

STUDY OF FLOW PATTERNS AND VOID FRACTION
IN VERTICAL DOWNWARD TWO PHASE FLOW

By

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STUDY OF FLOW PATTERNS AND VOID FRACTION IN VERTICAL
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NOMENCLATURE

A	Area
B	Multiplying factor in drift velocity expression of Usui and Sato (1989)
C	Constant in Beggs (1972) and Mukherjee (1979) correlation
C_A	Armand coefficient
C_o	Distribution parameter
D	Pipe diameter
Eo	Eotvos number defined as $Eo = (\rho_l - \rho_g)gD^2/\sigma$
f	Friction coefficient in Usui and Sato (1989) correlation
Fr	Froude number defined as $Fr = U/\sqrt{gD}$
g	Acceleration due to gravity
G	Mass flux
K	Experimental constant in Yamazaki and Yamaguchi (1979) correlation
L	Pipe Length
m_{liq}	Mass of liquid drained from the test section
m_c	Mass of water trapped in fittings
m_{tot}	Total mass of water ideally drained from the test section

N_{gu}	Non dimensional liquid velocity number in Mukherjee (1979) correlation
N_{lu}	Non dimensional liquid velocity number in Mukherjee (1979) correlation
N_l	Liquid Viscosity number in Mukherjee (1979) correlation
P	Pressure
Q	Volumetric flow rate
Re	Reynolds number
U	Velocity
V	Volume
w	Uncertainty
W	Watt
x	Quality
X	Function of input liquid content in Beggs (1972) correlation
z	Weighting parameter

Greek Symbols

α	Void fraction
α_0	Void fraction in horizontal orientation
β	Gas volumetric flow fraction
θ	Pipe Inclination
λ	Input liquid content in Beggs (1972) correlation
σ	Interfacial surface tension
ρ	Density

δ	Multiplying factor for downhill flow in Bonnecaze et al. (1971) correlation
μ	Dynamic viscosity
$\langle \rangle$	Weighted average

Subscripts

atm	atmospheric condition
cr	critical
dn	down
g	gas
GM	Drift
i	Interface
l	liquid
M	mixture
s	superficial
up	up
w	wall

Superscripts

n	Exponent in Yijun and Rezkallah (1993) correlation
m	Exponent in Yijun and Rezkallah (1993) correlation
*	Superscript for Goda et al. (2003) non dimensional mixture velocity

CHAPTER I

INTRODUCTION

Multiphase flow is a simultaneous flow of several phases which may be a gas, liquid or a solid. The two phase flow is the simplest case of the multiphase flow. The two distinct phases can be a combination of any two chemically different species or a combination of the gas-liquid, liquid-liquid, gas-solid or solid-liquid and suggest the flow situation of these two distinct phases moving together along a common path. The two phase flow can be further classified as one component two phase flow as in case of steam water flow whereas the air water flow can be treated as two component two phase flow. The complexity in the two phase flow is primarily due to the turbulent mixing of two phases, compressible nature of the gas phase and can also be attributed to other factors like mass flow rates of individual phases, fluid thermo physical properties, channel geometry and orientation etc. In the present study we are concerned and deal with the two component two phase air water flow in a vertical downward orientation.

The two phase flow phenomenon is of prime importance in the chemical, petroleum, nuclear and power industries. The two phase flow encountered in nuclear and power industries is usually boiling two phase flow while those practiced in the chemical and petroleum industries is essentially non-boiling in nature. The installation of two

phase flow lines has been proven economical in the oil and natural gas transportation system. The two phase flow is used in chemical industry to enhance the mass transfer rate as in case of the bubble columns. It is also a common occurring phenomenon in condensers, evaporators, gas lift pumps and boiler tubes etc. The two phase flow is of significant interest in the refrigeration loops where the quality of the mixture changes continuously with the flow length due to the pipe friction. Thus due to its common occurrence in industrial processes the two phase flow had been studied extensively throughout years. The research in the field of two phase flow particularly for a combination of gas liquid flow dates back to 1930's. Since then a lot of research has been done to improve understanding of this phenomenon.

The research in the field of two phase flow can be classified in terms of the investigation of flow patterns, void fraction, pressure drop and convective heat transfer. The present study is focused on detailed analysis of flow patterns and void fraction as the accurate knowledge of void fraction is required for the calculation of pressure drop and heat transfer rates. The two phase gas liquid flow is confined within the pipe boundaries and is subjected to the interaction between the two phases. This result in an interesting feature of the two phase flow recognized as flow patterns which change with the phase mass flow rates, fluid properties and pipe orientation. These flow patterns are governed by different physical mechanism; influence the mass, momentum and heat transfer rates and hence results in the complication in the analysis of two phase flow. The inquisitiveness about the analysis of these complex flow patterns had resulted into the extensive research in the field of two phase flow. Most of this research work is dedicated to the horizontal and vertical upward two phase flow. Some attempts were done to

analyze the two phase flow behavior in inclined and vertical downward systems but majority of these investigations were limited to the study of flow patterns. Though the two phase flow research was initiated long back, still there is no general agreement over the universal flow pattern map, the void fraction and pressure drop prediction models.

The present study was carried out for air-water two phase flow flowing vertically downward in a 0.0127 m diameter pipe. The principal objective of this study was to study the major flow patterns occurring in downward two phase flow followed by a detailed analysis and then the recommendation of the best correlation to predict void fraction in downward two phase flow. The flow visualization aided with the photographic evidences was useful for elaborate analysis of the flow patterns. This also helped to explain the effects of various forces like buoyancy, gravity, inertia etc on the two phase flow. The most popular drift flux model used to predict the void fraction was also analyzed in detail. Some key features of this model are highlighted in the present study which makes it versatile and applicable for upward as well as downward two phase flow.

The present work is divided into four major chapters. The second chapter deals with the exhaustive literature review of the flow patterns, flow pattern maps and the void fraction correlations available for the downward two phase flow. Chapter III explains the experimental procedure followed to measure the void fraction data and confirms the validity of the experimental setup and hence the flow patterns observed and the measured void fraction data in the present study. The chapter IV is the results and discussion about hydrodynamics of the two phase flow in context to the flow patterns. It presents a detail discussion on the coring bubble phenomenon, effect of increasing the mass flow rate of the gas and liquid phase on the bubbly flow pattern as well the effect of buoyancy and

inertia forces on the slug motion and shape. The chapter IV (Results and Discussion) also elaborates on the performance analysis of the different void fraction correlations and concludes by recommending the best available correlation to predict the void fraction in downward two phase flow. The chapter V (Conclusions and Recommendations) is the conclusions drawn from the present study and the recommendation for future possible research in the field of two phase flow.

CHAPTER II

LITERATURE REVIEW

2.1 Flow Patterns

The complexity of two phase flow is not only due to the many variables involved in it but also the different flow patterns that may exist. A two phase flow may vary from nearly all liquid to all gas flow depending upon the respective distribution of individual phases. By varying the quantity of liquid and gas flowing within pipe different types of flow occur. Many experimental observations of flow patterns have been reported in the literature. Most of these observations are for air- water two phase flows, but some of them report the flow patterns observed with air-kerosene, air-glycerin and air-oil fluid combination. The nomenclature and description of flow patterns has been discussed differently by different investigators. Since a flow pattern can be very chaotic it is very difficult to objectively identify most of these subcategories, but more or less the basic idea of flow pattern definition remains same. The aim of this chapter is to highlight the flow patterns and general agreement or discrepancies in the investigation done so far by different researchers, followed by a brief discussion on flow pattern maps. The last part of this chapter reports on the investigation in the field of void fraction correlations.

Oshinowo (1971) carried out experiments in a 0.025 m diameter pipe in vertical upward and downward co-current air-water flow. He observed coring bubbly, bubbly-

slug, falling film, froth and annular (annular- mist flow) patterns. The bubbly flow was referred to as coring bubbly flow since the bubbles had a tendency to migrate towards the tube center. The radius of core and size of the bubbles increased with increasing flow rates. He observed round Taylor shaped bubbles called as air-slugs with no wake at the slug tail, but the leading edge appeared frothy because of the liquid draining down from the side of gas slug. He found that as the gas flow rate increased the gas slug was distorted and its edge moved towards the pipe wall. At very low gas and liquid flow rates, liquid phase glides smoothly over the tube surface surrounding the inner gas core containing very little or no liquid entrainment inside. This flow pattern was recognized as falling film flow. A similar flow pattern called as falling bubbly film was also observed in which the liquid film was thicker and contained some gas bubbles. The froth flow was characterized by totally distorted gas slugs and turbulence. The fast moving gas core with some liquid entrainment, surrounded by liquid moving in downward direction was observed in annular flow.

