mixing point and the T- junction to accommodate for fully developed flow.

4.3 Procedure

4.3.1 Calibration of Water Rotameter

1. The branch arm of the system was shut off to allow flow to run arm only.
2. Rotameter was set at a calibrated level of 1.
3. The time was taken for the water to fill a 2 litre measuring cylinder.
4. Step 3 was repeated twice to reduce errors
5. Steps 3 and 4 were then repeated with rotameter set at different calibrated levels.
6. Volumetric flow rates were calculated and a plot of rotameter readings vs. volumetric flow rate was done.

N.B. The procedure was done twice, once for each T-junction.

4.3.2 Experimental Data

1. The valves in the run and branch arm of the rotameter were both set at fully opened positions.
2. The water flow rate was set to a rotameter reading of 15 and the air rotameter set at a value of 4.
3. After a short period of time volumetric analysis was taken from the branch arm of the T-junction, as was done in steps 3 and 4 for rotameter calibration.
4. This was then repeated for air rotameter values of 8, 12, 20 and 26.
5. Steps 2-4 were repeated but instead using water rotameter readings of 18 ,21, 23 and 25.

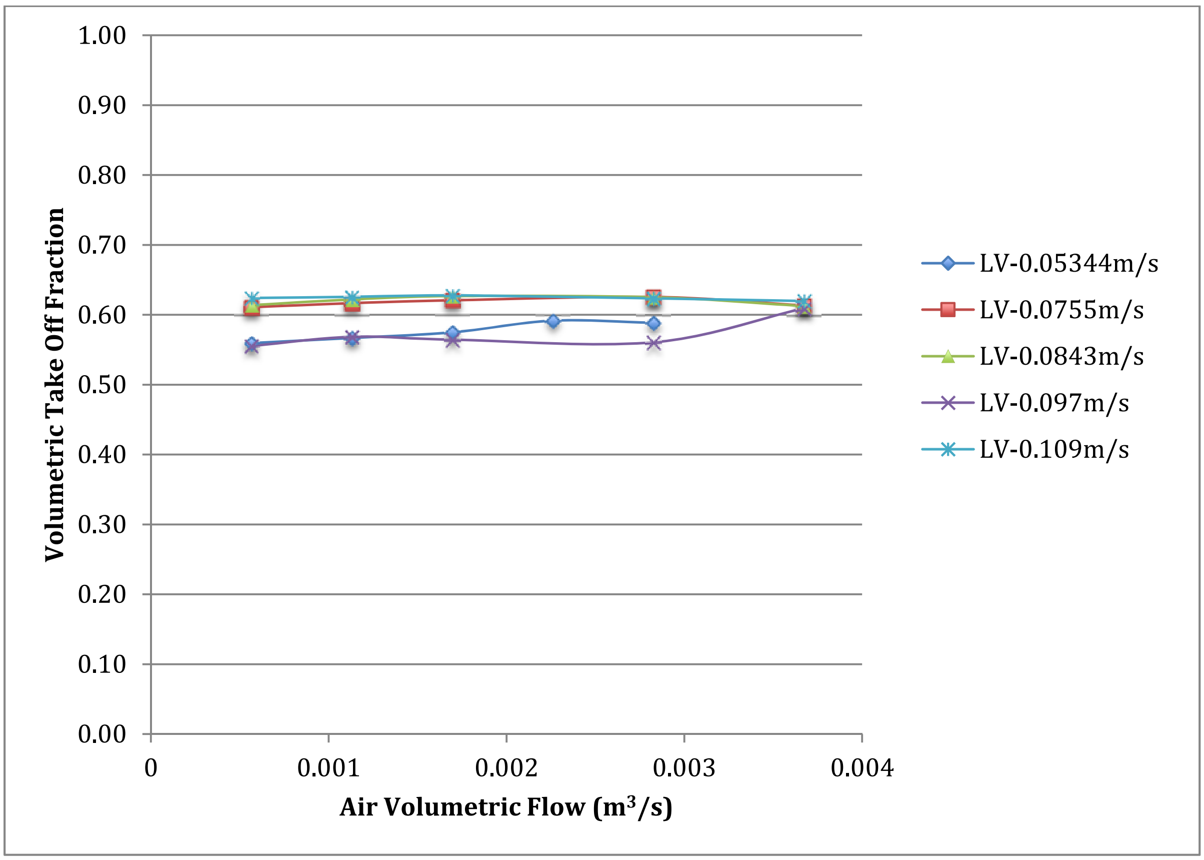
6. The results obtained were tabulated and graphs were plot of fractional liquid take off as a function of air flow rate and also water flow rates.

The values obtained from the experiment were then qualitatively compared to the predicted data obtained from the Shoham model.

