Phase Separation Phenomena through Tee Junction

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Master of Technology

in

Mechanical Engineering

(*Specialization – Thermal Engineering*)

by

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May 29, 2016

Supervisor's Certificate

This is to certify that the work presented in this dissertation entitled "***Phase Separation Phenomena through Tee Junction***" by **"*DIBYENDU GHOSH*"**, Roll Number **214ME3309**, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements for the degree of ***Master of Technology*** **in** ***Mechanical Engineering***. Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

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Dedicated to My Parents

Declaration of Originality

I, **Dibyendu Ghosh**, Roll Number **214ME3309** hereby declare that this thesis entitled "***Phase Separation Phenomena through Tee Junction***" represents my original work carried out as a master's student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section ''Bibliography''. I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

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List of Symbols

d	Diameter of Tee junction
v	Velocity
V	Volume
t	Time
V_q	Velocity of q^{th} phase
P	Pressure
X_p	Interfacial area concentration
U_g	Velocity of gas phase
g	Acceleration due to gravity
$\dot{m}$	Mass flux
α_q^n	Volume fraction of q^{th} phase at n^{th} time step
k	Turbulent kinetic energy
ω	Specific dissipation rate of turbulent kinetic energy
ρ	Density
μ	Dynamic viscosity
α	Volume fraction
G_k	Production of k
Y_k	Dissipation of k due to turbulence
S_k	Source term of k
G_ω	Production of ω
Y_ω	Dissipation of ω due to turbulence
S_ω	Source term of ω

D_ω	Cross diffusion term for ω
U_f	Volume flux through the face
$\vec{F}$	Body force
S_{RC}	Sink term for random collision
S_{WE}	Sink term for wake entrainment
S_{TI}	Source term for turbulence impact
S_{α_q}	
Γ_k	Diffusivity of k
Γ_ω	Diffusivity of ω

List of Abbreviations

VF	Volume fraction
IAC	Interfacial area concentration

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Abstract

The current work is an effort to investigate the phase separation phenomenon through a horizontal Tee junction numerically and experimentally for liquid-liquid two phase flow. There are four principal purposes of this work. First objective is to investigate the effect of the inlet mixture velocity on the phase split. Second objective is to identify the effect of inlet volume fraction on the phase split phenomenon. Third objective is to find out the effect of change in diameter of the Tee junction on phase separation. And the last objective is to study the variation in phase split for different set of fluid pairs. Kerosene water, Diesel water and soybean oil water fluid pairs are used to numerically simulate the problem. Experiments have been carried out for 11 mm diameter Tee junction on diesel-water fluid pair.

***Keywords*: Phase Separation, Tee Junction, Multi Phase Flow, Void Fraction, Multi-Fluid VOF**

CHAPTER 1:

INTRODUCTION

Tee junctions are very essential in pipe networking systems and are having wide range of industrial applications. Multiphase flow is much more complex in compare to single phase flow phenomenon due to the involvement of greater no. of variables. Also for single phase flow empirical relations are readily available in most of the cases which makes the design simpler. The mixing and partitioning of the different phases are governed by highly nonlinear differential equations. When multiphase mixture flows through Tee junction, component phases distribute themselves in run and branch outlets in an uneven way which is not easy to predict. This uneven distribution of the component phases sometimes creates operational problems and safety issues in industry. In gas supply lines due to the low ambient temperature in winter, condensate is formed. Now due to the unequal distribution of phases, one supply station might get gas with high condensate and some other might get dry gas. This also might lead to serious safety problems.

1.1) Multiphase flow dynamics

Matter can exist in any one of the three phase namely solid, liquid and gas. In multiphase flow more than one phase flow at a time. Two phase flow is most simple case of the multiphase flow phenomenon. Sometimes the term “two components” is used to define flows in which the components are of different chemical compositions. The mathematical approach used to analyze two phase flow and two component flow are same. So, broadly the term “multiphase flow” is used to define multiphase as well as multicomponent flow.

In practical life, it is really difficult to find ideal single phase flow. In coffee percolator liquid and vapor phase flow simultaneously. When liquid is poured from a bottle, the liqui8d discharge rate is restricted by the velocity of the rising slug flow bubbles in the neck section of the bottle. The bubbles generating from the defects in the wall of the glass rise to form foam at the surface. Bread and cake making processes also involve complex multiphase mixing phenomenon. Body fluid, for example blood, semen, milk are all multiphase which contains cells, particles and droplets in suspension. Paint, ink, pastes, nuclear fuel slurries are all multiphase. Fire-fighting system is a technical example of multiphase flow. Various methods involved in fire-fighting process use sprays, jets, foams, powders etc. Some systems use pure gas as fire-fighting elements, but these systems cannot be analyzed without considering the flash evaporation which occurs when the high pressure gas is expelled from the cylinder. Fire itself results due to reaction between the solid or liquid fuels and oxygen and produce smoke and steam. All these are two phase phenomenon. In boilers, automobile engines and rockets, deliberate fire is developed to burn two phase dispersions.

In industry there are many occasions where multiphase flow phenomenon can be observed. Especially in chemical engineering, most of the processes carried out concerned about multiphase flow. In the analysis of multiphase flow the basic governing equations are same as single phase flow, the only difference is that they are much more complex. Following are the methods used in analyzing multiphase flow:

- Correlations
- Simple analytical models
- Integral analysis
- Differential analysis
- Universal phenomenon

CHAPTER 2:

LITERATURE SURVEY

Most of the research works done in the field of multiphase flow are based on experimental observations. The aim is to develop suitable co-relations which satisfy these observational consequences. Identification of flow regimes when multiphase flow is happening through junction is an important task. Another challenge is that for different flow input conditions the prediction of flow regimes using suitable techniques.

Azzopardi and Whalley (1982) studied the air-water two-phase flow in a sharp edged Tee junction. They observed the inlet flow pattern affects the behavior of the flow. They observed that in case of churn and annular flow pattern at the inlet of the junction, the liquid phase preferred to flow through the side arm. However, in case of bubbly flow, it was observed that the gaseous phase preferred to flow through the side arm. In case of annular flow pattern, the liquid that enters the side arm, comes from the liquid film travelling along the wall of the tube rather than from the liquid droplets trapped in the gaseous phase. For the experiments they developed correlations which showed that the liquid film that enters the side tube is linearly proportional to the gas flow rate in the side tube. Azzopardi (1984) further modified the model and added a correction term. It was assumed that the liquid entering the side arm was the liquid drifting in that portion of the film occupying the same segment as the gas taken off.

To predict the phase separation phenomenon in a horizontal Tee junction for stratified wavy and annular flow regime, a mechanistic model has been presented by Shoham et al. (1987). Their study captured the effect of inertia and centripetal forces on the separation mechanism. When the flow regime is annular, the liquid phase prefers to go into the branch section due to the dominance of the centripetal forces. For stratified flow when the liquid flow rate is high, inertia force is dominant and hence the liquid phase prefers to flow straight into the run section. For low liquid flow rate and stratified flow regime, centripetal force is dominant and the liquid flows into the branch section. When the velocity of the gaseous phase is low and the flow regime is smooth stratified, liquid phase prefers the run section due to the dominance of the inertia force. An experimental observation on the phase separation of air-water and steam-water two phase flow performed by Seeger et al. (1986) for horizontal, vertically downward and vertically upward branch arm. Diameter of the Tee junction selected for this work was 50 mm. The flow parameters were changed over a wide range to get a variety of flow regimes at the inlet section. It was observed that the phase separation phenomena strongly depended on the branch position. Phase separation also found to be depended on the inlet flow pattern and the ratio of inlet mass flux to branch mass flux. Also for different orientation of the branch arm, empirical correlations were developed.

Ottens et al. (1999) developed a model to characterize flow separation phenomenon in a Tee junction for air-water two phase flow for small values of liquid hold up. Gas-liquid flow separation has been found to be greatly affected by the inclination angle of the branch arm. With the increase in the mass input fraction of the gaseous phase in the branch, liquid phase has found to leave the branch arm and at one point all the liquid phase found to be departing the branch arm. They also studied the effect of viscosity on the separation phenomenon. To change the properties of the liquid phase a desired, glycerol was added to water. Penmatcha et al. (1996) studied the phase separation effect varying the branch inclination angle for air-water stratified flow regime. They also measured the pressure drop in the inlet, run and branch arm of the Tee junction. For downward inclined and horizontal branch arm they presented a mechanistic model to predict the flow separation phenomenon. There experiments revealed the great significance of the gravity force on the phenomenon. In case of the downward inclination angle of the branch section it was observed that more amount of liquid was diverted in the branch arm when compare to the horizontal branch arm case. When the downward inclination angle reached the threshold value of 60°, there is no liquid flow in the run section.

A model was presented to predict the flow separation for annular flow pattern at the inlet by Roberts et al. (1997) for a Tee junction with an inclined branch arm. Their model predicted the liquid film flow rate and film width around the perimeter of the inlet pipe. This information was then used to predict the flow separation phenomena. In certain cases there was an abrupt increase in the liquid taken off in the side arm. This is due to the liquid phase coming to rest at the main pipe. Diameters of the Tee junction used for the experiments were 32 mm and 38 mm.

An experimental observation for gas liquid two phase flow was performed by Conte (2000) to study the phase separation phenomenon. High liquid flow rate was used to create the annular flow regime. Initially flow rate of both the component phases were minimum and then they were increased to predefined values. Film thickness were measured and it was found that the developed film is not symmetric in nature. At the bottom the film had stratified like structure and then at the top the film became thin abruptly. Three different type of probes had been used in this study – flush mounted probe, wire robe and needle probe to measure the film thickness. An attempt had been made to characterize the distribution of the liquid film around the Tee junction. Hydraulic jump occurs when Froude no. changes from greater than 1 to less than 1, which is transition from momentum domination to gravity domination. In case of Tee junction, hydraulic jump is found in the run section due to the interference of the momentum driven film flow from the inlet with the gravity driven flow in the run outlet. From this study it was found that the effect of gaseous phase is dominant. Liquid film gets thinner as the flow rate of the gaseous phase increased. Separation phenomenon was observed to be increased due to the hydraulic jump in the run arm.

Baker (2003) combined the knowledge of phase separation phenomenon through Tee junction with control tactics to make a compact fractional flow separator which will work continuously. He conducted a series of experiments to optimize the configuration of the Tee junction. The flow is controlled by means of control valves which are placed on the outlets of the Tee junction. He found that flow separation is gas dominated in case of vertically upward side arm. The flow separation is dominated by liquid phase when the side arm is vertically downward. The work found out the optimum setting for the control valves to get maximum separation effect and this setting does not depend on the inlet superficial velocities of the component phases but depends on the flow regimes. With the increase in the inlet superficial velocity of the gaseous phase, liquid flow through the upward arm found to be increased dramatically. The liquid hold up was measured successfully with the help of electrical capacitance tomography system. Ottens et al. (2001) developed a model to capture the transient phenomenon when gas-liquid two phase mixture is flowing through the horizontal Tee junction. The model is derived from continuity and momentum equation for liquid and gas phase. The separation phenomenon is captured by using “steady state macroscopic mechanical energy balance equation”. The diameter of the Tee junction used by them is 51 mm. The experimentally observed transient behavior is very accurately predicted by combining the transient flow model and the steady state flow separation model.