Golan (1968) in his work with 0.038 m diameter round tube containing air-water as working fluids observed bubbly, slug, oscillatory and annular flow patterns. The annular flow occupied the largest portion on the flow map. The very unstable flow called as oscillatory flow was observed when the bubble rise velocity was equal to the downward liquid velocity. This flow pattern was apparently observed because of the U-bends used in the experimental setup. However he commented that such kind of flow pattern should not occur in vertical down flow without using U-bends. He observed that the bubbly-slug flow pattern occurred only if the downward water velocity was greater

than bubble rise velocity. Both Taylor and distorted slugs occurred in down flow. Unlike Oshinowo (1971) froth and falling film flow were not observed.

Nichols (1965) in his experimentation of vertical two phase flows in a 0.054 ID pipe observed the bubbly, bubbly-slug, slug, falling film and annular flows. He observed that falling film flow pattern occurred at low gas and liquid flow rates, and concluded that annular flow is the most dominant and obvious flow region observed in down flow. Similar to Golan (1968) he did not observe any froth flow regime.

Crawford (1983) studied two phase flow phenomenon with R-113 and its vapor as working fluids in a 0.038 m diameter round pipe and observed coring bubbly, slug, churn, falling film and annular flows. He found that the smaller fast moving bubbles tend to agglomerate at the tube center, where as the large bubbles were found near the wall. Slug flow contained air slugs with diameter almost equal to the channel diameter. True Taylor type bubbles were observed only at the low system pressure. A distorted slug was observed at higher operating pressure. Oscillating slug was also observed because of the imbalance between the buoyant and drag and fluid viscous forces. Unlike other investigators Crawford observed Churn flow due to the turbulent agitation caused by either high flow rates or high system pressure. The falling film and annular flow observed in his experimental work is similar to the flow description made by other authors.

Nguyen (1975) carried out extensive work on flow patterns from vertically upward to vertically downward for air-water flow in a 0.0455 m diameter pipe. For vertical downward flow, he observed seven flow patterns – bubble, slug, slug-froth, annular-slug, annular, annular-roll wave and annular-droplet. However, the detailed

description of these observed flow patterns is not mentioned in his work. Nguyen reported that annular-slug flow observed in his study was similar to churn or semi-annular flow reported in other studies.

Yamazaki and Yamaguchi (1979) studied two phase phenomenon in a 0.025 m diameter pipe using air-water as working fluids. The determination of flow patterns was done by visual observation and photographic techniques. The flow patterns observed in down flow were bubbly, slug, wispy annular and annular flows. A typical flow similar to annular flow but with smooth gas-liquid interface and a small amount of entrainment was observed at relatively low water flow rates and moderate air flow rates called wetted-wall flow. The description of wetted wall flow pattern appears similar to the falling film flow pattern observed by other investigators.

Paras (1982) studied experimentally two phase flow in a 0.0195 m diameter pipe oriented downwards. He used air-water as working fluids and observed slug flow with successive Taylor bubbles separated by water slugs. Bubbly flow involved axially random distribution of bubbles but a definite tendency to move to the center of pipe. His flow map consisted of large portion of churn flow in which bubbles surrounded an irregular void region. Similar to slug flow this flow pattern had a tendency to fluctuate. Paras (1982) observed an annular regime with essentially annular film falling over the edges of the pipe.

Mukherjee (1979) performed experiments with air-kerosene and air-oil fluid combination in a 0.038 m diameter pipe for a wide range of inclination from vertical upward to vertical downward. Four distinct flow patterns observed were bubble flow,

slug flow, stratified flow and annular mist flow. He observed a bubble concentration gradient over the pipe cross section for bubbly flow regime. Conventional Taylor slugs and the pressure fluctuations were observed in the slug flow. The frequency of these fluctuations was observed to depend on individual phase flow rates. At higher gas flow rates the slug appeared to be very frothy preventing correct visual description of slugs. He noticed that as the gas flow rate is increased at fixed liquid flow rate, annular flow is attained with almost negligible slippage between the two phases, at all pipe inclinations including downward flow. The gas phase was observed to be continuous along the pipe core and concentric or remain eccentric depending upon the pipe inclination. This flow pattern was referred to as annular mist flow as some liquid drops are always entrained into the gas core.

The experimental work of Yijun and Rezkallah (1993) in a 0.0095 m diameter pipe in vertical downward direction with air-water fluid combination reported bubble, slug, froth, annular and falling film flow. Bubble flow pattern was observed at high liquid flow rates and low gas flow rates. The description of flow patterns remains similar to as mentioned by other investigators.

Usui and Sato (1989) investigated two phase flow with air-water fluid combination at atmospheric pressure in a 0.016 m diameter round tube. He observed four distinguished flow patterns namely, bubbly flow, slug flow, falling film flow and annular flow. In the bubbly region the bubbles had a tendency to move toward the center of tube due to lift force acting on bubbles caused by velocity gradient in continuous phase. Usui and Sato (1989) observed that in a slug flow regime most of the gas slugs do not acquire bullet shape. The slugs were distorted due to buoyancy force acting in opposite direction

of flow and assumed a wedge shape in proximity to the wall. The annular flow appearance was similar to those described by other authors. At low liquid and gas flow rates the liquid appeared to be falling smoothly over the pipe wall described as falling film flow. They observed that as the gas and liquid flow rates are increased transition to annular flow occurs.

Troniewski and Spisak (1987) investigated two phase flow with air-mineral oil as working fluids in three different pipe diameters of 0.001, 0.015 and 0.0254 m, respectively. The flow patterns were determined by visual observation in stream of special light passing through it, in addition to the photographic techniques. He classified the two phase flow in eight different flow patterns namely, film Smooth flow, wavy flow, froth, annular, bubbly, plug, core and stalactite flows. In the film smooth flow it was observed that liquid flows in a form of thin smooth film and the gas is displaced along the tube axis. A little wavy version of film smooth flow with very few or no liquid droplets in the gaseous core was termed as wavy flow. The highly turbulent intermixed flow of air and oil was recognized as froth flow. In the bubbly flow, he observed that the gas phase was dispersed in form of individual hemispherical bubbles flowing along the pipe axis one by one. The flow pattern similar to bubbly flow but with much bigger bubble size was defined as plug flow. In core flow liquid film was observed to surround gaseous core. The gaseous core was found comparable to liquid film thickness. Stalactite flow was characterized by a liquid flow inside gas bubbles which were dispersed in the form of individual bubbles in the liquid.

Wang et al. (1996) did two phase flow investigation for air-oil mixture in a 0.029 m vertically downward pipe. The major flow patterns observed were bubble flow,

intermittent flow, stalactite flow, falling film and annular flow. A combined method of visual observation and pressure drop fluctuation analysis was used to identify the flow patterns. Large bubbles were observed in bubbly flow at low air velocities. At higher velocities gas bubbles were observed to collapse into small bubbles with spherical shapes. The intermittent flow pattern was defined to accommodate the slug and churn flow because of its pulsation characteristics. They found that the slug flow contained Taylor bubbles and liquid slugs with small air bubbles entrained in it. The churn flow was highly chaotic version of slug flow. The authors found it difficult to distinguish between falling film and annular flow because of its similar flow nature. From the experimental investigations of Troniewski and Spisak (1987) and Wang et al. (1996) it appears that stalactite flow pattern appears in the two phase flow of fluids incorporating highly viscous liquids.

Abdullah and Al-Khatab (1994) analyzed two phase flow phenomenon in a 0.038 m diameter downward oriented tube using air-water as working fluids. Flow regime map was determined on the basis of direct visual observations. Annular, slug and bubbly flow patterns were observed distinctly. In contrast to bubbly flow description reported by other investigators, they found that at low air flow rates small air bubbles flow randomly in downward direction and tend to move away from the pipe axis. With increasing air flow rate large bubbles were observed due to coalescence and bubble movement augmentation. Further increase in air flow rate resulted in slug formation moving through the pipe center. Bullet shaped slugs were observed despite of the downward flow direction. Finally the increment in air flow rate resulted in annular flow and the liquid film thickness decreased with increasing air flow rate.

From the above review of flow patterns studied by different investigators it is clear that there are no quantitative measures to decide upon the existence of distinguished flow patterns. It can be anticipated that the flow patterns are governed by the pipe geometry, orientation and the physical properties of fluid combination used. However, bubbly, slug, falling film and annular flow patterns are highlights of most of the research work carried out in downward two phase flow. Similar flow patterns were observed in the present study and are discussed in Chapter IV with pictorial evidences.