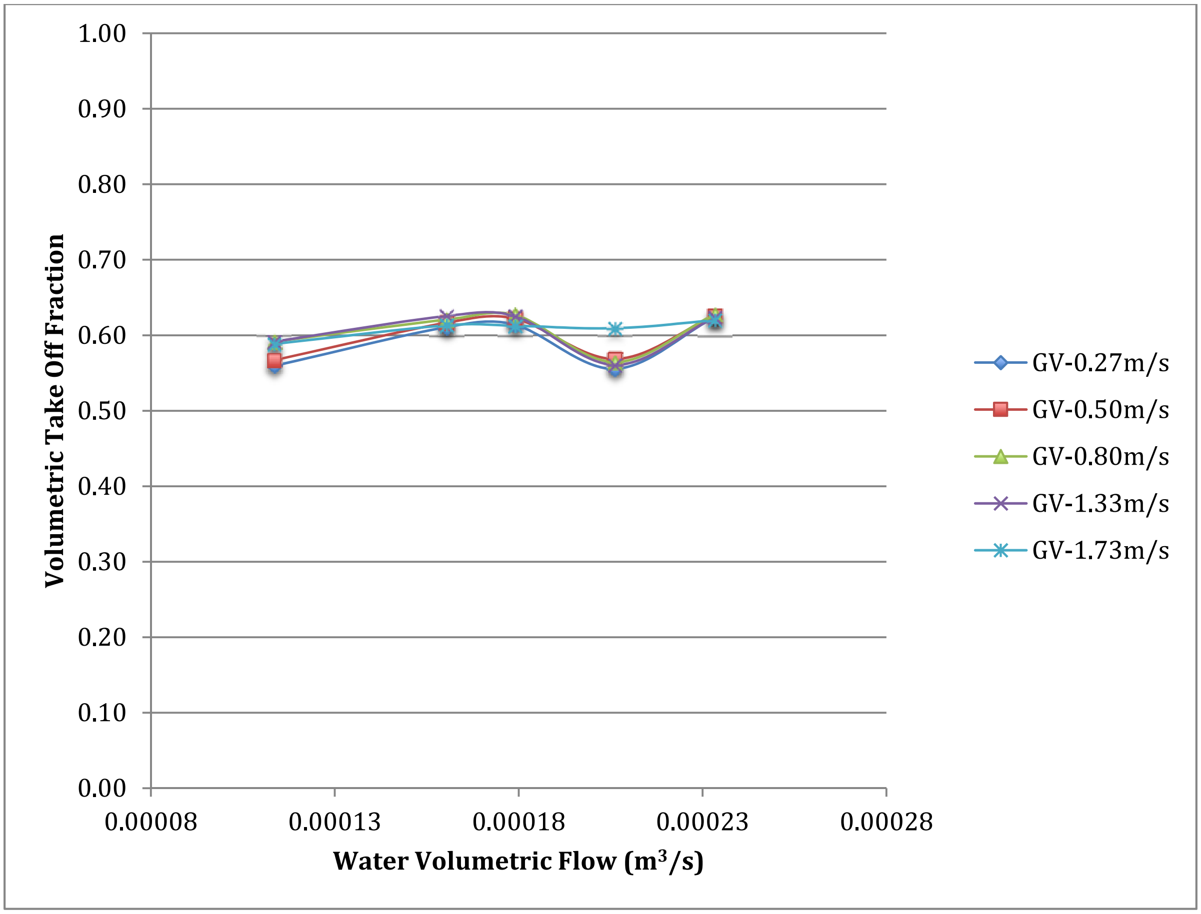
5 Results and Discussion

5.1 Phase Split Data for PVC T-Junction

From the experiment conducted the liquid take off was obtained from the volumetric measurements of water flow from both the run and branch arm of the T-junction. The data obtained was tabulated (see Appendix) and then graphically expressed as seen below.



(a)



(b)