Baker et al. (2008) used kerosene as the liquid phase and air as the gaseous phase. Kerosene is having high flash point. They placed two Tee junction in series. The first Tee junction had side arm in vertically upward direction whereas the second one had side arm in vertically downward direction. In their experiments the transient effect showed by the Tee junction is quite similar to the transient effect observed in the straight pipes. Flow separation strongly depends on the highly non-linear and unanticipated flow regimes at the inlet section. They observed that the change in the superficial velocity of the gaseous phase at the inlet of the Tee junction had more impact than the change in the superficial velocity of the liquid phase on the transient responses like the liquid hold up. Margaris (2007) presented a mathematical model to evaluate the pressure drop across the Tee junction. The model also predicted the volume fraction. The results obtained from the model were compared with the experimental results and there were a good agreement between them. The worked showed the way to obtain more effective phase separation effect, especially in case of slug flow. This has been accomplished by modelling of pressure drop and phase distribution along with special geometrical design. El-Shaboury et al. (2007) observed even phase separation can only be obtained at an even mass separation for air-water two phase flow through a horizontal Tee junction. The flow regime at the inlet were annular, stratified and wavy type for the experiment. To predict then phase separation and pressure drop a mathematical model was also presented. They observed that in case of stratified flow, there is an alteration of gas-liquid interface and this highly affects the pressure distribution in the Tee junction. But this effect is not present in case of annular and wavy flow regime. The system pressure has been kept at 1.5 bar during the experiment.

Li-yang et al. (2008) studied the oil-water two phase flow separation numerically and experimentally. The numerical simulation performed using a 3-D two fluid model. They used the k-$\mathcal{E}$ model to capture the turbulence effect. Experimental results showed that flow patterns and the volume fraction at the inlet largely affects the flow separation phenomena. They found reasonable agreement between the numerical and experimental results.

Azzi et al. (2010) used air-water mixture to study the phase separation phenomena. Input parameter for the Tee junction at the inlet were the volume fraction and the superficial velocities of the two phases. They measured the volume fraction of the liquid as well as the gaseous phase at the outlet section s of the Tee junction after flow passes through the Tee junction. Experiments conducted by them confirms that the phase separation depends on the superficial velocities of the liquid and gaseous phases at the inlet of the Tee junction. Although there is not any substantial effect of the pressure on the phase separation phenomenon. An increase in the liquid superficial velocity at the inlet decrease the liquid coming out of the branch section. On the other hand, if the superficial velocity of the gaseous phase is increased, the liquid coming out of the branch section is found to be increased.

Mohamed et al. (2011) showed the effect of change in outlet inclination angle on the phase separation phenomenon when gas-liquid mixture flows through the Tee junction. Air and water have been used as two phases in this study. The outlet sections of the Tee junction were adjusted according to the desired values. Their work is based on experimental observations. They found out phase distribution very much depends on the outlet inclination angle when there is stratified flow regime at the inlet of the Tee junction. They also observed that full separation occurred at an outlet inclination angle of 0.7 degree. In compare to stratified flow, wavy flow regime is less dependent on the inclination angle. Annular flow regime is even less sensitive to the inclination angle.

2.1) Gaps in the literature

From the literature survey it is clear that, more concentration on gas-liquid pair has been given so far. Also the boundary conditions at the branch and run outlet are restricted. More experiments have been conducted for the horizontal Tee junction.

CHAPTER 3:

PROBLEM FORMULATION

A Tee junction is characterized by three sections. They are inlet, branch and run. Liquid-liquid two phase mixture enters in to the Tee junction through the inlet section. After it reaches the junction, the flow separation occurs and the component phases come out through the branch and run section. But when the two phase mixture comes out of the branch and run section, the volume fraction measured at these section differs from the volume fraction at the inlet. So there is a misdistribution of the phases. The objective of the present study is to characterize the uneven distribution of the phases when they pass through the Tee junction. This can be done by studying the effect of the following parameters:

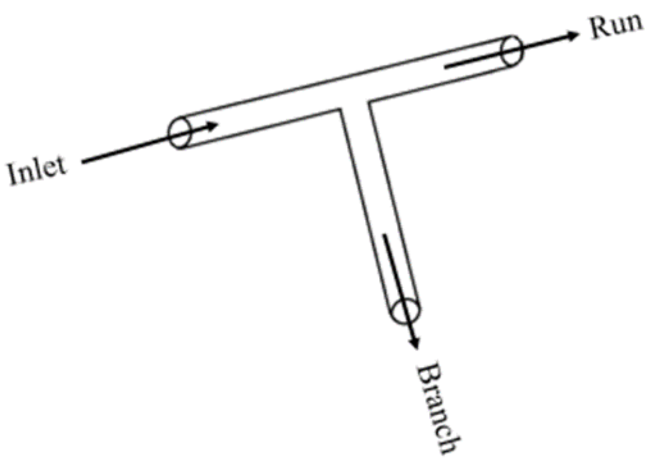

Figure 1: Schematic of a Tee junction

(a) Effect of inlet mixture velocity: For a specific fluid pair and geometrical set up of the Tee junction, the superficial velocities of the component fluids are changed. This will result in different type of flow regimes at the inlet of the Tee junction. For each set of superficial velocities of the component phases, the volume fraction is measured at the branch and run outlet.

(b) Effect of inlet volume fraction: Keeping the inlet volume fraction fixed for a specific Tee junction, the effect of change in inlet volume fraction on the phase separation phenomenon has been observed for a particular set of fluid pair.

(c) Effect of change in diameter of the Tee junction: The present study has been performed for three different diameter of the Tee junction. For a fixed liquid pair, the inlet volume fraction and the superficial velocities of the component phases have been kept constant and then the effect of changing the diameter of cross section of the Tee junction on the phase separation is studied.

(d) Effect of change of fluid properties: For a constant value of superficial velocities and volume fraction at the inlet of the Tee junction, the phase separation phenomenon for different fluid pairs is studied keeping the diameter of the Tee junction constant. Changing the fluid pair will vary the fluid properties like -

a) Density

b) Viscosity

c) Interfacial tension

For a set of gas-liquid and liquid-liquid pair, keeping the void fraction fixed, the inlet superficial velocities will be varied to get different kind of flow regimes at the inlet. Then void fraction will be varied and again for the new void fraction the superficial velocities will be varied within a certain range. The whole procedure will be repeated for different gas-liquid and liquid-liquid pair.

Table 1: Properties of fluids

Fluid	Density (Kg/m^3)	Viscosity (Kg/m-s)	Interfacial tension with water (N/m)
Water	998.2	0.001003	NA
Kerosene	780	0.0024	0.048
Diesel	817.1	0.002	0.0294
Soybean oil	919	0.0622	0.0556

3.1) Numerical methods

The numerical calculations have been done by using Ansys Fluent 15.0 software. Finite volume technique is used to solve the governing differential equations.

3.2) Grid generation

The grids chosen in this case are tetrahedron in type. In view of the complexity of the phase separation phenomenon, small enough grid size has been used to capture the flow physics. To capture the effect of boundary layer phenomenon near the wall of the Tee junction, 'inflation' is used.

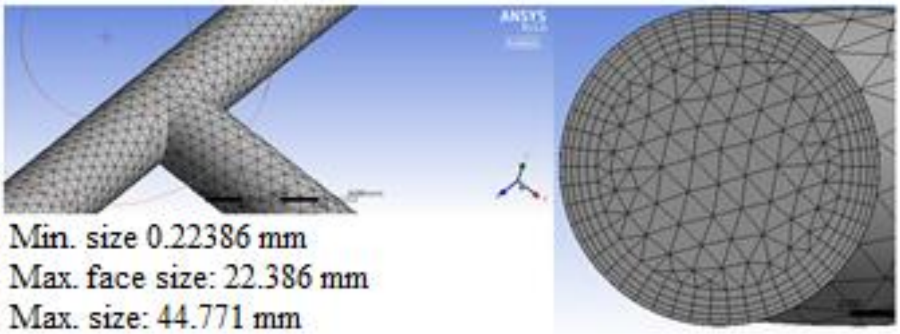

Figure 2: Meshing of the Tee junction

3.3) Numerical schemes

There are eleven governing differential equations in this present case. They are solved using Eulerian multi fluid VOF model. SIMPLE scheme is used in this case. Shear Stress Transport (SST) k-ω turbulence model is applied to arrest the turbulence effect.

3.4) Boundary conditions

Inlet section of the Tee junction is chosen as the velocity inlet. The velocities of the two liquid phases quantified there. Also the volume fraction for the secondary phase is mentioned at the inlet. Atmospheric pressure outlet condition have been employed at the runa nd branch outlet section of the Tee junction. The velocity of each of the two phases is zero at the wall, i.e. no slip condition prevails. Also there is no penetration of the fluids across the walls. Temperature is assumed to be set at a constant value of 25° celsius throughout the experment.

3.5) Convergence standards

For all governing equations 10-6 has been set as the convergence limit for the scaled residuals. All the scaled residuals decreasd below 10-6 mark except continuity. Scaled rsiduals for continuity hovers around 10-5 and after 1500 iterations it becomes constant.

3.6) Governing differential equations

Total eleven number of equations need to be solved to capture the flow physics of the current problem. They are continuity equation, x, y and z momentum equations for primary and secondary phases separately, turbulent kinetic energy (k) equation, specific dissipation rate of turbulent kinetic energy (ω) equation, interfacial area concentration (IAC) and volume fraction (VF) equation.