2.2 Flow Pattern Maps

The flow pattern map is a graphical representation of different flow patterns that may exist with varying flow rates of respective phases. The set of coordinates that can be used to plot a flow pattern map and hence to represent the flow pattern transitions can consist of superficial phase velocities, mass flow rates, mass fluxes or the non dimensional parameters, such as Reynolds number or Froude number, of individual phases. Thus, flow map is a tool to identify the existence of a particular flow pattern, for known parameters mentioned above. The transition of the flow patterns from one to another is gradual and hence there are no well defined sharp transition boundaries between the individual flow patterns. In the present study the issue of flow pattern maps is not emphasized, but a concise discussion about the flow pattern maps is presented in this section.

It should be noted that since the flow pattern definition and hence their recognition depends more on an individual's perception, there is no well defined universal flow pattern map. The other reasons could be the effect of fluid properties and

pipe diameters on the flow patterns and their transition. The literature reports several flow pattern maps proposed by different investigators. These flow pattern maps are plotted using different physical parameters for the abscissa and ordinate, respectively. As shown in Figure 2.1, Oshinowo (1971) presented a flow pattern map using mass flow rates of individual phases (lb/min) as coordinates. This map was based on his own experimental work with air water fluid combination in a 0.025 m diameter pipe.

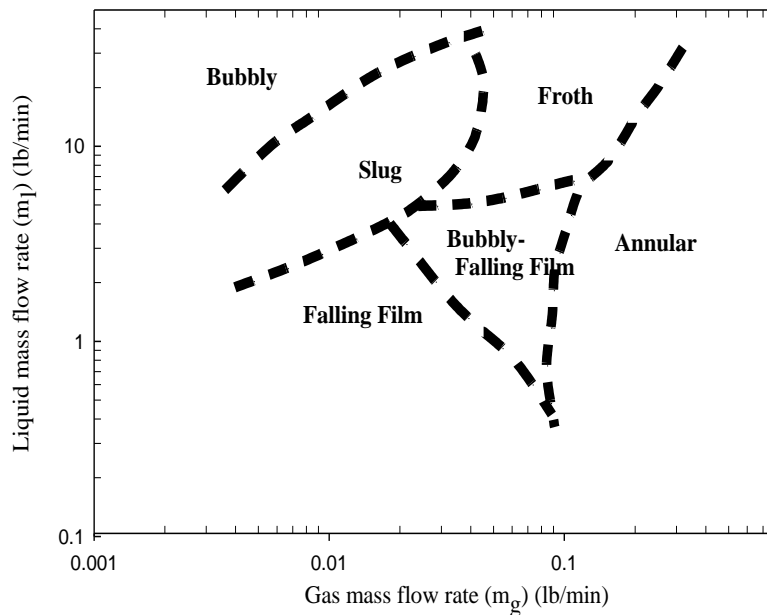


Figure 2.1 Flow pattern map proposed by Oshinowo (1971)

He observed the bubbly flow pattern to occur at high water mass flow rate and low air mass flow rate. The falling film regime was divided into the falling film and bubbly falling film flow, respectively. It can be seen from his flow map that these flow patterns along with the annular flow regime occupy the largest portion of the flow pattern map without a clear transition line between the falling film and annular flow regimes at low liquid mass flow rates.

Yamazaki and Yamaguchi (1979) proposed a flow pattern map for their experimental study, as shown in Figure 2.2. The map was plotted with the individual phase mass flux ($\text{kg}/\text{m}^2\text{s}$) as the coordinates. They did not observe the bubbly flow pattern. This is the only flow map reported in the literature, presented in terms of the mass flux of each phase.

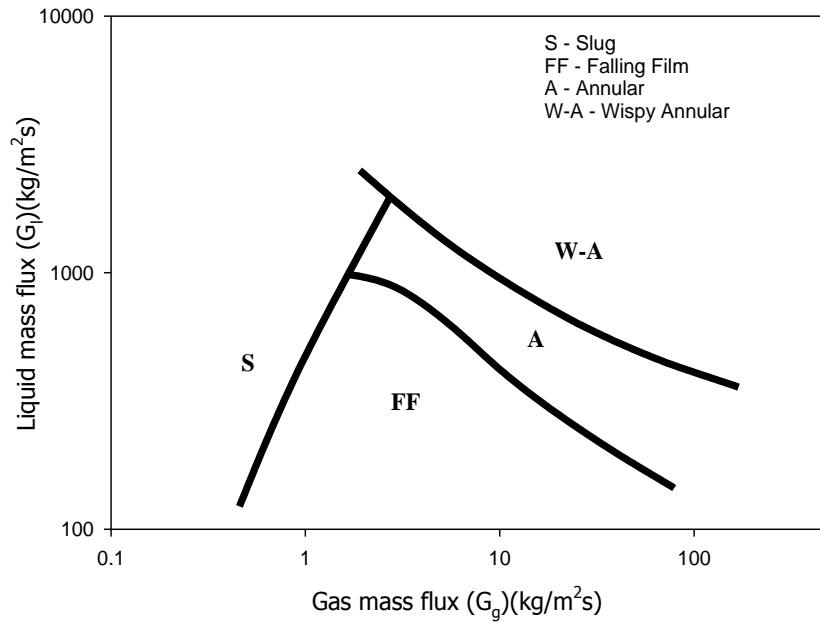


Figure 2.2 Flow pattern map of Yamazaki and Yamaguchi (1979)

The flow pattern map of Troniewski and Spisak (1987) as shown in Figure 2.3 was based on their experimental work using air-oil fluid combination. As mentioned earlier in this chapter, Troniewski and Spisak (1987) observed the unique flow regime of stalactite flow which appeared between the plug and froth flow regime on the flow map. The wavy core and plug flow reported in their investigation were not observed in the present study. The flow pattern map proposed by Paras (1982) is presented in Figure 2.4. He did not observe the falling film flow pattern and the boundaries of the churn flow were not well defined.

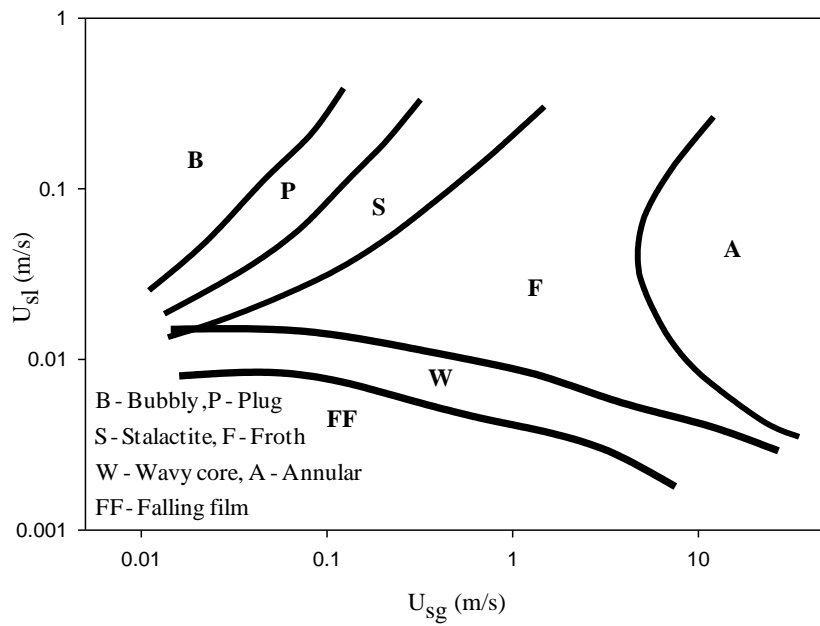


Figure 2.3 Flow pattern map of Troniewski and Spisak (1987)

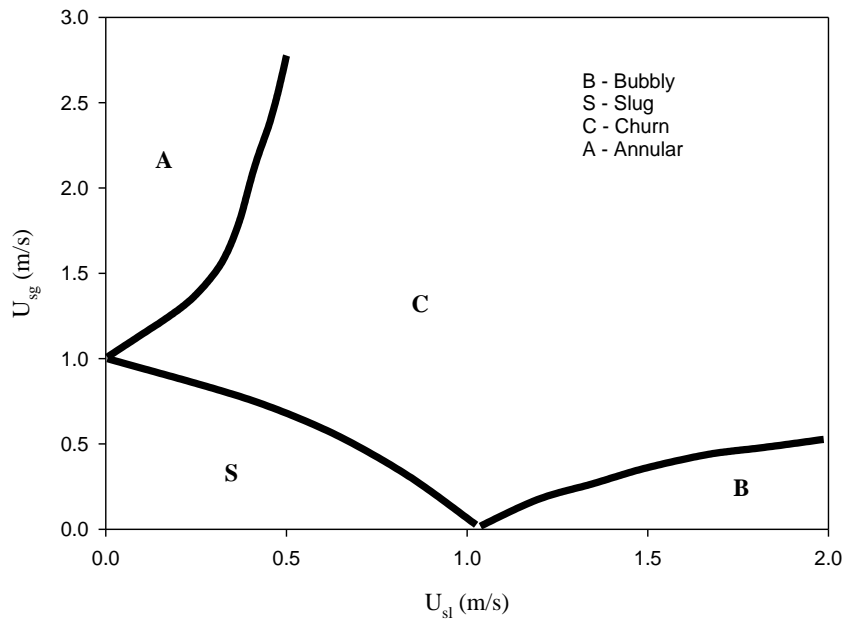


Figure 2.4 Flow pattern map of Paras (1982)