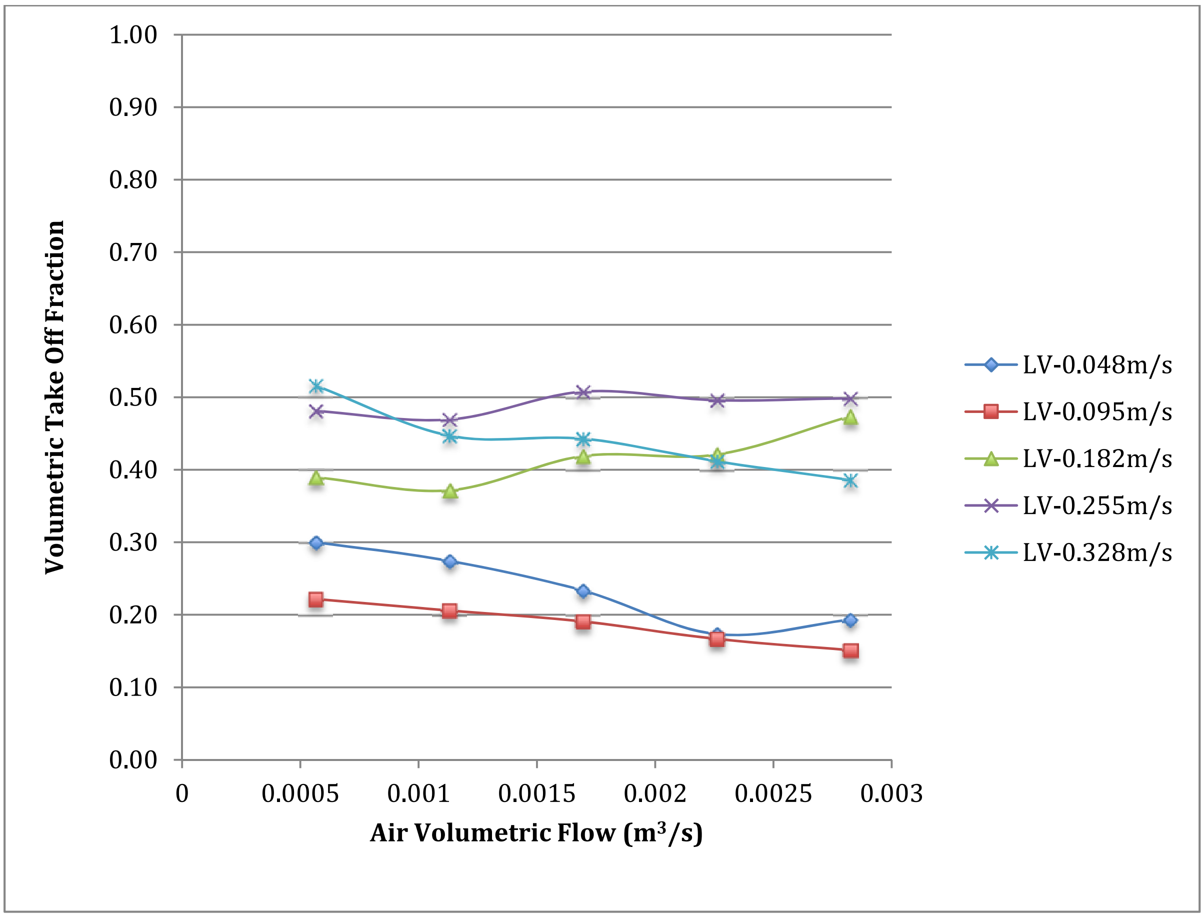
Figure 12: (a) Effect of Air Flow Rate on Liquid Take Off at different Liquid Velocities and (b) Effect of Water Flow Rate on Liquid Take Off at different Gas Velocities for PVC T-Junction

As seen in both of the plots above for the obtained results, the liquid fraction take remains relatively constant. From Figure 12(a), it is seen that for a given liquid velocity, the fractional take off of the liquid doesn't really change. The take off ranges between 0.55 and 0.65 for the tested flow parameters. At liquid velocity of 0.097ms^{-1} there is a slightly lower liquid fraction in the branch arm as compared to a velocity of 0.0755ms^{-1}.

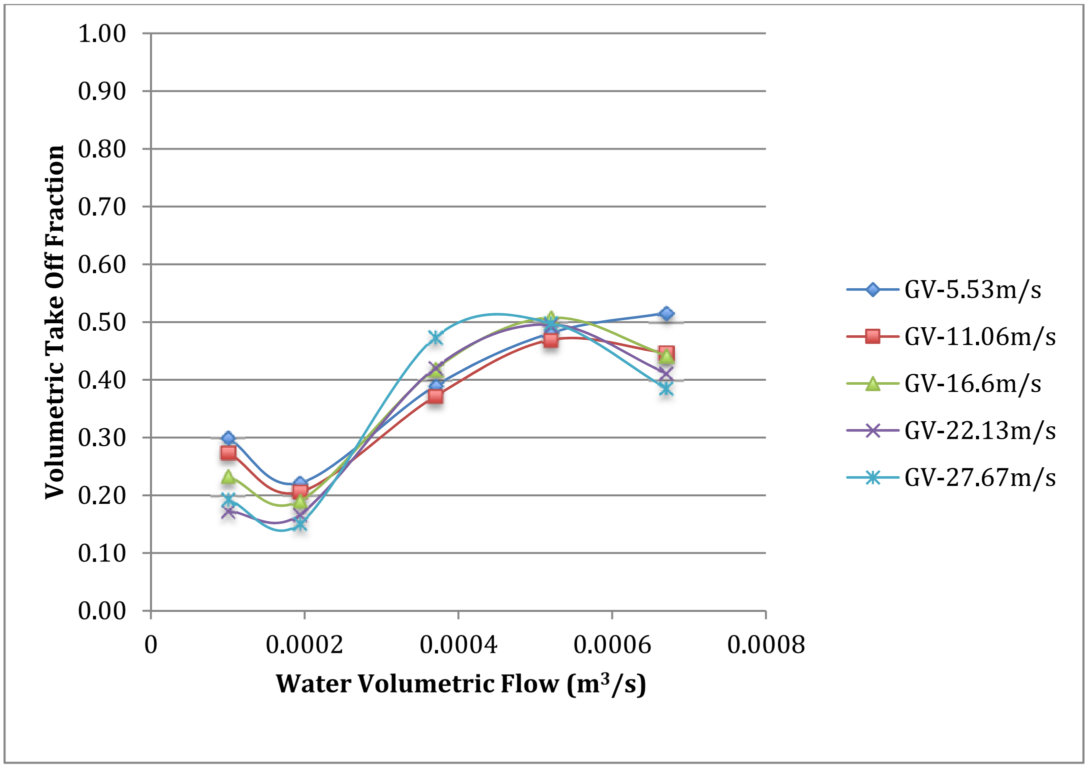
The data collected does not coincide with the experiments conducted by Shoham et al. (1987) and Azzopardi et al. (2002) as were previously mentioned in the Literature Review section of the project. The work conducted by Dr. Ovadia Shoham involved the use of an identically sized T-junction. His gas and liquid superficial velocities were 6.1m/s and 0.0029-0.059m/s respectively. The reason for these values were chosen on the basis of obtaining flow regimes ranging from stratified to annular flow. The flow rates used in this experiment resulted in mostly annular flow as was interpreted from the flow pattern map in the Literature Review section. From his results for annular flow it can be seen that increasing the liquid velocity decreases the liquid take off. The data collected from this experiment shows almost constant take off.