$\frac{1}{\rho_q}\ [\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q\right) = S_{\alpha_q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})$ (Continuity equation)

$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla p + \nabla.[\mu\ (\nabla\vec{v} + \vec{v}^{T})] + \rho\vec{g} + \vec{F}$ (Momentum equation)

$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j k\right) = \frac{\partial}{\partial x_j}\left[\Gamma_k \frac{\partial k}{\partial x_j}\right] + G_k - Y_k + S_k$ (*k-equation*)

$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j \omega\right) = \frac{\partial}{\partial x_j}\left[\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right] + G_\omega - Y_\omega + D_\omega + S_\omega$ (*ω*-equation)

$\frac{\partial(\rho_g x_p)}{\partial t} + \nabla.\left(\rho_g \overrightarrow{u_g}\, x_p\right) = \frac{\mathrm{D}\rho_g}{\mathrm{Dt}} x_p + \frac{2}{3}\frac{\dot{m}_g}{\alpha_g} x_p + \rho_g(S_{RC} + S_{WE} + S_{TI})$ (IAC equation)

$\frac{\alpha_q^{n+1}\rho_q^{n+1} - \alpha_q^{n}\rho_q^{n}}{\Delta t} V + \sum_f\left(\rho_q^{n+1} U_f^{n+1} \alpha_{q,f}^{n+1}\right) = [S_{\alpha_q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})]\, V$ (VF equation)

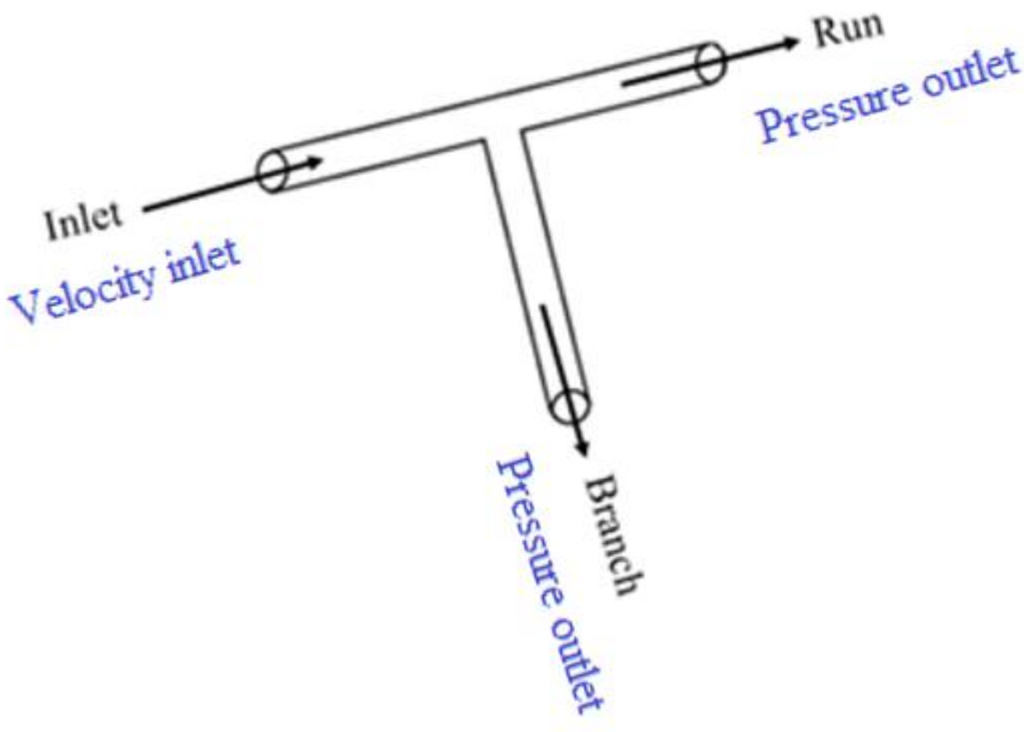

Figure 3: Boundary conditions implemented

CHAPTER 4:

RESULTS AND DISCUSSION

4.1) Results obtained through numerical investigation:

4.1.1) Grid independence test

To confirm the solution acquired is independent of the grid size, grid independence test has been performed. Volume fraction along the branch arm of the Tee junction has been plotted along the ordinate while position of the plane at which the area weighted volume fraction is determined, is plotted along the abscissa.

The current mesh size has been increased to 10 percent and reduced to 10 and 20 percent to test the grid independency of the current model. From figure 3 it is clear that results obtained from different grid size is very much close to each other and hence the result is not dependent on grid size.

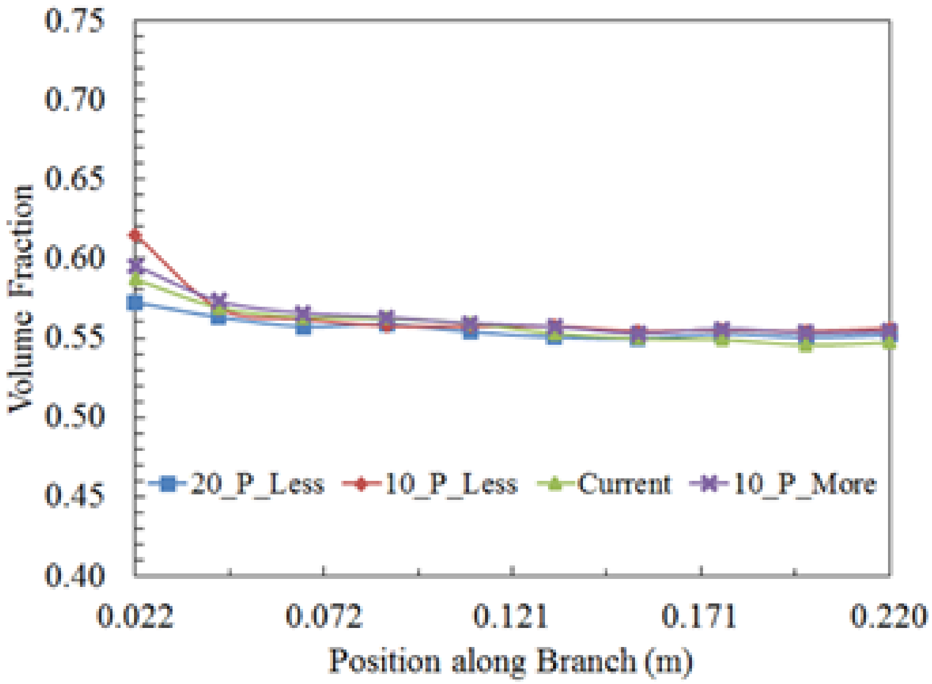

Figure 4: Volume fraction variation for different grid size along inlet and branch arm.

4.1.2) Hydrodynamics of phase separation:

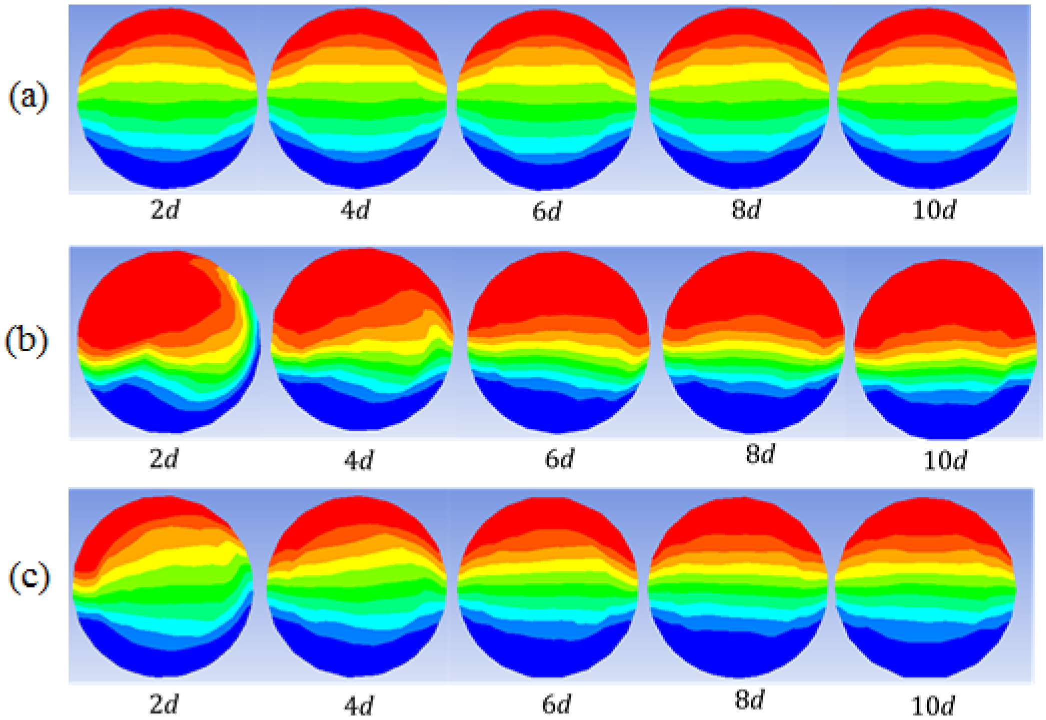

Figure 5: Phase distribution at different cross-section of (a) inlet, (b) branch and (c) run arm

Figure 5 shows phase distribution at different cross-section of inlet, branch and run arm. The distance of the planes at which the phase distribution has been shown are measured in terms of the diameter of the Tee junction from the intersection point. At the inlet section, there is not much variation of the phase distribution as the flow is already developed. But right after the intersection point, the phase distribution in the branch and run arm are very much different. Again when moved along the branch and run arm, the phase distribution initially changes with distance but once the flow develops there is not much change in the phase contour. It has been observed that, after a distance of 10*d* there is not any substantial amount of change in the phase distribution in both branch and run arm.

Figure 6 and 7 shows the 3-D plot of volume fraction along the inlet, run and branch arm for two different cases of inlet mixture velocity and volume fraction for kerosene-water fluid pair. Along the *x* axis position along inlet and run has been plotted. Along the *y* axis position along branch arm has been plotted. Along *z* axis volume fraction has been plotted. There are four different cases shown in the figure. In the first and fourth case, the branch volume fraction is the highest and run volume fraction is the lowest. In second case, there is negligible variation in the volume fraction. So the phase separation phenomenon is minimum there. In the third case, the run volume fraction is maximum and branch volume fraction is minimum. From these four cases it is clear that depending on the various factors, there is an uneven distribution of the phases in the outlet arm of the Tee junctions. These figure typically shows the importance of the present work.