Yijun and Rezkallah (1993) presented a flow pattern map as depicted in Figure 2.5. This map was represented in terms of liquid and gas superficial velocities as the ordinate and abscissa, respectively. The comparison of this flow pattern map with the map of Troniewski and Spisak (1987) shows that, yet for similar coordinates, the two flow pattern maps differ in terms of the transition boundaries, location of the flow patterns on flow map and their corresponding values of liquid and gas superficial velocities, respectively. This confirms that the flow pattern map is highly dependent on the experimental parameters i.e. pipe diameters and the fluid combination. Conclusively this study concentrates more on the flow patterns and the void fraction.

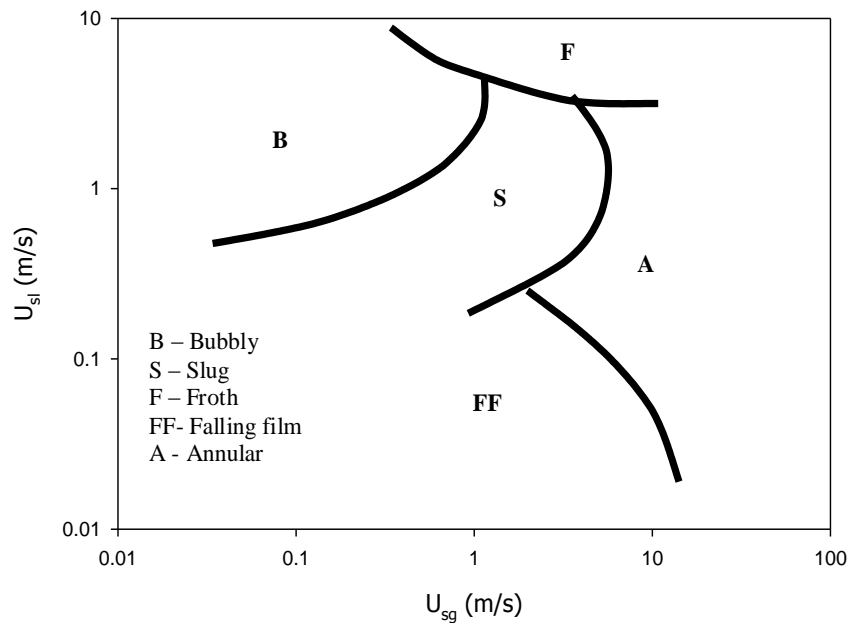


Figure 2.5 Flow pattern map of Yijun and Rezkallah (1993)

The flow pattern map obtained in the present study is compared with the map of Oshinowo (1971) and is presented in the Chapter IV of results and discussion. The next section and rest of the chapter deals with the literature review of the void fraction correlations.

2.3 Void Fraction

As discussed earlier the present work is divided into two parts, study of flow patterns and void fraction. In contrast to exhaustive literature and void fraction correlations available for horizontal and vertical upward flow, little research has been done so far for downward two phase flow. The void fraction correlations available in literature can be classified in terms of the method and physics involved in deriving these correlations. Further they can be subcategorized as flow dependent, flow independent and correlations not developed for but applicable to downward two phase flow. The literature search in the present work showed that most of the correlations available for downward two phase flow are flow pattern dependent designed typically for the bubbly and the slug flow regime and based on the concept of drift flux model. This section of literature review highlights correlations available to predict the void fraction in downward two phase flow and some of the correlations which are not designed for but applicable to downward flow owing to their flexibility as a drift flux model.

2.3.1 Concept of Void Fraction

Before the discussion on available literature of void fraction correlations, it is necessary to understand the concept of void fraction and differentiate it from the quality and gas volumetric flow fraction. A brief discussion on general concept and basic definition of void fraction is presented below.

The void fraction is one of the most important parameters used to characterize the two phase flow. There are different definitions associated with void fraction for example local void fraction, cross sectional void fraction and volumetric void fraction. These

definitions are based on the technique used to measure void fraction. As the name suggests the local and cross sectional void fraction represents the void fraction at any given point in the flow channel (pipe) and its distribution across the pipe cross section. These definitions also reflect the method of measurement i.e void fraction is measured using miniature probe and optical or electromechanical means. The cross sectional void fraction is defined as, $\alpha = A_g/(A_g + A_l)$ where A_g and A_l are the pipe (channel) cross sectional area occupied by the gas and liquid phases, respectively. In most of the experimental studies of two phase flow including the present study, the void fraction is measured using the quick closing valves method and hence the volumetric void fraction is defined in terms of volumes of gas and liquid phases trapped in a section of a pipe. It is defined as, $\alpha = V_g/(V_g + V_l)$ where V_g and V_l are the volume of channel occupied by gas and liquid phases, respectively. More discussion on this measurement technique is presented in chapter III.

Quality of the two phase flow defined as the ratio of mass flow rate of the gas phase over the mass flow rate of mixture is sometimes confused with the void fraction definition. It should be noted that though the definition of void fraction and quality is analogous, conceptually these two terms are altogether different. The quality is expressed in terms of mass and is a function of the phase density and void fraction. The concept of void fraction and its difference with respect to quality is very well illustrated in Wolverine Engineering Data Book III.

Another important definition in two phase flow is the gas volumetric flow fraction denoted as β in the present study. It indicates the ratio of the gas volumetric flow rate over the mixture volumetric flow rate written as, $\beta = Q_g/(Q_g + Q_l)$ where Q_g and Q_l

are the volumetric flow rates of gas and liquid phases, respectively. The major difference between void fraction (α) and gas volumetric flow fraction (β) being that the former considers slip between the two phases, an important feature of two phase flow due to the density difference of respective phases; while the later assumes that both phases move with same velocity and hence referred to as void fraction in the homogeneous flow.

2.3.2 Void Fraction Correlations

As mentioned earlier the void fraction correlations can be classified as empirical or semi empirical. This section presents void fraction correlations based on the experimental data and hence categorized as empirical correlations.

Sokolov et al. (1969) proposed a correlation which relates the downward void fraction to the upward void fraction. The correlation has a simple form shown below,

$$\alpha_{dn} = 2\beta - \alpha_{up}$$

Yijun and Rezkallah (1993) compared this correlation against their own data and found a general agreement except at very low values of void fraction of $\alpha < 0.2$. The graphical representation of this comparison is reported in Yijun and Rezkallah (1993). They found that in this region of void fraction Sokolov et al. (1969) correlation can be replaced by Armand (1946) correlation written as,

$$\alpha_{dn} = \frac{2\alpha_{up}}{C_A} - \alpha_{up} = 1.4\alpha_{up}$$

Where C_A is the Armand coefficient with a value of 0.83 in this region of low void fraction.

Yijun and Rezkallah (1993) conducted an experimental investigation of two phase flow in a 0.095 m diameter pipe and air-water fluid combination. They concluded that the void fraction should be a function of fluid physical properties, the pipe diameter and phase velocities. It was proposed that the void fraction correlation for a downward flow could be represented in terms of the void fraction in a upward flow. The correlation is represented as follows,

$$\alpha_{dn} = 0.076 + 0.074Re_l^{0.05}\alpha_{up} \text{ for } Re_l < 17400$$

$$\alpha_{dn} = 0.025 + 0.058Re_l^{0.05}\alpha_{up} \text{ for } Re_l > 17400$$

The Re_l and Re_g are the liquid and gas superficial Reynolds number denoted as,

$$Re_l = \frac{\rho_l U_{sl} D}{\mu_l} \text{ and } Re_g = \frac{\rho_l U_{sg} D}{\mu_g}$$

The upward flow void fraction reported by Yijun and Rezkallah (1993) is written as,

$$\frac{\alpha_{up}}{1 - \alpha_{up}} = \frac{x}{1 - zx}$$

And $z = Re_l^n [Re_g Fr_g^2]^{-m}$ is a weighting parameter which is a function of the flow patterns and indicates the increase in the void fraction with increase in the gas flow rate. The values of the powers obtained were 0.95 and 0.332 for n and m , respectively. Yijun and Rezkallah (1993) verified the upward void fraction correlation against the data of other investigators but the downward void fraction correlation was compared only with the correlation of Sokolov et al. (1969) and for their own data. The percentage error between the measured and predicted values of void fraction was found to be within $\pm 25\%$.