5.2 Phase Split Data for Reduced Diameter Glass T-junction

As with the PVC T-junction, an identical method was used to obtain the liquid split data across it. From the results the following two graphs were obtained.



(a)



(b)

Figure 13: (a) Effect of Air Flow Rate on Liquid Take Off at different Liquid Velocities and (b) Effect of Water Flow Rate on Liquid Take Off at different Gas Velocities for Reduced Diameter Glass T-Junction

The graphs show a distinctive difference from those plotted for the 51mm PVC T-junction. It is quite distinctive from Figure 13(a) that the volumetric take off at a given air volumetric flow rate is affected by the change in the liquid velocity. As interpreted from the graph it is seen that for the range of air flow rates used in the experiment that a liquid superficial velocity of 0.255m/s resulted in the highest fractional take off. Contrarily a liquid superficial velocity of 0.095m/s resulted in the lowest fractional take off. This trend can also be seen from figure 16(b) where the gradient of the graphs increase with the increase in liquid flow rates.

From the almost straight lines of figure 13(a) and from the close vicinity of each plot on figure 13(b) it can be interpreted that changing the air flow velocity for a given water flow rate has little effect on the liquid take off. The air flow seems to have the greatest effect on the phase splits at liquid flow rates of approximately 0.0001 and 0.0007m^3/s. No effect can also be seen from the points on figure 13(b) that intersect each other.

5.2.1 Flow Patterns in T-Junction

Since for this part of the experiment a glass T-junction was used it was possible to observe the flow patterns inside it.


(a)

(b)

(c)

Figure 14: different flow regimes observed during the experiment (a) Intermittent Flow (b) Stratified-Wavy Flow and (c) Bubbly Flow

As described in the Literature Review section, there are different flow regimes that occur due to the different flow velocities through the system. Shown in the pictures above, three distinct flow patterns are noted, intermittent, stratified-wavy and bubbly.

5.3 Comparison of T-Junction Types

For the purpose of comparison, identical flow conditions were used to analyse its effect on the liquid take off. From the data obtained the following graph was plotted.