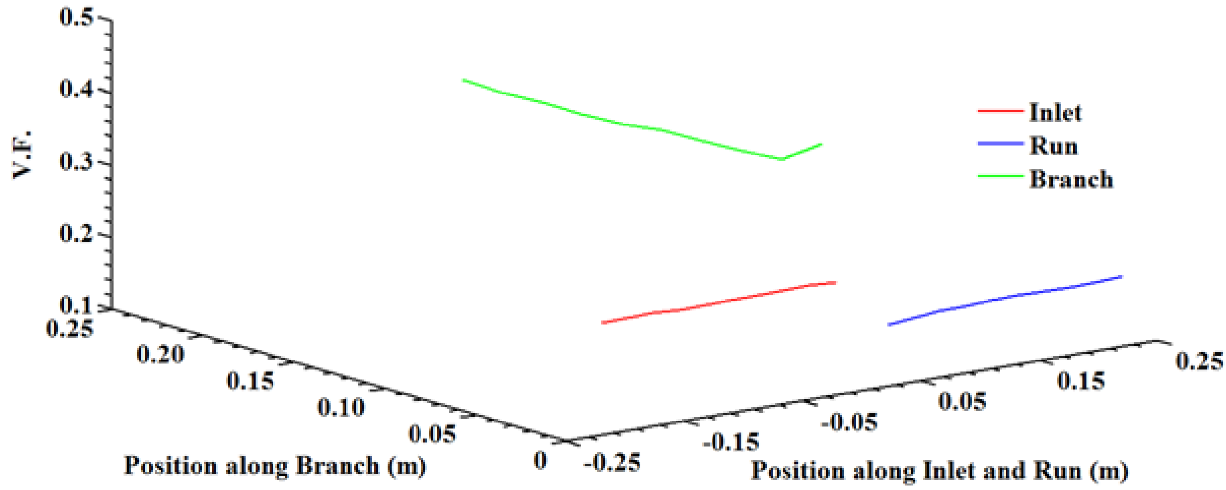

Figure 6: 3-D plot of volume fraction for inlet VF 0.2, inlet mixture velocity 0.5

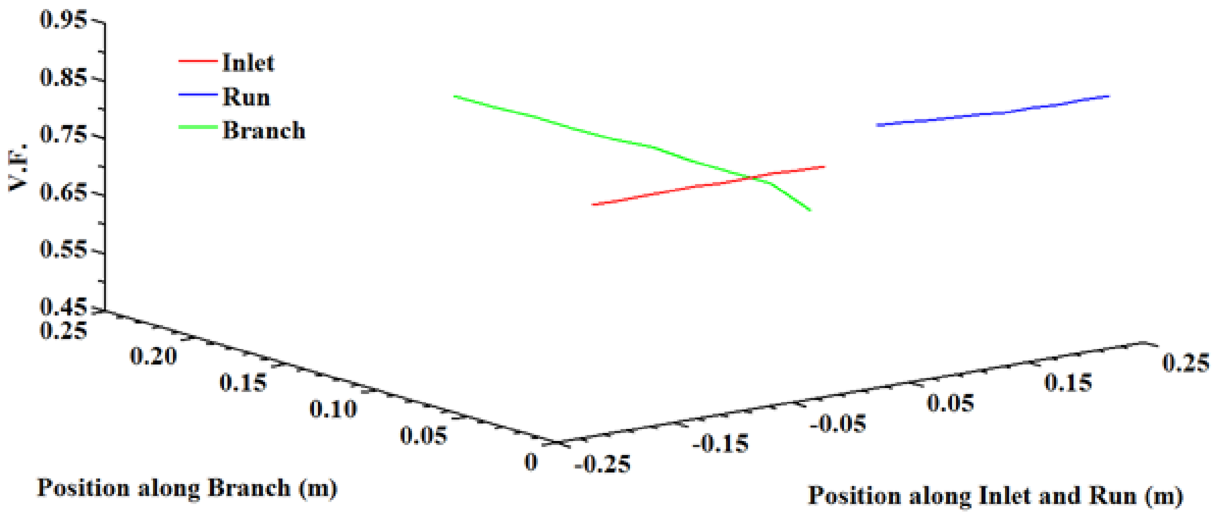

Figure 7: 3-D plot of volume fraction for inlet VF 0.9, inlet mixture velocity 0.5

4.1.3) Effect of inlet mixture velocity

Figure 8 shows the effect of inlet mixture velocity on volume fraction of the inlet arm at different positions for diesel-water fluid pair for a volume fraction of 0.5 at the inlet. The diameter of the Tee junction is 11 mm in this cases. There is a decrease in the inlet volume fraction with the increase in inlet mixture velocity in both the cases.

Figure 9 and 10 show the effect of the inlet mixture velocity for diesel-water fluid pair on volume fraction of the branch and run arm respectively at different positions. In this case also the volume fraction decreases with the increase in the inlet mixture velocity. It has been found out that diesel-water and kerosene-water fluid pair shows similar type of behavior when the mixture velocity at the inlet is changed. But for soybean oil-water pair, although the trend is similar, the effect is more prominent as shown in figure 11.