The void fraction correlations of Armand (1946), Sokolov et al. (1969) and Yijun and Rezkallah (1993) were not used in the present study since they require the measured void fraction for vertical upward flow to predict the void fraction in downward two phase flow at the same input mass flow rates.

Beggs (1972) studied behavior of air water two phase flow in a 0.025 and 0.038 m ID pipe at various inclinations from 0 to ± 90 degrees and suggested a flow pattern dependent correlation to predict liquid holdup or alternatively void fraction at all pipe inclinations. The correlation takes the following form,

$$(\alpha_\theta) = (\alpha_0) \left[1 + C(\sin(1.8\theta) - \frac{1}{3}\sin^3(1.8\theta)) \right]$$

Where the term α_0 for different flow patterns can be given as follows,

$$(\alpha_0) = \frac{0.98\lambda^{0.4846}}{Fr^{0.868}} \quad \text{for segregated flow pattern}$$

$$(\alpha_0) = \frac{0.845\lambda^{0.5351}}{Fr^{0.0173}} \quad \text{for Intermittent flow pattern}$$

$$(\alpha_0) = \frac{1.065\lambda^{0.5821}}{Fr^{0.609}} \quad \text{for distributed flow pattern}$$

$$C = (1 - \lambda) \ln \left[\frac{4.7N_{lv}^{0.1244}}{\lambda^{0.3692}Fr^{0.5056}} \right]$$

This correlation is based on the flow patterns in horizontal flow which can be determined based on the criteria reported by Beggs (1972).

If $Fr < L_1$, flow pattern is segregated

If $Fr > L_1$ and $> L_2$, the flow pattern is distributed

If $L_1 < Fr < L_2$, the flow pattern is intermittent.

The L_1 and L_2 are found out using,

$$L_1 = \exp(-4.62 - 3.757X - 0.481X^2 - 0.207X^3)$$

$$L_2 = \exp(1.061 - 4.602X - 1.609X^2 - 0.179X^3 + 0.000635X^5)$$

And $X = \ln(\lambda)$

Where α_0 , Fr , N_{lu} and λ are the void fraction in horizontal flow, Froude number, liquid velocity number and input liquid content, respectively. The validity of this correlation is not known since, Beggs (1972) did not compare his correlation with other experimental data or other existing correlations.

Mukherjee (1979) analyzed the two phase flow phenomenon for air-kerosene and air-oil two phase flow in a 0.038 m diameter pipe at all inclinations and proposed a flow pattern dependent empirical correlation for downhill flow. This correlation was derived with different regression coefficients to predict the void fraction in the downhill stratified and other flow patterns respectively. The correlation takes the following form,

$$1 - \alpha = \exp(C_1 + C_2 \sin\theta + C_3 \sin^2\theta + C_4 N_l) \frac{N_{gu}^{C_5}}{N_{lu}^{C_6}}$$

In the above equation N_l , N_{lu} , N_{gu} represents the liquid viscosity number, liquid velocity number and the gas velocity number, respectively. The equations of these non dimensional numbers are reported in Mukherjee (1979).

The correlation was developed using the non-linear BIOMED regression programs and compared against their own data. The void fraction prediction was found to be within $\pm 30\%$ of their measured values. The regression coefficients appearing in Mukherjee (1979) correlation are shown in Table 1.

Table 2.1 Regression coefficients used in Mukherjee (1979) void fraction correlation

Flow Patterns	Values of regression coefficient					
	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆
Stratified	-1.330282	4.808139	4.171584	56.262268	0.079551	0.504887
Others	-0.516644	0.789805	0.551627	15.519214	0.371771	0.393952

Mukherjee (1979) did not include the data points with large errors in deriving this expression using regression program. The validity of this correlation is not known since he did not compare his correlation against some other existing correlations or the other experimental data.

Chisholm (1973) proposed a correlation to predict void fraction. This expression was based on α - β relationship and applicable to a range of $\beta = 0.4$ to 0.9 . The correlation takes a complicated form in terms of density ratio and quality. A simplified version of this correlation is indicated in the following equation.

$$\alpha = \frac{\beta}{\beta + (1 - \beta)^{0.5}}$$

Chisholm (1973) devised this equation for vertical upward flow, but claimed that it can be successfully used to predict the void fraction in downward two phase flow. The performance of this correlation for a range of volumetric gas ratio mentioned above was verified in the present study. It is anticipated that this correlation works well for downward flow because, for higher values of void fraction the difference between the upward and downward void fraction decreases. The variation of void fraction for upward and downward flow with increasing volumetric gas flow rate is discussed in the later chapters.

Yamazaki and Yamaguchi (1979) derived a correlation in terms of the void fraction (α) and the volumetric gas flow concentration (β). The correlation had the following form,

$$\frac{\alpha}{(1 - \alpha)(1 - K\alpha)} = \frac{\beta}{1 - \beta}$$

Where ‘ K ’ is an experimental constant defined as,

$$K = 2.0 - \frac{0.4}{\beta} \text{ for } \beta \leq 0.2 \quad \text{and} \quad K = -0.25 + 1.25\beta \text{ for } \beta \geq 0.2$$

Thus using this correlation the void fraction can be determined based on β values and independent of the flow pattern. Yamazaki and Yamaguchi (1979) analyzed the variation of the void fraction with respect to the volumetric gas flow concentration. It was observed that the relation between α - β changed slope at a value of $\beta = 0.2$ and hence the two different expressions were developed for K values to take into account this deviation. The correlation was verified against 560 data points and the percentage error between measured and predicted values of void fraction was found to be within $\pm 20\%$.

2.3.3 Drift Flux Model

The most popular and versatile model to predict the void fraction in gas liquid two phase flow is the drift flux model. Drift flux model was first proposed by Zuber and Findlay (1964) as a general method for the prediction of void fraction and later developed by Wallis, Ishii and many other investigators. As defined by Wallis (1969) drift flux model essentially considers the relative motion between the two phases rather than the motion of individual phase and is convenient for analyzing the flow patterns in which the

gravity, buoyancy, pressure and interaction between the two phases are influential. Kleinstreuer (2003) mentioned that the drift flux model is used where the motion of two phases are strongly coupled and are subjected to the body or external forces typically as in case of gas-liquid flow. The drift flux model differs from the concept of homogeneous flow model in a sense that it accounts for the slip between the two phases in contrast to the assumption of the later that both phases flow at the same velocity. The drift flux model is represented in the following form,

$$\alpha = \frac{U_{sg}}{CoU_M \pm U_{GM}}$$

Where U_{sg} and U_M are the average superficial gas velocity and mixture velocity, respectively defined in terms of weighted average as, $\langle U_{sg} \rangle = Q_g/A$ and $\langle U_M \rangle = (Q_g + Q_l)/A$. The important ingredients of drift flux model are the distribution parameter Co and the drift velocity U_{GM} . The distribution parameter indicates the distribution of discrete phase usually the gas phase with respect to the mixture in pipe cross section. The drift velocity is a measure of the relative velocity of gas phase with respect to the mixture velocity. The positive and a negative sign on drift velocity term indicate that the gas phase may travel in or opposite to the direction of the mean flow. The switch in sign of the drift velocity term and its significance to predict void fraction using drift flux model is explained in the later chapters. The structure of drift flux model is similar to that of the equation of a straight line, $y = mx + c$ where m is the slope and c is the intercept made on y axis. The drift flux model can be rearranged as,

$$\frac{U_{sg}}{\alpha} = U_G = CoU_M \pm U_{GM}$$

The graphical representation of U_{sg}/α as y axis and U_M as x axis is shown in Figure 2.6. Thus comparing this equation with the equation of straight line shows that the distribution parameter is the slope and drift velocity is the y intercept.

The drift flux model was analyzed by many researchers to determine the distribution parameter and the drift velocity. Haramathy (1960) showed that the drift velocity for upward bubbly flow is given as,

$$U_{GM} = 1.53 \left(\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2} \right)^{0.25}$$

This equation when used for air water fluid combination yields drift velocity as $U_{GM} = 0.23$ m/s. This value of drift velocity was verified by many investigators simply by finding the y intercept on a plot similar to that shown in Figure 2.6. Hence forth the remaining chapter deals with the literature review of the void fraction correlations based on the drift flux model. It was observed in the present study that the void fraction correlations for upward two phase flow, developed on the basis of drift flux model can be applied to downward two phase flow by changing the sign of drift velocity from positive to negative. The physical reasoning and impact of this change of sign on the void fraction values is discussed in the later chapters. The sign of the drift velocity in the correlations developed for upward flow is indicated as it is as reported by the researchers.