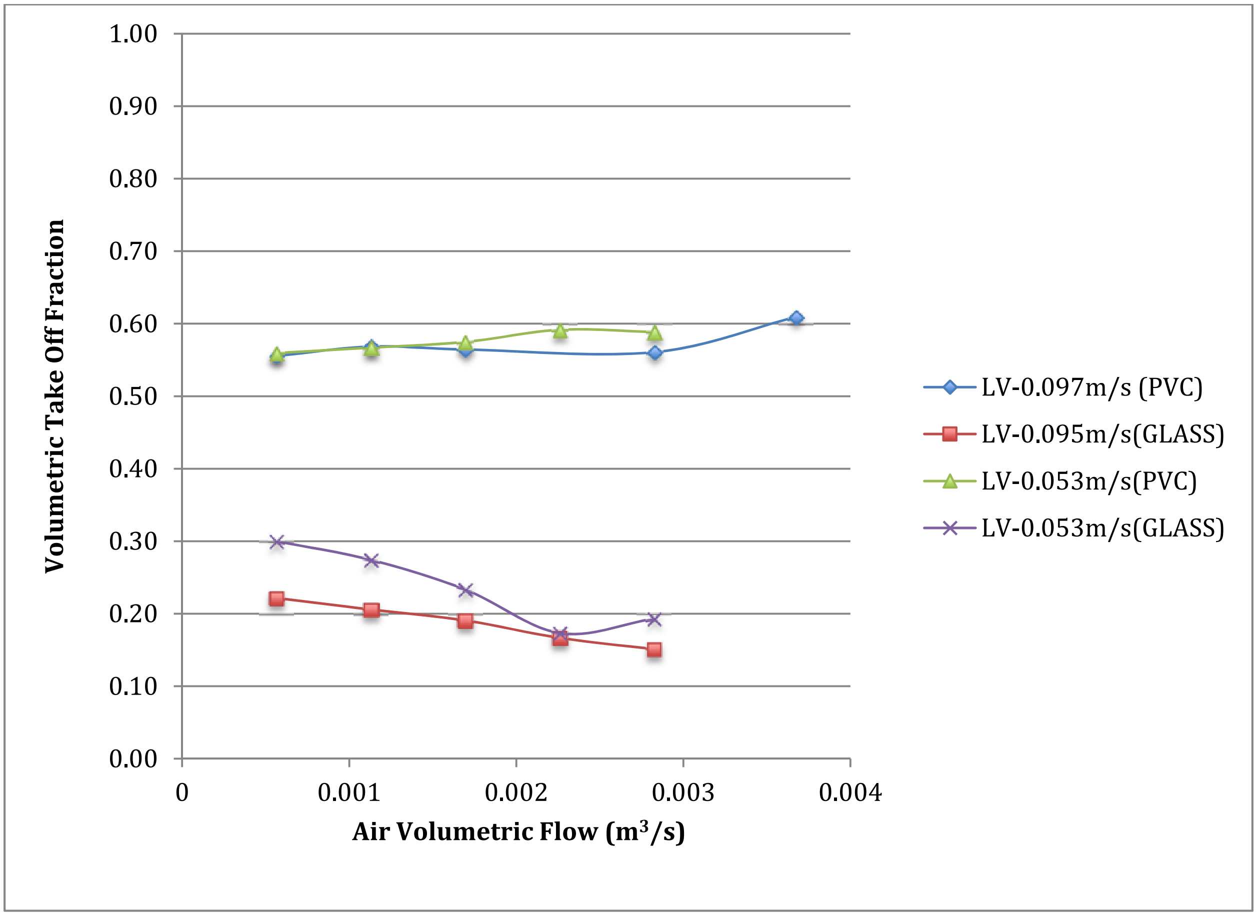


Figure 15: Comparison of Liquid Take Off Fractions for the two T-Junctions under similar flow conditions

It is clearly seen that there is a higher liquid take off with the PVC T-junction as compared to the glass T-junction that has reduced entrance and exit diameters. The liquid splits were found for liquid velocities of 0.095 and 0.053m/s for both T-junctions over the same air flow rate values. For the glass junction the fractional take off was ranged between 0.15 and 0.30 while for the PVC junction it was in the range of 0.55 and 0.6. this is expected as the adapters added cause a lot of restriction to the flow.

5.4 Shoham Split Predictions

As discussed previously, Shoham et al. (1987) developed a geometrical model for the prediction of phase splits.