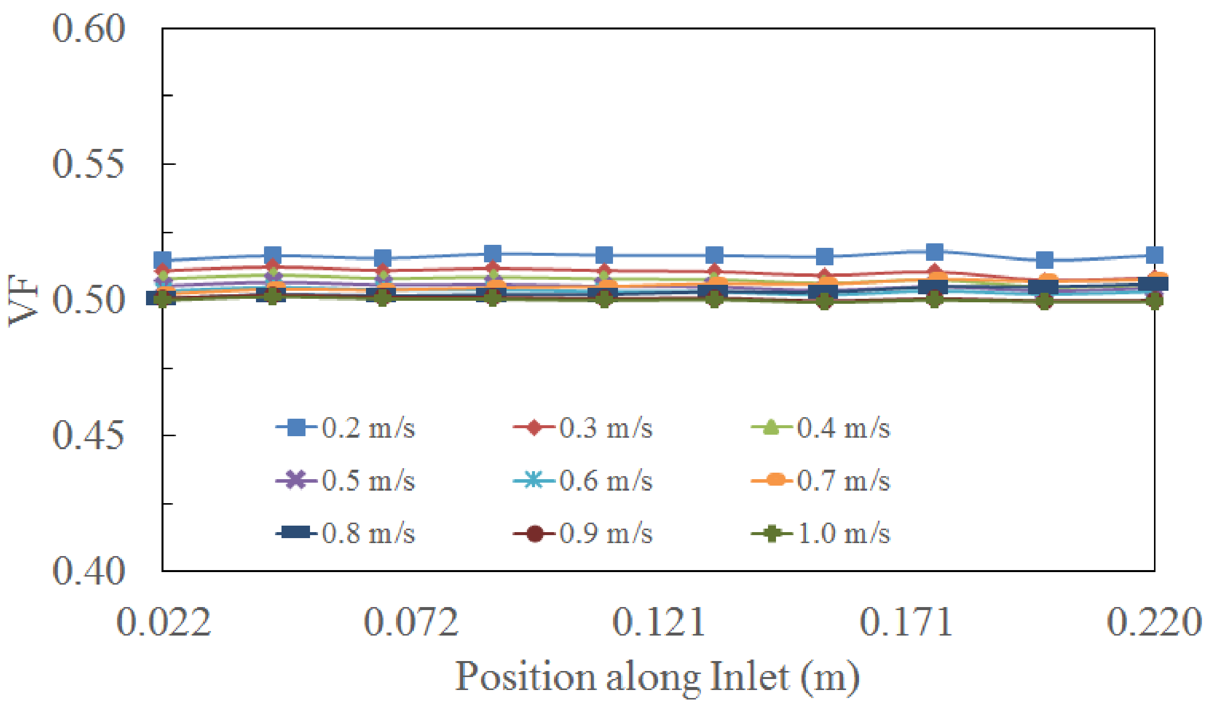

Figure 8: Variation in VF along inlet arm for diesel-water pair

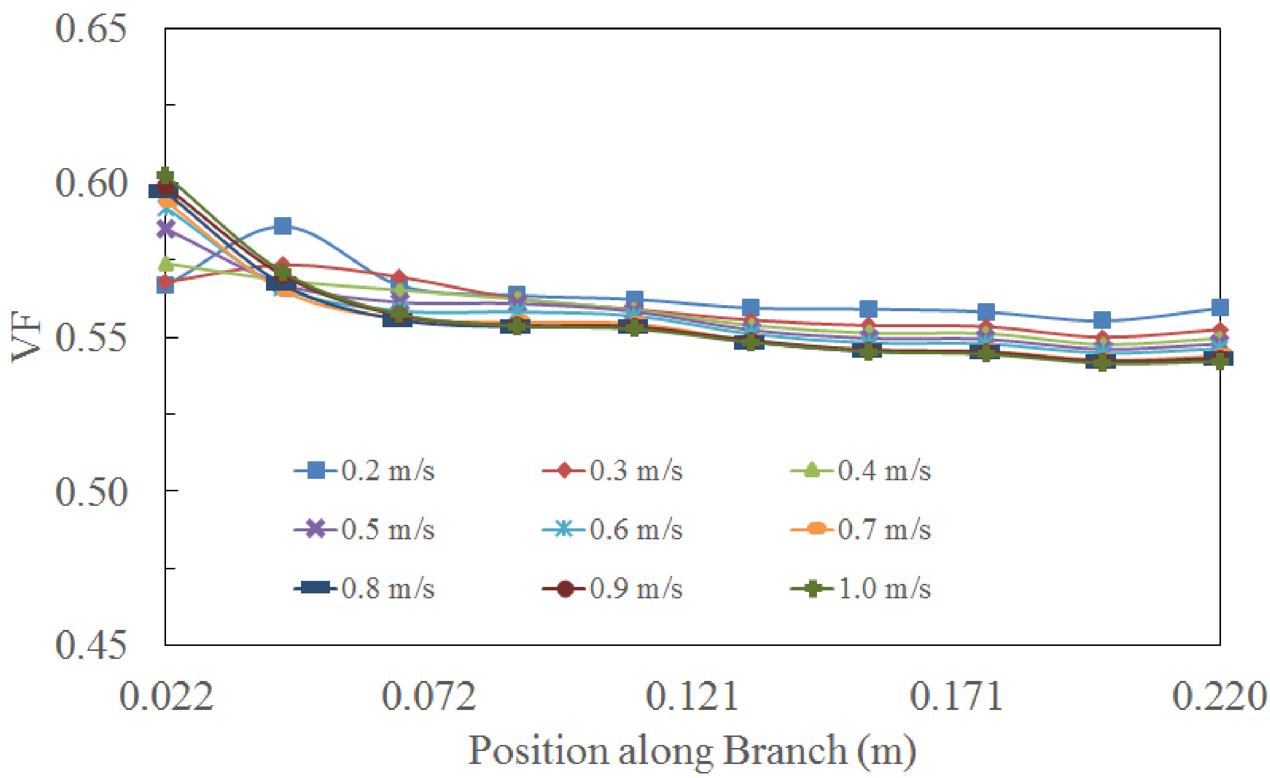

Figure 9: Variation in VF along branch arm for diesel-water pair

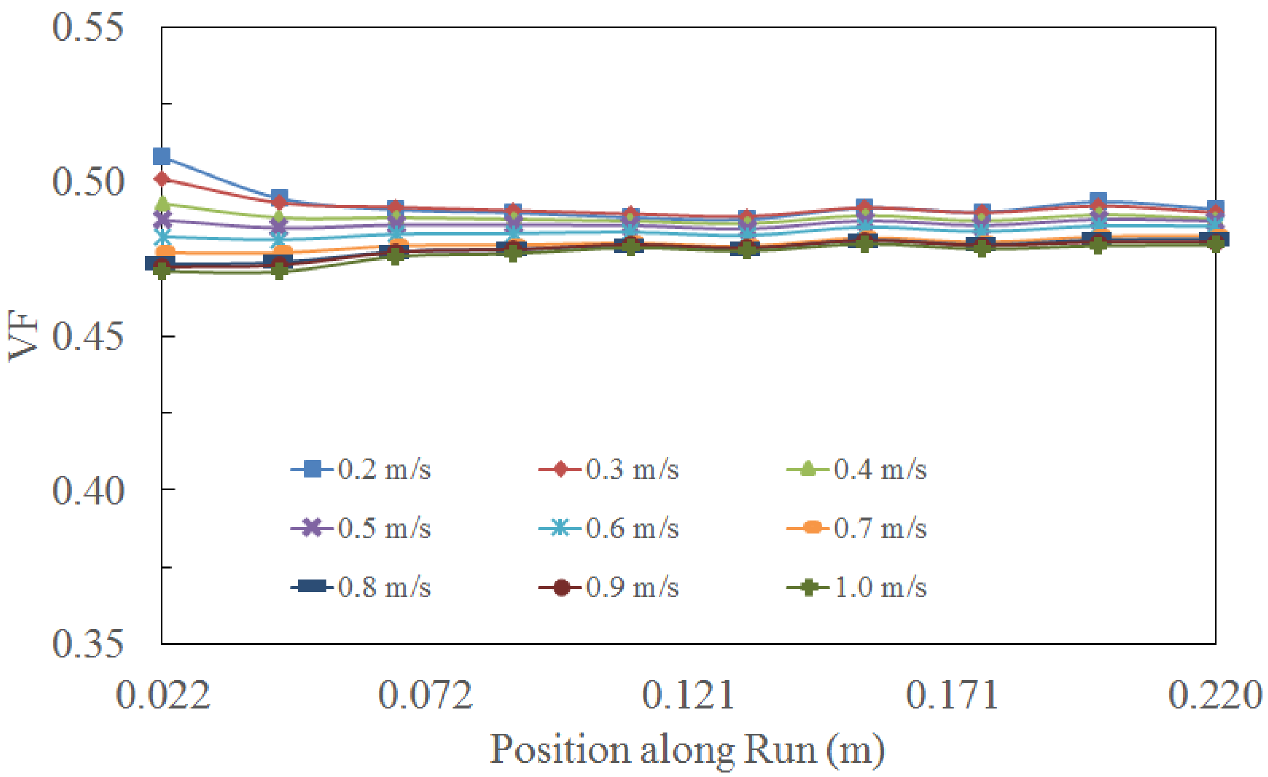

Figure 10: Variation in VF along run arm for diesel-water pair

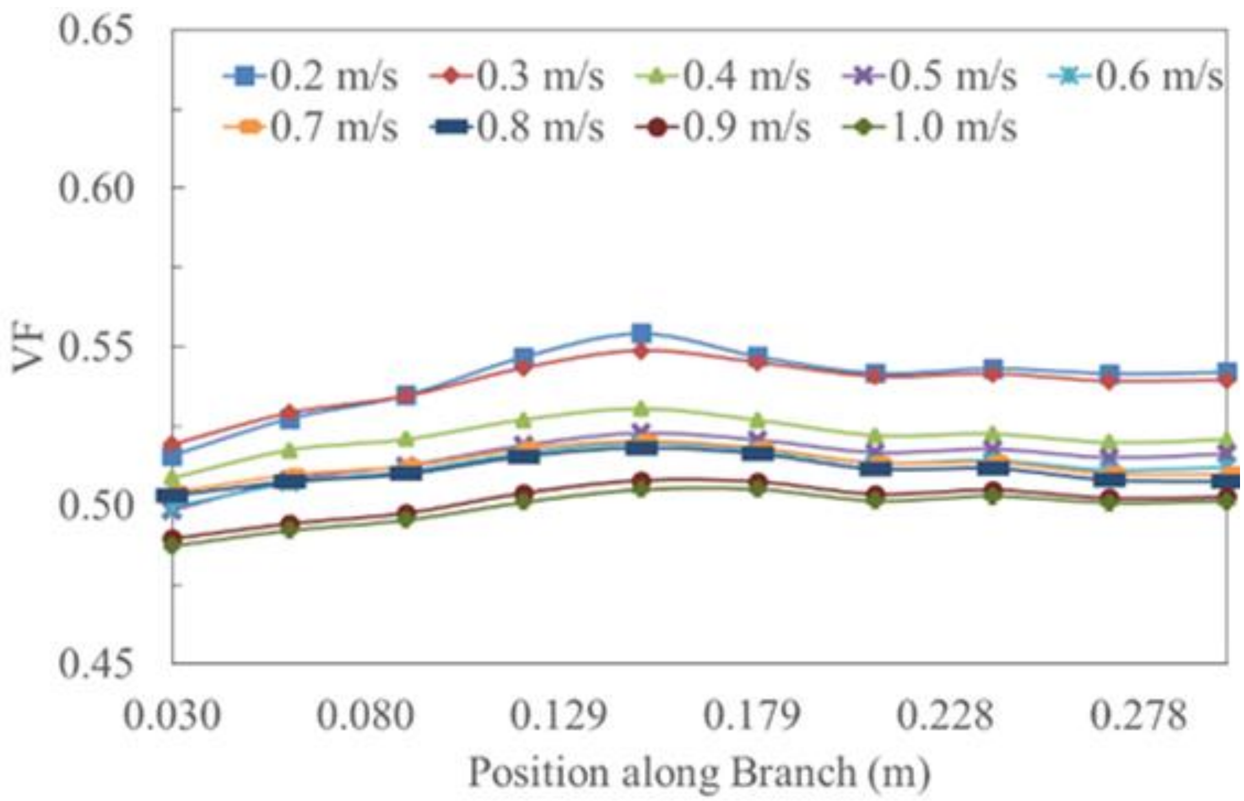

Figure 11: Variation of VF along branch arm for soybean oil-water pair

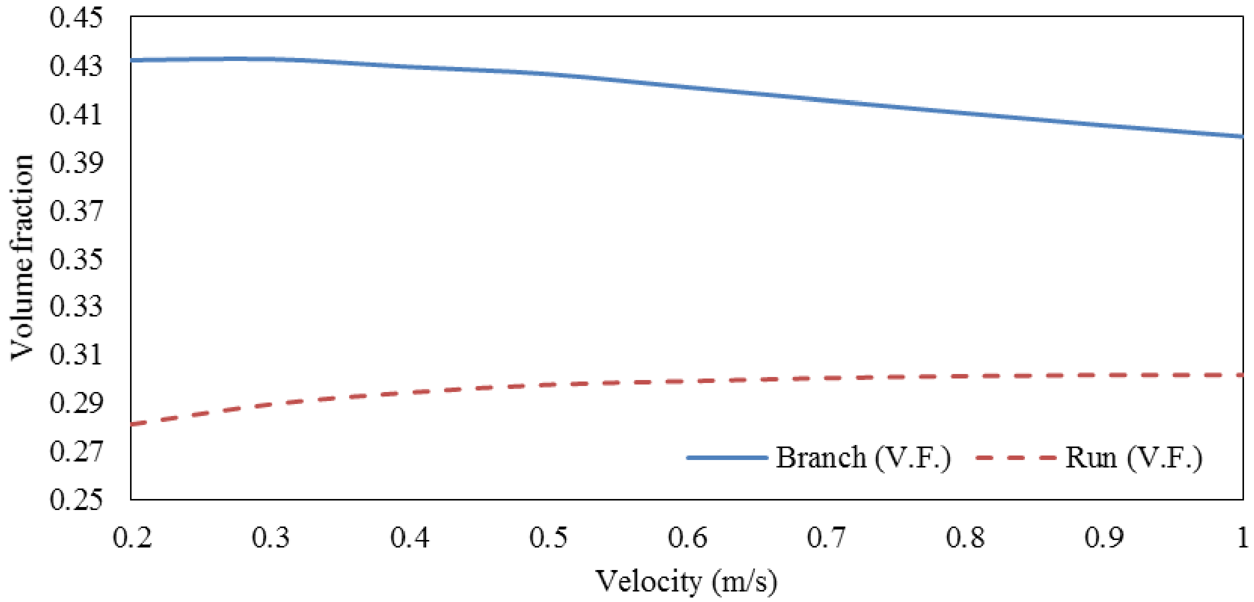

Figure 12: Effect of inlet mixture velocity for diesel-water fluid pair, 11 mm diameter Tee junction, inlet VF 0.3

Figure 12 shows the change in volume fraction of branch and run arm with the change in inlet mixture velocity. The volume fraction is measured in a plane which is at a distance of twenty times the diameter of the Tee junction from the intersection point along the branch and run arm. Figure 12 predicts the response for diesel-water pair. In this case, branch volume fraction decreases and run volume fraction increases with the increase in the inlet mixture velocity. The same trend is also observed for kerosene-water pair. But in case of soybean oil-water, the volume fraction in both branch and run arm are found to be decreased with the increase in the inlet mixture velocity.

4.1.4) Effect of inlet volume fraction

It has been observed that the effect of change in inlet volume fraction is quite similar in case of diesel-water and kerosene-water pair. In both the cases there is a certain value of the inlet volume fraction for which there will be even distribution of phases in branch and run arm as depicted in figure13 and 14.