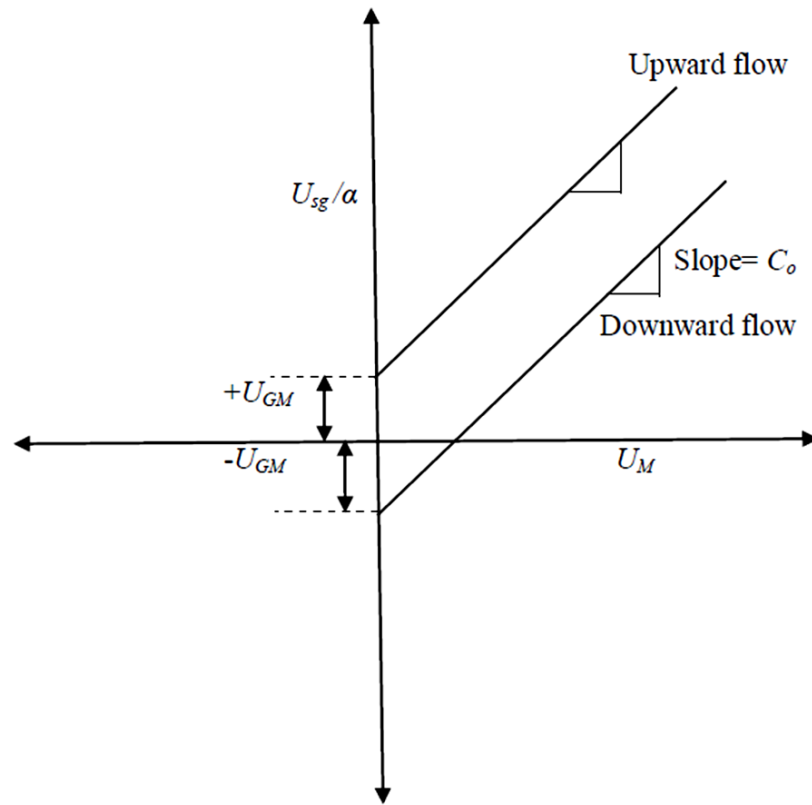


Figure 2.6 Graphical representation of drift flux model

2.3.4 Void fraction correlations for downward two phase flow based on drift flux model

The void fraction correlation based on the drift flux model are presented below and classified in terms of their origin if they are derived exclusively for the downward two phase flow or not derived for but applicable to the downward two phase flow. This section first reports all the drift flux models available in the literature developed for downward flow and the later.

Kawanishi et al. (1990) did experimental study on drift flux parameters in vertical round tubes of 0.019 m and 0.103 m and using a steam-water fluid combination. They proposed that the drift velocity can be determined by correlation proposed by Ishii (1977) given as,

$$U_{GM} = \sqrt{2} \left\{ \frac{\sigma g (\rho_l - \rho_g)}{\rho_l^2} \right\}^{1/4}$$

The distribution parameter can be selected based on the mixture velocity. The different equations for distribution parameter are,

$$Co = 0.9 + 0.1 \left\{ \frac{\rho_g}{\rho_l} \right\}^{0.5} \text{ for } 0 > U_M > -2.5 \text{ m/s}$$

$$Co = 1.2 - 0.2 \left\{ \frac{\rho_g}{\rho_l} \right\}^{0.5} \text{ for } U_M < -3.5 \text{ m/s}$$

$$Co = 0.8 + 0.1 \left\{ \frac{\rho_g}{\rho_l} \right\}^{0.5} - 0.3 \left(1 - \left\{ \frac{\rho_g}{\rho_l} \right\}^{0.5} \right) (2.5 + U_M) \\ \text{for } -3.5 \text{ m/s} < U_M < -2.5 \text{ m/s}$$

Kawanishi et al. (1990) compared his proposed correlation for downward flow against his own data and Petric (1962) data. The correlation was found to work satisfactorily with RMS error of 0.168 and average error of -0.005. This correlation is compared for the void fraction data set used in the present study and discussed in later chapter.

Goda et al. (2003) proposed a drift flux model for downward two phase flow. They derived a relationship between the distribution parameter and non dimensional drift velocity. The idea behind development of this equation was that the value of distribution parameter Co increases up to a certain value and then again

decreases and eventually approaches unity as the mixture velocity increases. The distribution parameter was represented as shown in the following equation,

$$Co = (-0.0214 < U_M^* > + 0.772) + (0.0214 < U_M^* > + 0.228) \sqrt{\frac{\rho_g}{\rho_l}}$$

$$for -20 \leq < U_M^* > < 0$$

$$Co = (0.2e^{0.00848(< U_M^* > + 20)} + 1.0) - 0.2e^{0.00848(< U_M^* > + 20)} \sqrt{\frac{\rho_g}{\rho_l}}$$

$$for < U_M^* > < -20$$

The non-dimensional mixture velocity is given as $< U_M^* > = U_M / U_{GM}$ and the drift velocity is represented by equation proposed by Hirao et al. (1986)

$$U_{GM} = \sqrt{2} \left(\frac{g \sigma \Delta \rho}{\rho_l^2} \right)^{0.25}$$

This correlation was compared with experimental data set of 462 data points by Usui and Sato (1989), Clark and Flemmer (1985), Hirao et al. (1986). and data by Kashinsky and Randin (1999), for pipe diameters in a range of 0.016 -0.1023 m and maximum system pressure of 1.5 MPa. The range of mixture velocity used was -0.45 to -24.6 m/s. The negative sign of the velocities were used to indicate the downward direction of flow. This correlation was reported to predict the data with an average relative deviation of $\pm 15.4\%$. The void fraction correlation of Goda et al. (2003) was verified for the data set used in the present study and was found to be satisfactory only for the system pressure and range of volumetric fluxes it was designed from.

Usui and Sato (1989) did experimentation with two phase flow air-water system in a 0.016 m diameter pipe and proposed flow pattern specific correlations to predict the void

fraction. The proposed correlations for bubbly and slug flow were based on drift flux model. They investigated the relationship between surface tension force, buoyancy force and the distribution parameter and proposed an equation for distribution parameter for bubbly flow in terms of Eotvos number. It was observed that Co may approach 1.2 with decreasing Eotvos number.

$$Co = 1.2 - \frac{1}{(2.95 + 350 Eo^{-1.8})}$$

And the drift velocity could be represented by Haramathy (1960) equation.

Usui and Sato (1989) proposed that the void fraction in slug flow can also be predicted using the drift flux model. The distribution parameter was found using the above equation and the drift velocity was calculated by using a relation of $U_{GM} = B \sqrt{gD \frac{(\rho_l - \rho_g)}{\rho_l}}$

This expression is similar to that obtained by Nicklin et al. (1962) for drift velocity, but the coefficient B is expressed in terms of Eotvos number.

$$B = 0.345 \left[1 - \exp \left\{ \frac{3.37 - Eo}{10} \right\} \right]$$

Usui and Sato (1989) observed that in the falling film region void fraction is independent of the gas flow rate while the void fraction in annular region gradually increased with increase in the gas flow rate. Based on this observation they derived two different expressions to correlate the void fraction with liquid flow rate. It was assumed that the turbulent profile of liquid flow in annular region can be approximated with 1/7 power law and that both the interfacial and wall shear stress are significant, the correlation for the void fraction prediction in the annular region was devised accounting for interfacial and wall friction factors. The definition of these friction factors can be found in Usui and Sato (1989). The correlation is shown in the following equation,

$$(1 - \alpha)^{23/7} - 2f_w Fr_l^2 \left[1 \pm \frac{f_i}{f_w} \frac{(1 - \alpha)^{16/7}}{\alpha^{6/2}} \frac{\rho_g}{\rho_l} \left(\frac{U_{sg}}{U_{sl}} \right)^2 \right] = 0$$

Assuming the interfacial shear stress to be negligible for the falling film flow they reported that the simplified form of above equation can be used to predict the void fraction in falling film region.

The equation for falling film flow as reported by Usui and Sato (1989) is $\alpha = 1 - (2f_w Fr_l^2)^{7/23}$. They compared all these flow pattern dependent void fraction correlations with their own experimental data and found a good agreement. The performance and accuracy of these void fraction correlations as reported by Usui and Sato (1989) is presented graphically in their paper.