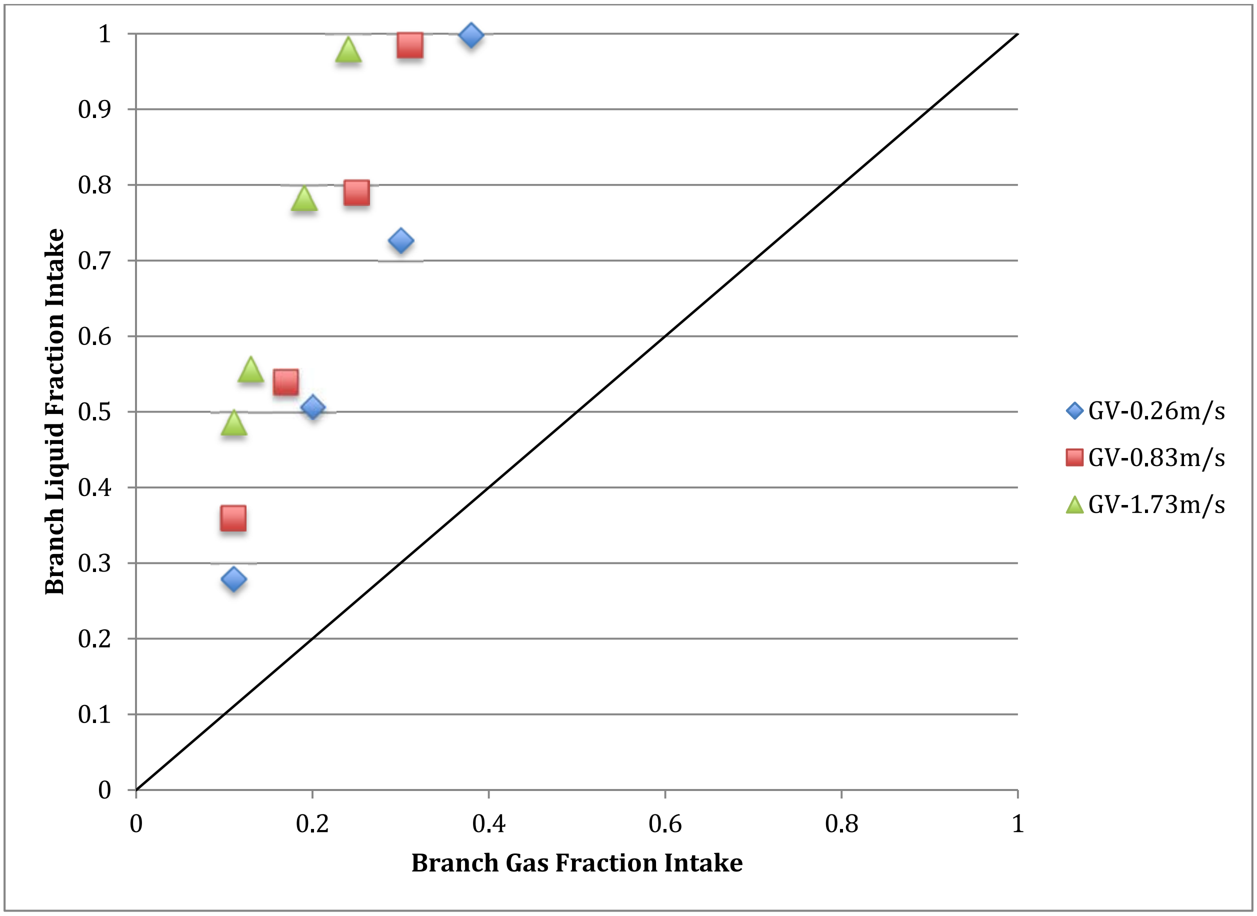


Figure 16: Shoham predicted phase distribution for a superficial liquid velocity of 0.055m/s at various gas velocities, GV

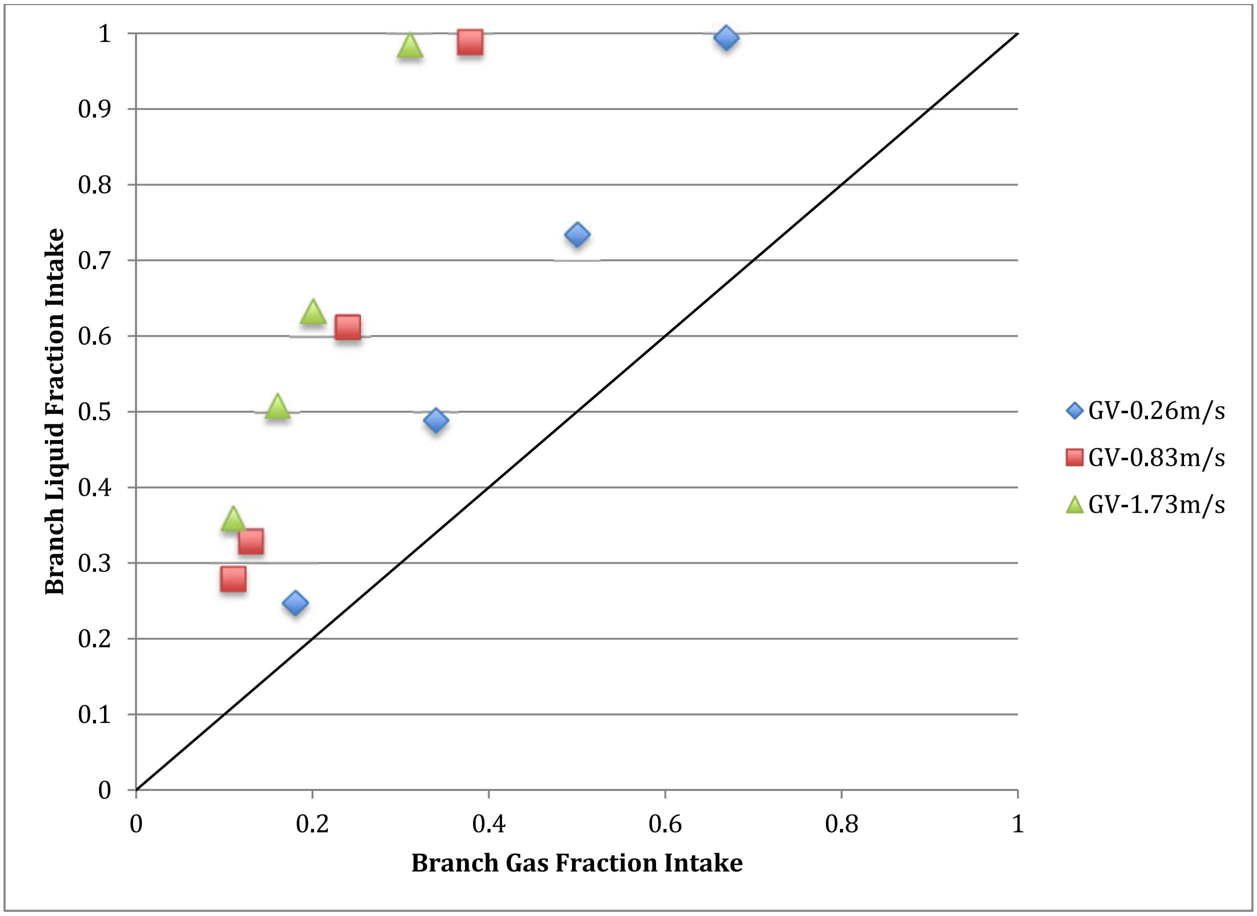


Figure 17: Shoham predicted phase distribution for a superficial liquid velocity of 0.114m/s at various gas velocities, GV