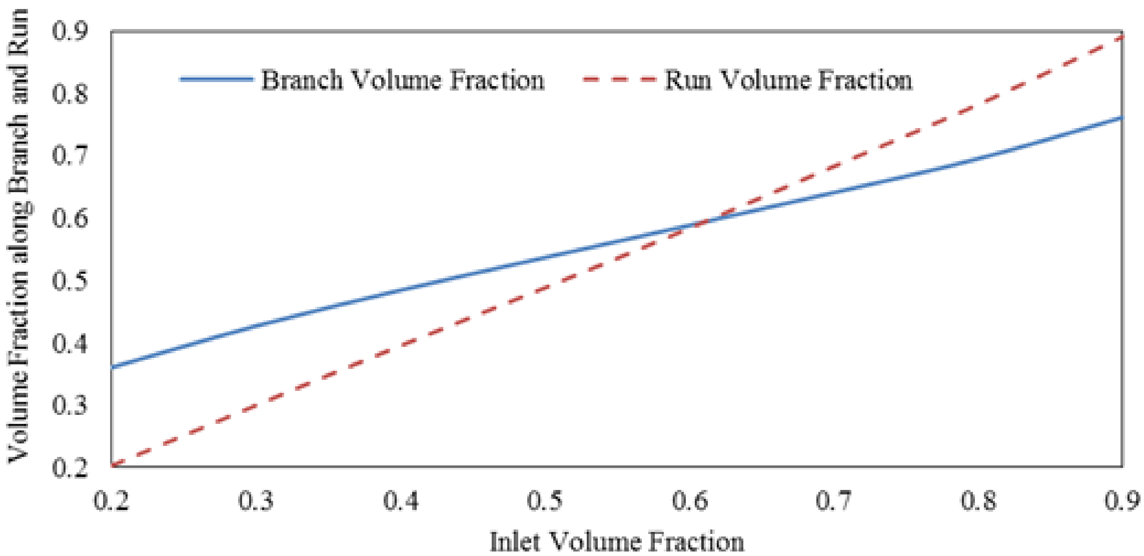

Figure 13: Effect of inlet volume fraction on branch and run volume fraction for diesel-water, 11 mm dia. Tee junction

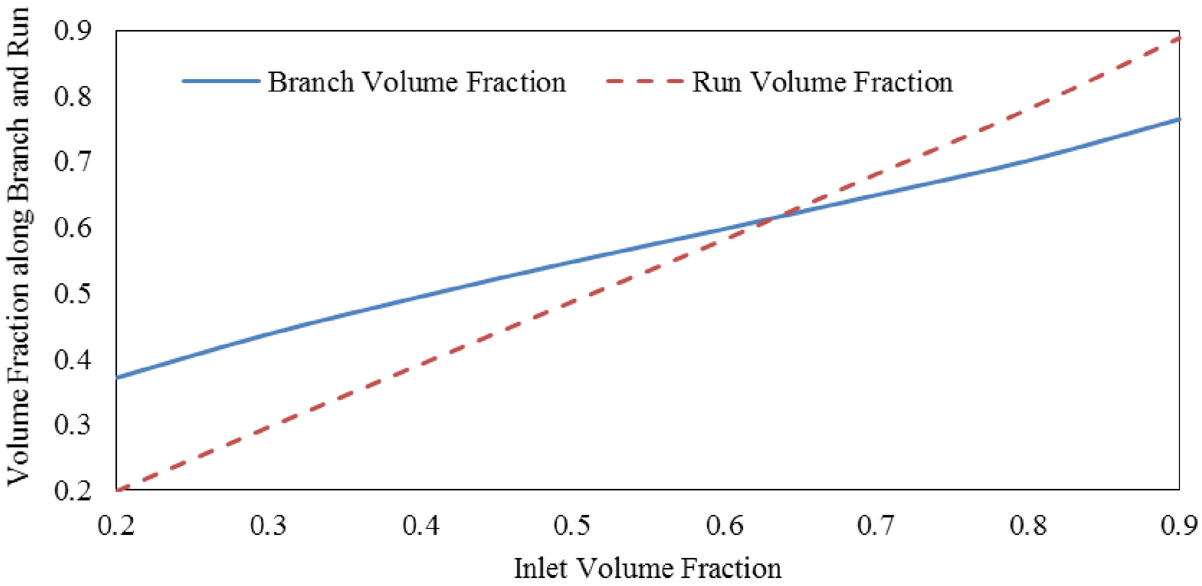

Figure 14: Effect of inlet volume fraction on branch and run volume fraction for kerosene-water, 11 mm dia. Tee junction

But in case of soybean-oil water pair the change in volume fraction in run and branch arm with the change in inlet volume fraction is same and so the curves overlapped as shown in figure 15.

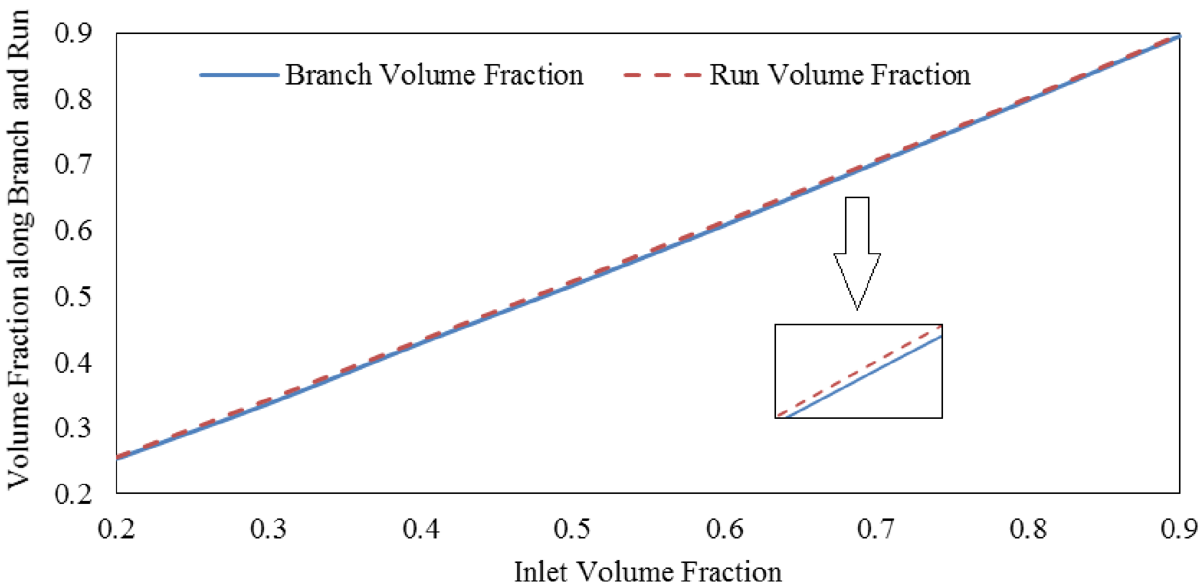

Figure15: Effect of inlet volume fraction on branch and run volume fraction for soybean oil-water, 11 mm dia. Tee junction

4.1.5) Effect of the diameter of the Tee junction

Figure 16 shows the effect of change in diameter of the Tee junction for soybean oil-water on the area weighted volume fraction of a plane which is situated at a distance of 0.4 m from the intersection point along the branch arm.

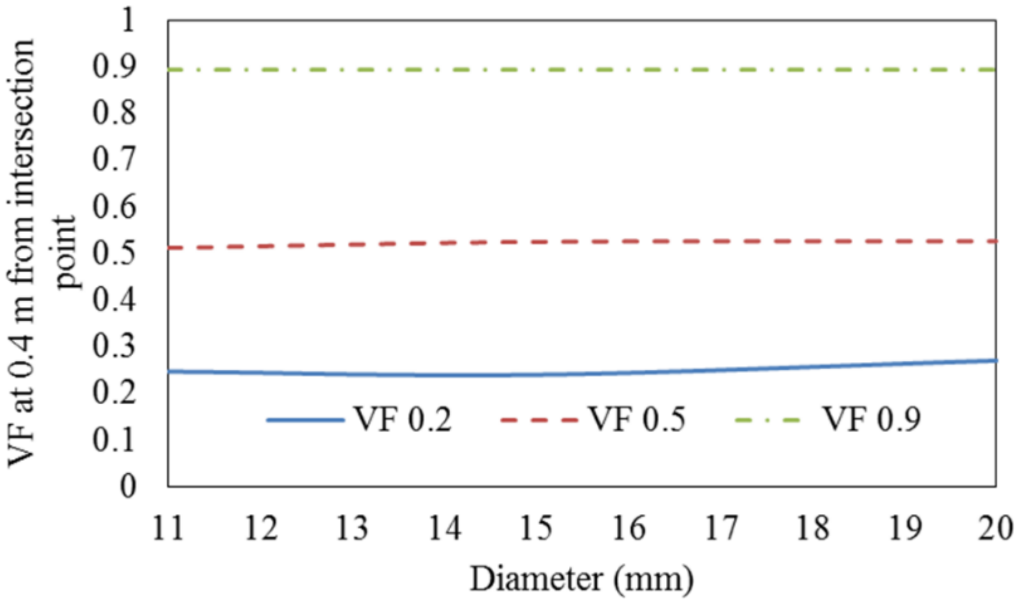

Figure 16: Effect of diameter of Tee junction for soybean oil-water fluid pair

From these figures it is concluded that diameter of the Tee junction has no influential effect on the phase separation phenomenon through the Tee junction. Similarly for kerosene-water and diesel-water fluid pair also there is no influential effect of diameter on the phase separation.

4.1.6) Effect of the fluid properties

Figure 17 and 18 show respectively how the branch and run volume fraction varies for different set of fluid pairs for 11 mm diameter Tee junction. Diesel-water and kerosene-water pair behaves quite in the same way but the behavior of soybean oil-water pair is different from the other two pairs.

In this comparison the inlet mixture velocity is fixed at 0.5 m/s and the inlet volume fraction is 0.5. For this particular case the volume fraction of secondary phase for diesel-water and kerosene-water pair at different branch cross section is greater than that of soybean oil-water pair. On other hand, volume fraction of secondary phase for soybean oil-water pair at different run cross section is greater than that of other two pairs. However, as the inlet mixture velocity and volume fraction changes, the response of different pair also varies.

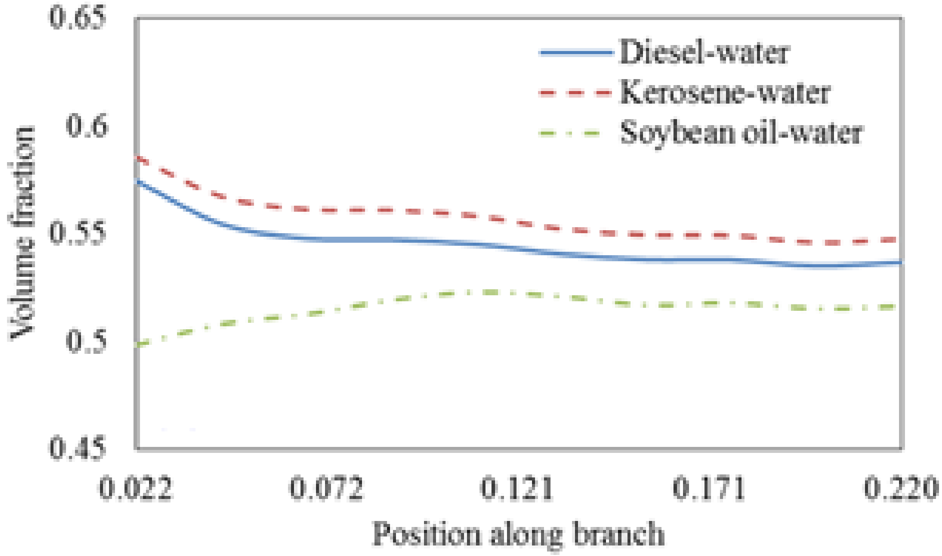

Figure 17: Effect of change in fluid pair on branch arm volume fraction for11 mm diameter Tee junction