Hasan (1995) studied drift flux model to predict void fraction in the downward two phase flow. He found that the distribution parameter $Co = 1.2$ and Haramathy (1960) equation for drift velocity with negative sign satisfies the prediction of void fraction in the downward bubbly flow. To predict the void fraction in slug regime at various inclinations he modified the Nicklin et al. (1962) equation for the Taylor bubble rise velocity. The value of distribution parameter was found to be 1.12 to give the best fit. The modified drift velocity in slug regime reported is,

$$U_{GM,\theta} = U_{GM} \sqrt{\sin\theta} (1 + \cos\theta)^{1.2}$$

Where U_{GM} is the Taylor bubble rise velocity given by Nicklin et al. (1962). The experimental data of Beggs (1972), Mukherjee (1979) and Kokal and Stainslav (1989) was used to verify the proposed drift flux model to account for inclination effects.

Cai et al. (1997) analyzed the downward two phase flow in a 0.044 m ID pipe using air-oil fluid combination. They presented a model based on drift flux approach for

estimating void fraction in the bubbly and the slug flow regimes. The model is similar to that proposed by Zuber and Findlay (1964), except the bubble rise velocity assumes a negative sign since it is in direction opposite to the flow direction. Cai et al. (1997) used their own experimental data in addition to that of Clark and Flemmer (1985) to find the value of the distribution parameter. They found that the distribution parameter C_o is different than in upward flow and the best fit line yielded $C_o = 1.185$ for vertical downward two phase flow. The bubble rise velocity was estimated using Haramathy (1960) equation. The standard error observed was 0.078 for pressure less than 0.3 MPa and 0.052 for higher system pressures. Similarly for the slug flow Cai et al. (1997) proposed that the distribution parameter should carry a value of 1.15 and the Taylor bubble rise velocity can be determined using equation proposed by Hasan (1995).

Clark and Flemmer (1985) analyzed the Zuber and Findlay (1964) drift flux model for both the up and downflow. They performed experiments for the air-water fluid combination in a 0.1 m ID pipe and performed a regression on results using equation proposed by Wallis (1969) and found that the bubble rise velocity is approximately equal to 0.25 m/s and was in good agreement to that proposed by Haramathy (1960) equation. The distribution parameter $C_o = 1.165$ gave the best fit for all data in a bubbly flow for downflow and 1.07 for upflow. This result is in contrast to the results obtained by Zuber and Findlay (1964) where they proposed that the distribution parameter would remain same for both up and downflow. For slug flow Clark and Flemmer (1985) suggested the drift velocity to be given similar to that of the Nicklin et al. (1962) equation. They observed a certain relationship between the distribution parameter and gas void fraction for the slug flow. The expression for distribution parameter C_o in terms of void fraction

is given as, $Co = 1.521(1 - 3.67\alpha)$. However, they claimed that this linear relation between Co and gas void fraction may or may not be valid for other pipe geometries since dependence of Co on void fraction may vary for varying pipe diameters. The reliability of this expression is open to question since the correlation was not compared with another data and the percentage accuracy of the void fraction correlation is not mentioned.

Arosio and Stogia (1976) investigated two phase flow phenomenon in large diameter pipes with air-water fluid combination. They used their own experimental data for 0.044 m and 0.09 m ID pipes along with the data reported by De Rauz (1976). Using the drift flux model they concluded that the distribution parameter value Co should assume a value as low as 1.03 and the drift value should be equal to 0.24 m/s. These values were obtained using curve fitting techniques as illustrated in Figure 1.

2.3.5 Drift flux models not derived for but applicable to downward two phase flow

The drift flux model, based on the physical mechanism of the motion of two phases, is recognized as the versatile model that can account for the pipe inclination effects on the void fraction. It is shown in the present study that the void fraction correlations which are not derived for the vertical downward orientation can also be successfully used to predict the void fraction in this orientation. This is in fact due to the flexibility of the drift flux model by the virtue of varying drift velocity term at different pipe inclinations. This section presents a brief review of the void fraction correlation derived for upward or inclined flows but applicable to the vertical downward orientation. Since these correlations were not developed for downflow there are no reports available about their performance and accuracy to predict void fraction in vertical downward flow.

The present study analyzed the performance of these correlations with the modification in the drift velocity explained earlier. The results are presented in chapter IV.

Bonnecaze et al. (1971) studied two phase slug flow for an inclination of ± 10 degrees from horizontal and proposed a correlation based on the drift flux concept to predict the void fraction in a gas- oil two phase inclined flow. They analyzed the effect of the inclination on the drift velocity and concluded that the drift velocity magnitude first increases with decrease in inclination from vertical orientation and then decreases.

They proposed a correlation of the form given in the equation given below,

$$\alpha = 1 - \frac{(1 - \beta)}{1.2 + 0.35(1 - \rho_g/\rho_l)/\delta\sqrt{Fr}} \text{ where } \delta = -1 \text{ for downhill flow}$$

This equation reduces to Nicklin et al. (1962) correlation when simplified. The Bonnecaze et al. (1971) void fraction correlation was compared against 154 data points from their own experimental investigation with a maximum standard deviation of $\pm 20\%$. Though this correlation was developed for slightly inclined slug flow from horizontal orientation, it was found to predict void fraction successfully for the data used in the present study.

Gomez et al. (2000) modified the drift velocity expression proposed by Hasan and Kabir (1988) to take into account the void fraction in two phase bubbly flow at various inclinations from 0 to +90 degrees. The correlation is of the form,

$$\frac{U_{SG}}{\alpha} = (CoU_M + U_{GM}\sin\theta(1 - \alpha)^{0.5})$$

Where U_{GM} is the drift velocity given by Haramathy (1960) equation and value of Co was found to be 1.15. Since this correlation was developed for upward inclined flow it was not compared against any data of downward two phase flow. The Gomez et al.

(2000) void fraction correlation was verified against vertical downward flow data used in the present study. The results of void fraction prediction are presented in chapter IV.

Kokal and Stainslav (1989) investigated the void fraction and the pressure drop in two phase flow at slightly inclined and declined angles. Based on their experimental data the drift flux model was used to predict void fraction in slightly inclined and declined pipes typically ± 9 degrees from horizontal. The value of distribution parameter was fixed as 1.2 and the reported expression for drift velocity can be expressed as,

$$U_{GM} = 0.345 \left(gD \frac{(\rho_l - \rho_g)}{\rho_l} \right)^{1/2}$$

Unlike other investigators Kokal and Stainslav (1989) did not change the sign of drift velocity term and used the above expression as a drift velocity in the drift flux model. They reported that for the range of pipe inclinations considered in their study any inclination effect on the drift velocity was not observed and the expression given in equation was used without any modification. However, it should be noted that for vertical upward and downward flow the sign of drift velocity significantly contributes in the lower range of void fraction in the prediction of the void fraction.

Rouhani and Axelsson (1970) reported a void fraction correlation for upward two phase flow based on the drift flux approach. The expression was developed for the experimental data of steam water two phase flow. The distribution parameter in this correlation is expressed as,

$$Co = 1 + 0.2(1 - x) \text{ for } \alpha < 0.25$$

$$Co = 1 + 0.2(1 - x) \left(\frac{gD\rho_l^2}{G^2} \right)^{0.25} \text{ for } \alpha > 0.25$$

The drift velocity is expressed in terms of the phase densities, quality and surface tension at liquid interface as shown in the following equation,

$$U_{GM} = 1.18 \left(g \sigma \frac{\rho_l - \rho_g}{\rho_l^2} \right)^{0.25}$$

Nicklin et al. (1962) proposed an expression to predict the void fraction for bubble velocity in a slug flow for air-water fluid combination in a 0.025 m ID pipe. The expression can be written in the following form,

$$\alpha = \frac{U_{sg}}{Co U_M + U_{GM}}$$

Where $Co = 1.2$ and $U_{GM} = 0.35\sqrt{gD}$

As reported by Godbole (2009), Sun et al. (1981) proposed a void fraction model based on drift flux concept. This correlation was developed for vertical upward flow and the pressure dependency was introduced in the distribution parameter. It was represented as,

$$Co = (0.82 + 0.18(P/P_{cr}))^{-1}$$

And the drift velocity was expressed as shown below,

$$U_{GM} = 1.41 \left(\frac{g \sigma (\rho_l - \rho_g)}{\rho_l^2} \right)^{0.25}$$