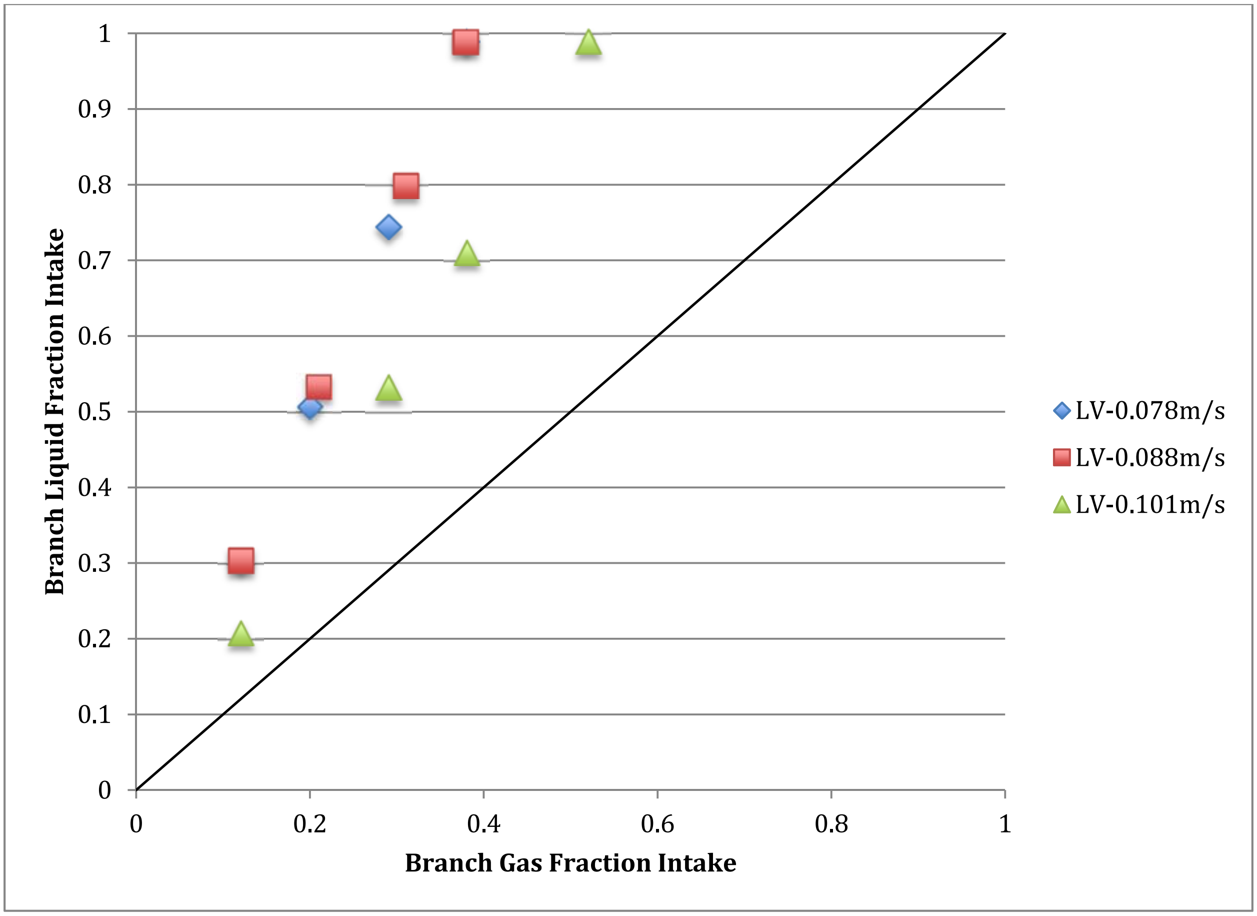


Figure 18: Shoham predicted phase distribution for a superficial gas velocity of 0.55m/s at various liquid velocities, LV