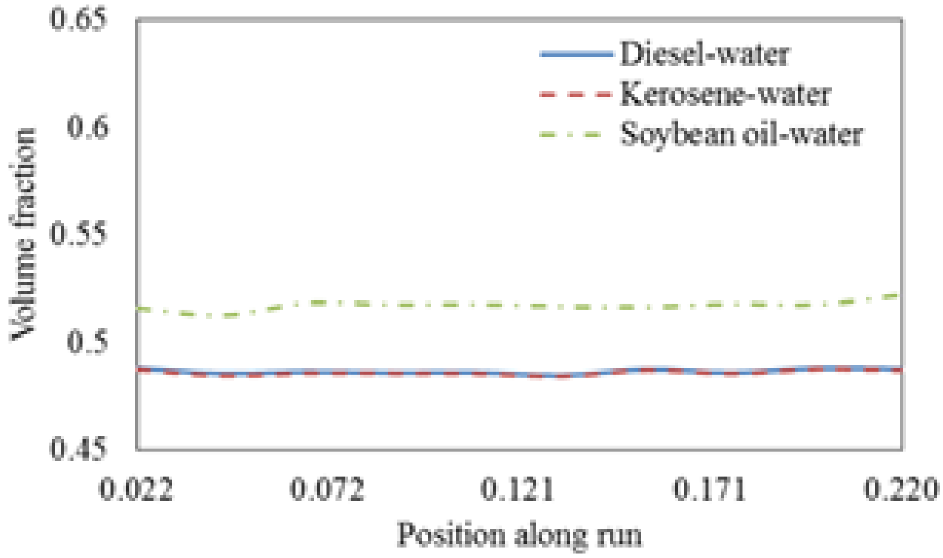

Figure 18: Effect of change in fluid pair on run arm volume fraction for11 mm diameter Tee junction

Figure 19 shows how the phase distribution varies for three different type of fluid pairs at the inlet, branch and run arm of the Tee junction. The inlet mixture velocity and volume fraction have been kept constant in all the three cases.

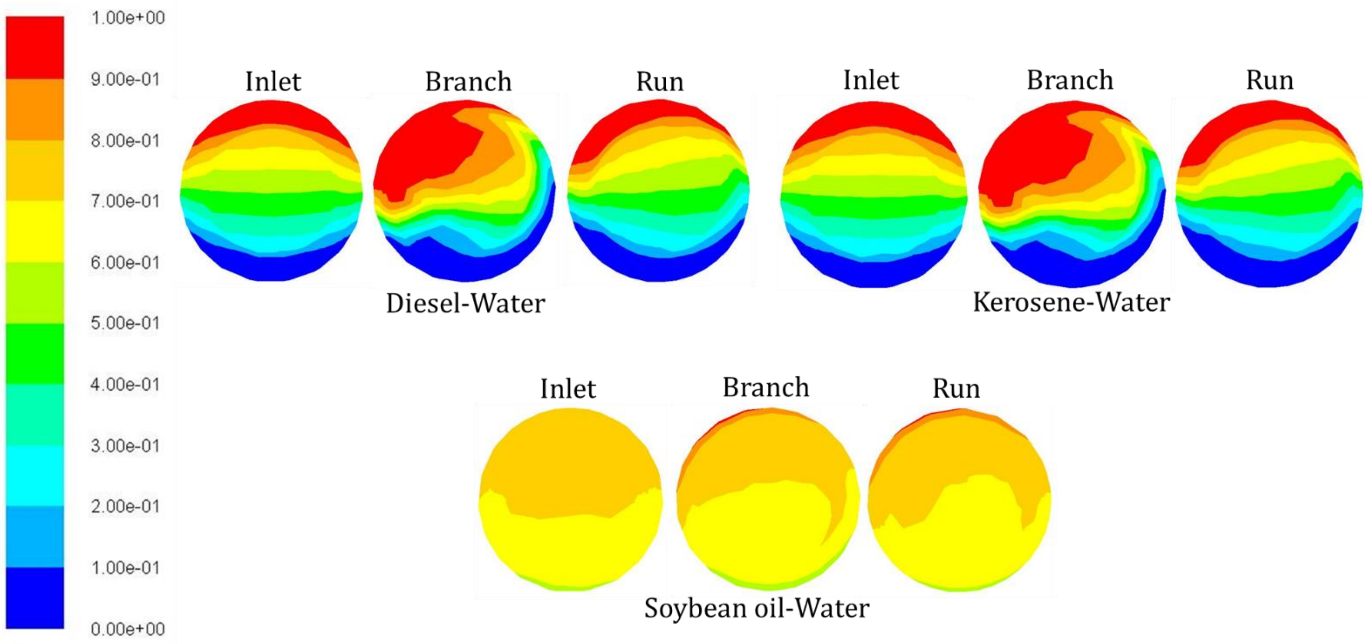

Figure 19: Phase contour for three different type of fluid pair for a fixed inlet mixture velocity and volume fraction

4.2) Results obtained through experimental investigation:

4.2.1) Details of experimental set up

Figure 20 shows the design of 11 mm internal diameter Tee junction. Each of the inlet, branch and run arm are 30 cm long. The material used for the manufacturing of the Tee junction is acrylic resign. Thickness of the wall is 2 mm in this case.

To measure the volume fraction of the component phases for the gas-liquid flow, hold-up arrangement has been made. The total volume of the hold-up system is known from its design parameters. When two phase flow is happening through the arrangement, if the two valves which are placed at the right and left side of the hold-up system is closed at the same time, then some amount of gas and liquid will be tapped inside the system. Now by opening the cork the liquid phase is taken out of the system and the volume of the liquid is measured by using the measuring cylinders. This liquid volume when subtracted from the total volume of the hold-up system will give the volume of the gaseous phase trapped. It is thus possible to calculate the volume fraction of the multiphase mixture. The hold-up arrangement is put across the three arms of the Tee junction to measure the volume fraction at the inlet, ranch and run arm separately.

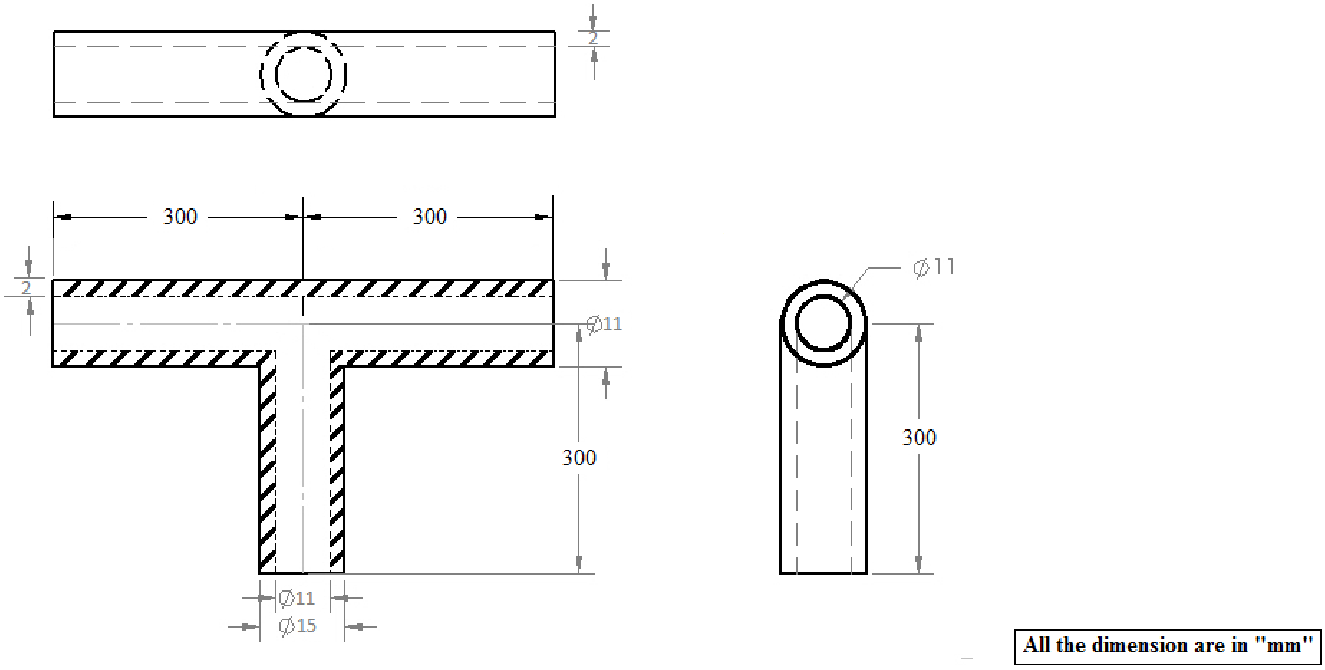

Figure 20: Design of 11 mm internal diameter Tee junction

4.2.2) Selection of Tee junction

Table 2: Selection of Tee junction

Sl no.	References	Inclination angle	Cross-section	Inlet arm length (m)	Branch arm length (m)	Run arm length (m)
1	Azzopardi et al (1982)	Horizontal, vertical	Square Tee, internal dia. Of side tube ϕ 6.35 mm, 12.7 mm, 19 mm	3.6	-	-
2	Azzopardi (1984)	Vertical	same	4.3	-	-
3	Seeger et al (1986)	Horizontal, vertically upward and vertically downward	ϕ 50 mm	2	3	3.1/2.1/0.76

4	Shoham et al (1987)	Horizontal	ϕ 51 mm	8.5 m entrance length	-	-
5	Penmatcha et al (1996)	-5, -10, -25, -40, -60, 1, 5, 10, 20, 35 from horizontal	ϕ 50.8 mm	13.7 m entrance length, 1.016 m inlet arm	0.838	0.838
6	Ottens et al (1999)	Branch inclination 0-0.5 degree	ϕ 50.8 mm	8	14	6
7						
8	Ottens et al (2001)	Horizontal	ϕ 50.8 mm	8	14	6
9	Conte (2000)	Horizontal	ϕ 127 mm	4	2.5	2
		Vertical	ϕ 76 mm	6	1.9/0.7	1.1
10	El-Shaboury et al (2007)	Horizontal	ϕ 37.8 mm	1.4478	1.4478	1.9304
11	Margaris (2006)	Vertical branch, conical section 82/52 mm	ϕ 203 mm at inlet, ϕ 203 mm at run	-	-	-
12	Baker et al (2007)	Vertical	ϕ 38.1 mm	12.6	1.9	1
13	Mohamed et al (2011)	Horizontal inlet and inclined outlet	ϕ 13.5 mm	203.2 mm	90 mm	76.2 mm
				203.2 mm	179 mm	86.2 mm

Based on the literature review, the diameter of the Tee junction selected are

a) 11mm

b) 15 mm

c) 20mm

4.2.3) Experimental procedure

Pump sucks fluid from the tank. There is a bypass connection between the pump outlet and flowmeter inlet. While low flow rate is required, the two bypass valves are controlled in such a way that most of the fluid from the pump outlet returns back to the tank and only small desirable amount of fluid is allowed through the flowmeters. This arrangement is same for both the fluids. Then both the fluids enters the mixing section. Mixing section is designed in such a way that heavier fluid enters from top and lighter fluid enters from bottom. This ensures proper mixing of the two fluids. After the mixing of the two fluids, the mixer flows through a distance of 1.5 m to ensure proper flow development. Then the flow enters the Tee junction. After getting separated in the junction, the flow comes out from the branch and run section. At the run and branch outlet the fluids are collected over a time span of 60 seconds. The mixture is then separated and the volume of the individual phases are measured by using measuring cylinders at both branch and run outlets. Then the time average volume fraction is calculated.