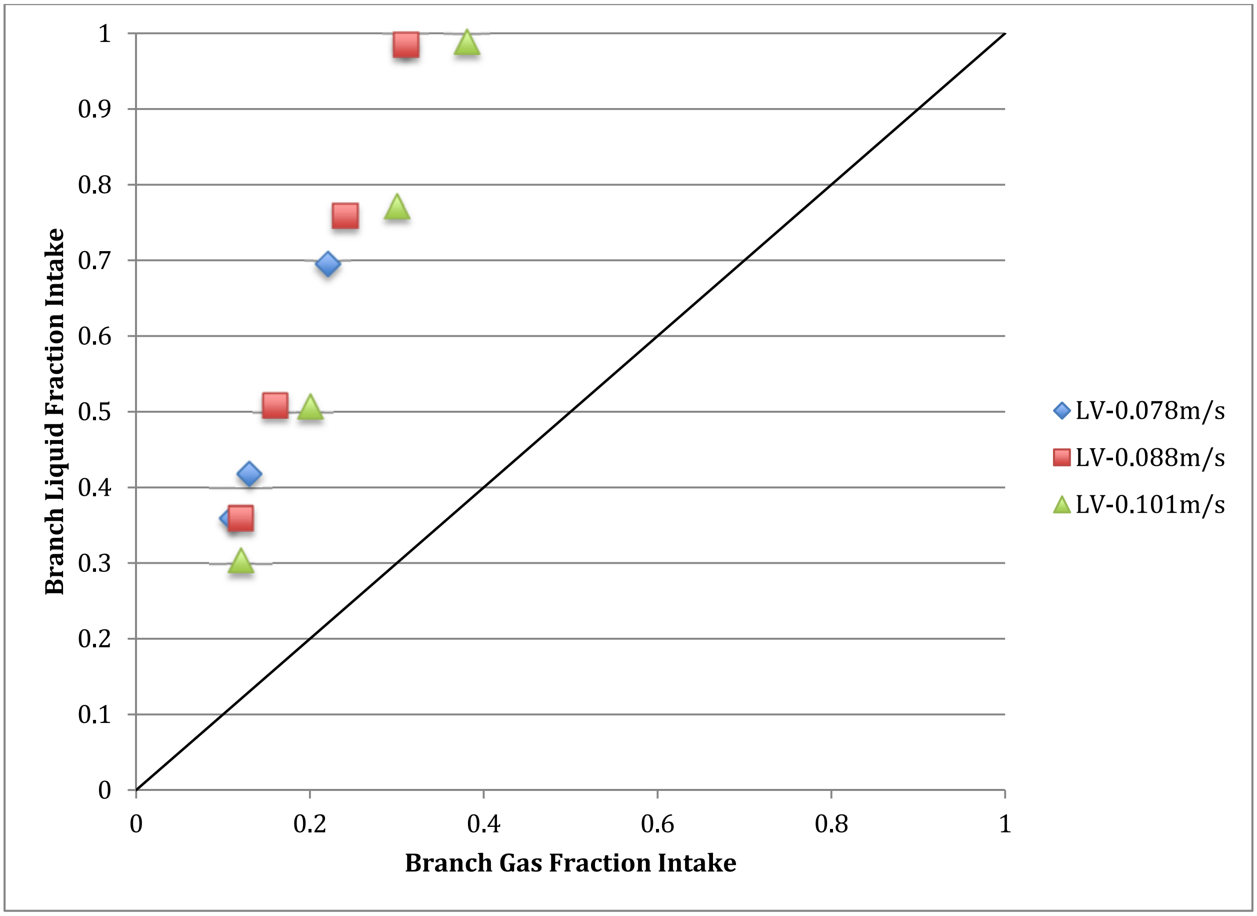


Figure 19: Shoham predicted phase distribution for a superficial gas velocity of 1.1m/s at various liquid velocities, LV

The graphs illustrate that for all the gas and liquid superficial velocities , the branch flow is in the liquid rich zone. The plot of phase distribution at a liquid velocity of 0.55m/s (figure 19) illustrates that changes in the gas velocities have minimal effect on the on the distribution. For a liquid flow rate of 0.114m/s (figure 20) there is a movement of flow distribution to the equal distribution line, more so for the lower gas flow rate of 5.53m/s. This trend is similar to that found by G. Das et al (2005).

For a gas superficial velocity of 22.14m/s (figure 22) there is little to almost no effect of the changing liquid velocity on the distribution. For the lower gas velocity there is a small movement towards the equal split line, a trend also found by G. Das et al. (2005).

5.5 Comparison of experimental data with Shoham's predicted data

At a liquid superficial velocity of 0.055m/s the predicted plot shows that there would be a similar liquid take off for all the superficial gas velocities and slightly lower take off as velocity decreases. From the experimental data we see that the prediction corresponds with the trend for the PVC junction but for the Glass junction an increase of gas superficial velocity decreases the fractional take off.

For a liquid superficial velocity of 0.11m/s the prediction data shows that there is a small decrease in the liquid take of at the higher gas velocities and a larger decrease for a gas velocity of 5.53m/s. Similarly with both T-junctions there is a decrease in the fractional take off of the liquid phase.

The predicted data for air flow velocities of 11.07 and 21.1m/s also show much similarity to the experimental data collected for the liquid take off in the PVC junction. In both sets of values for the air velocity of 11.07m/s there is almost identical liquid take off for water velocities of 0.078 and 0.088m/s. This is interpreted from the overlapping of the respective curves that occur in each plot. The difference is that at higher water flow rate is predicted to have a lower fractional take off but the experiment shows that it actually has a higher take off. For the superficial air velocity of 21.1m/s there is a small increase in the liquid take off but the take off almost the same for the range of liquid velocities as shown from the overlapping of a majority of the points in the predicted data. The experimental data shows similar trend.

As mentioned previously, the geometrical prediction model can very closely predict the phase splits especially for annular flow regimes (Shoham et al. 1987) although not exactly. This is also supported for the experiment undertaken as seen from the trend similarities mentioned with the exception of some differences. A clearer comparison would be able with a quantitative analysis but insufficient data was collected to obtain the same plots for a direct comparison.

6 Conclusion

The experiment was conducted with the aim of determining the effect of superficial phase velocities for two phase flow on the phase distribution between the arms of a 2inch diameter T-junction. Due to limited apparatus availability only the fractional liquid take off was obtained. Additionally another T-junction was used with reduced entrance and exit diameters.

From the experimental data obtained it was found that:

- There was negligible change in fractional liquid take off over the range of superficial phase velocities used with the PVC T-junction.
- The use of the use of the glass T-junction with reduced entrance and exit diameter gave higher liquid take off.
- The data collected and the prediction models from Shoham show similar trends.

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