To calculate the inlet volume fraction, the valve just before the inlet of the Tee section is closed. So there is no supply to the Tee junction anymore. Before the valve, in the pipeline there is a small tapping hole which is closed by means of a cork. The cork is then opened and the mixture comes out from the hole. The mixture is then collected over a time of 60 seconds and the volume fraction of the individual phases are measured for each of the phases.

4.2.4) Experimental results

Figure 21 and 22 show the variation of branch and run volume fraction when the diesel superficial velocity is changed keeping the water superficial velocity constant for diesel-water fluid pair and 11 mm diameter Tee junction. In both the cases there is a nonlinear increase of the branch run volume fraction is observed with the increase in the diesel superficial velocity.

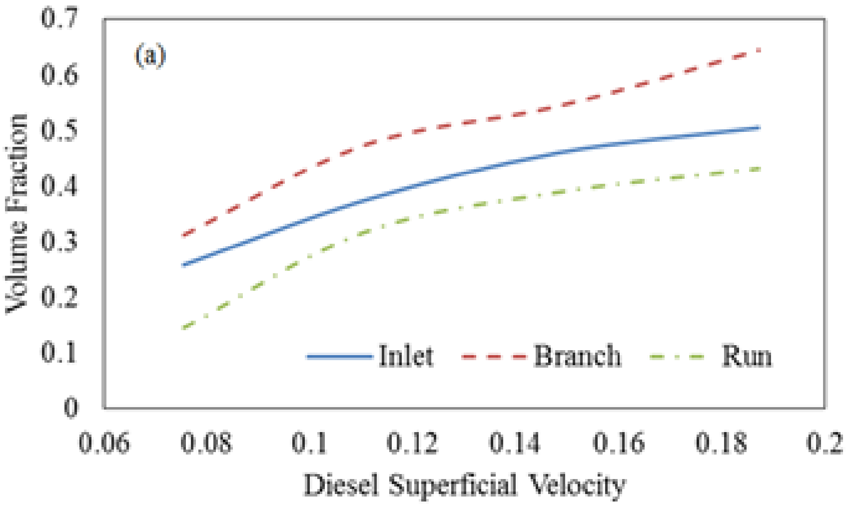

Figure 21: Effect of diesel superficial velocity on branch and run volume fraction for water superficial velocity of 0.1754 m/s

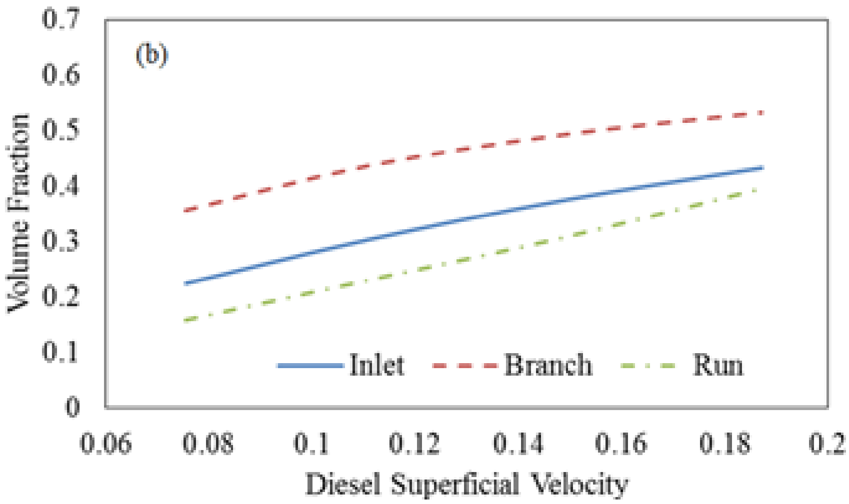

Figure 22: Effect of diesel superficial velocity on branch and run volume fraction for water superficial velocity of 0.2104 m/s

4.2.5) Probe signals

Figure 26, 27 and 28 show the probe signal recorded at the inlet, branch and run arm of the Tee junction respectively when the water flow rate is 0.8 LPM and diesel flow rate is 0.63 LPM. The abscissa of the plot is time in millisecond and along the ordinate normalized voltage has been plotted. The average normalized voltage for the inlet. Branch and run arm are 0.8517, 0.1145 and 0.0980 respectively. These average normalized voltage is directly proportional to the area weighted volume fraction of water in the each arm of the Tee junction individually. So by measuring the average normalized voltage it is possible to calculate the area weighted volume fraction. Also the standard deviation, skewness and kurtosis of the signals have been calculated. These statistical parameters are the identification mark for a particular type of flow regime.

It is possible to get objective description of the flow regime by analyzing the statistical parameters. By determining these statistical parameters associated with a particular type of signal, the flow regimes at any one of the three sections of the Tee junction can be determined.

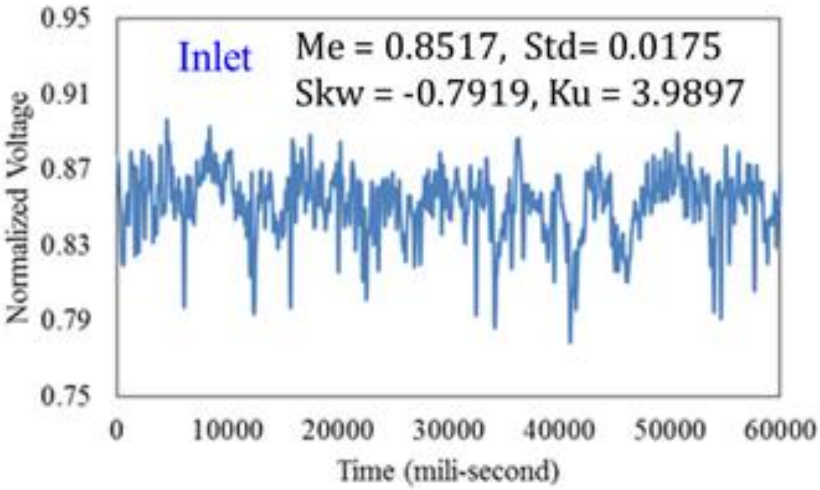

Figure 23: Probe signals for inlet arm

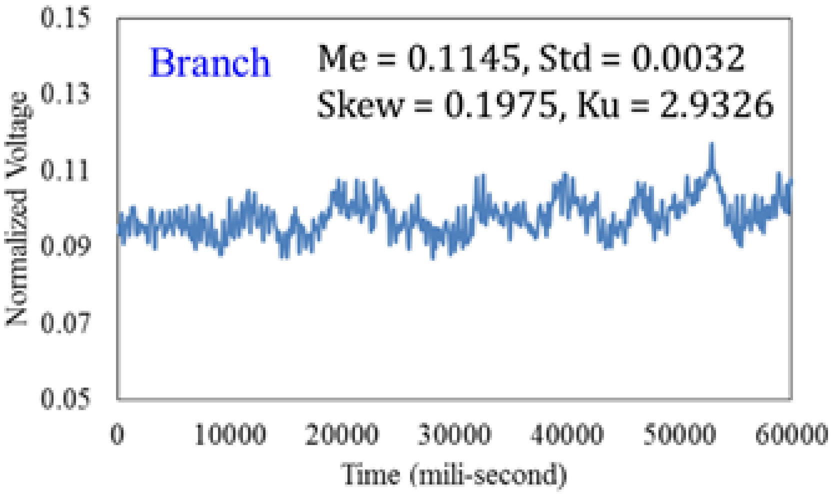

Figure 24: Probe signals for branch arm

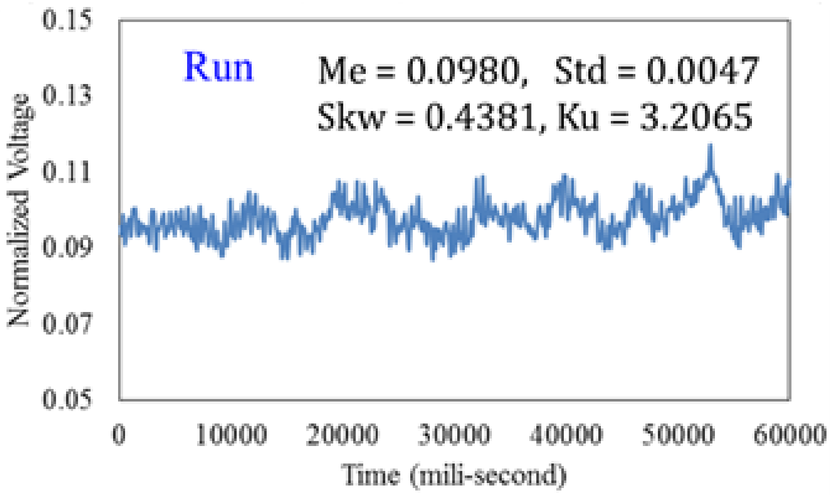

Figure 25: Probe signals for run arm

CHAPTER 5:

CONCLUSIONS & FUTURE WORK

From this work the following can be concluded:

- Inlet mixture velocity and volume fraction have a strong effect on phase separation.
- For a particular value of the inlet volume fraction branch and run volume fraction are equal.
- Diameter of the Tee junction has no significant effect on the volume fraction at the branch and run arm for all three fluid pairs used in this study.
- The volume fraction at the branch and run section strongly depends on the fluid properties such as density and viscosity.
- The effect of the fluid properties on the phase distribution is more prominent in case of lower diameter of the Tee junction.
- For different flow regimes, the statistical parameters of the probe signals are different.

In future the present work further can be extended to include the effect of some other parameters which are not included in the present study. Following points are future work scope of the present study:

- Study the effect of arrangement of junction (Horizontal, inclined, vertical junctions)
- Study the effect of branch position
- Study the effect of branch orientation
- Development of co-relation based on experimental results
- Numerical analysis on vertical Tee junction
- Experimentation on vertical Tee junction
- Statistical analysis of probe signal
- Experimental and numerical analysis on gas-liquid pair

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