Dix (1971) presented a void fraction correlation based on drift flux concept derived for the analysis of boiled water reactor. The drift velocity was taken from that of Zuber and Findlay (1964) with a different multiplying factor. The dependency of distribution parameter on the phase superficial velocities was introduced. The distribution parameter and the drift velocity were represented in the following form,

$$Co = \frac{U_{sg}}{U_{sg} + U_{sl}} \left[1 + \left(\frac{U_{sg}}{U_{sl}} \right)^{(\rho_g/\rho_l)^{0.1}} \right]$$

$$U_{GM} = 2.9 \left(g \sigma \frac{\rho_l - \rho_g}{\rho_l^2} \right)^{0.25}$$

Woldesemayat and Ghajar (2007) analyzed extensive void fraction data for different pipe inclinations from 0 to +90 degrees. They modified the Dix (1971) correlation to account for various pipe inclinations and fluid properties. The void fraction correlation is based on drift flux model and the distribution parameter is same as that of the equation given by Dix (1971) and the drift velocity is given as,

$$U_{GM} = 2.9(1.22 + 1.22\sin\theta)^{p_{atm}/p} \left[\frac{gD\sigma(1 + \cos\theta)(\rho_l - \rho_g)}{\rho_l^2} \right]^{0.25}$$

The leading coefficient 2.9, in the drift velocity term carries the unit of $m^{-0.25}$ thus making the unit of the drift velocity as m/s. This correlation performed well for a comprehensive data set of void fraction at various inclinations ranging from horizontal to vertical upward. Woldesemayat and Ghajar (2007) predicted the void fraction within $\pm 15\%$ error indices for the inclination of 0 to +90 degrees. All these correlation mentioned above in this section are verified for their performance and accuracy in chapter IV.

The synopsis of the literature review on void fraction correlations for the downward two phase is that, very few correlations are available exclusively for the downward two phase flow and most of the void fraction correlations available are designed for the vertical upward or inclined flow conditions. Majority of the void fraction correlations are based on drift flux model and are flow pattern dependent. The literature review revealed that the performance of the developed void fraction correlations was not

compared against other existing correlations or other experimental data. The performance and accuracy of a correlation based on only one experimental data cannot be gauged since it can fail for varying operating conditions. To overcome this deficiency in the literature of two phase flow a systematic analysis of the performance of void fraction correlations is done in the present study.

CHAPTER III

EXPERIMENTAL SETUP

From the previous discussion about flow patterns and flow maps, it is now clear, that there is no consensus about the description and appearance of flow patterns and the flow patterns are a function of experimental setup. Hence, the discussion about experimental setup used for two phase flow study is necessary. Literature review of the void fraction data for downward flow showed a scarcity of data for slug flow regime typically for $\alpha=0.3$ to 0.65. The accuracy of the entire available void fraction data is not known since some of the investigators did not report the accuracy and uncertainty of the measured data. Most of the data available in literature is for bubbly and annular flow regime; and for diameters 25 mm or higher. The purpose of this experimental work is to study two phase flow patterns for smaller diameter tube, and to produce and verify accurate and detailed data of void fraction. The experimental setup used for the present study is located at the Two Phase Flow lab, Oklahoma State University and was designed and verified by Cook (2008). This setup is capable of doing flow visualization through transparent test section and measurement of void fraction, pressure drop and heat transfer data. The details of experimental setup are briefly explained in this chapter.

3.1 Details of Experimental Setup:

The two phase flow lab at Oklahoma State University is equipped with a versatile experimental setup capable of observing flow patterns and measuring void fraction, pressure drop and convective heat transfer data at all orientations from $+90^\circ$ to -90° inclination.

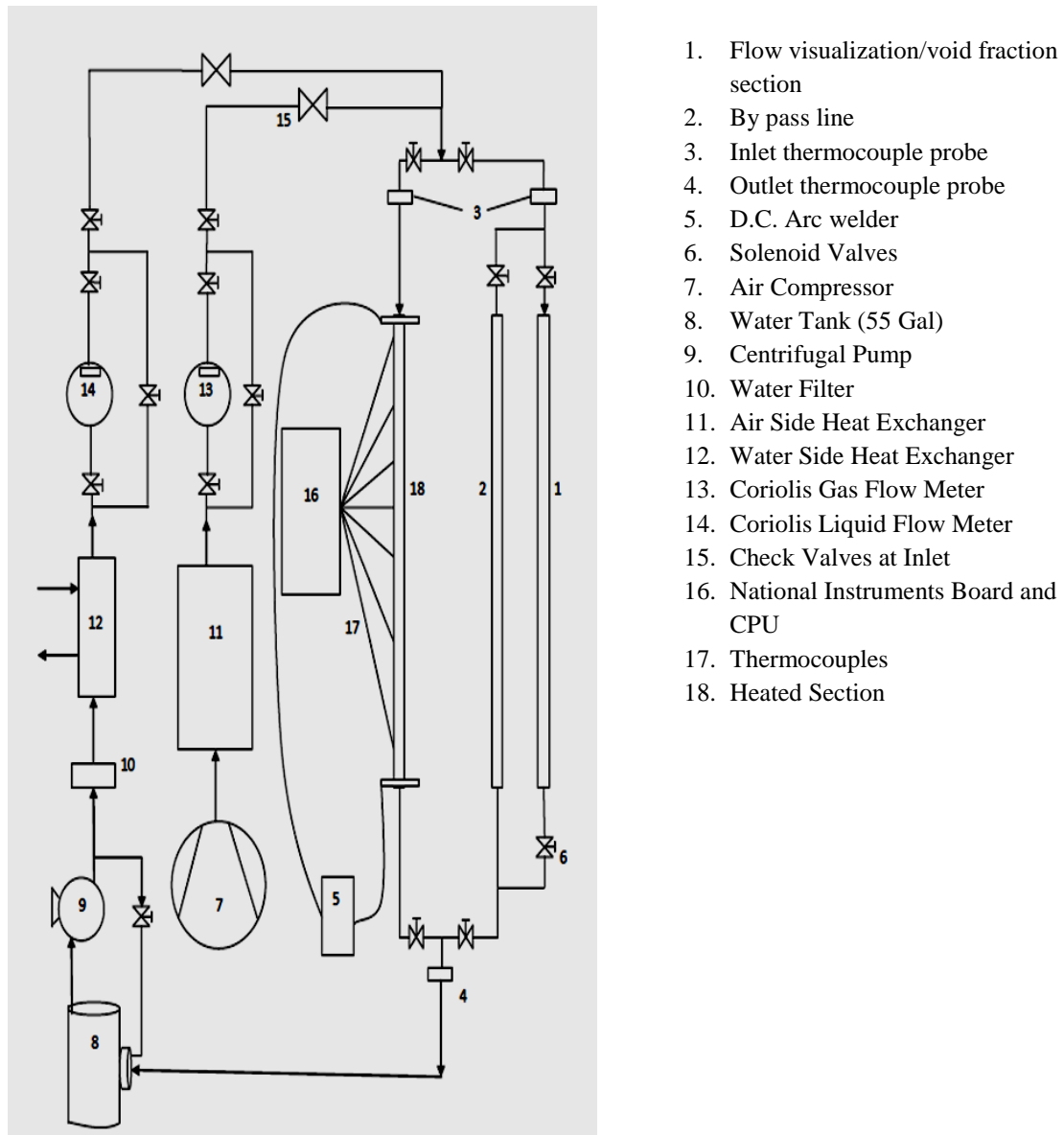


Figure 3.1 Schematics of the experimental setup for present study

The present study is focused on the study of flow patterns and measuring and verifying void fraction data in vertical downward two phase flow. The two phase flow was studied for air-distilled water fluid combination in a vertical downcomer 0.0127 m ID polycarbonate pipe. The schematic diagram for flow circuit and a photograph of the experimental setup is shown in Figures 3.1 and 3.2, respectively.

3.1.1 Details of Test Section

The four important components of test section are inlet and outlet mixers, thermocouple array, flow visualization section and a void fraction measurement system. The functional and working details of each component are given below,

Inlet and Outlet Mixers: In order to ensure good certainty in void fraction and flow pattern observation, it was desirable to mix the two phases thoroughly before they were introduced in the test section. This was achieved by use of a static mixer at the inlet of test section and introduction of another static mixer at the outlet in addition to inlet mixer. The two static mixers used were Koflo model 3-8 40-C-4-3V-2. Experiments in two phase flow done so far reported the use of different mixers for mixing the two phases. One could anticipate the influence of mixer design on appearance of a particular flow pattern. The issue of mixer design and inlet pipe geometry on two phase flow was addressed by Govier and Aziz (1972). They found that design of a mixing section or a mixer affected the flow pattern only up to a certain distance and provided a sufficient calming length after which no special mixing device was required.

Thermocouples: Two thermocouple probes of Omega Model TMQSS-06U-6 were installed at inlet and outlet. They served to measure two phase mixture temperatures at inlet and outlet.



Figure 3.2 Experimental Setup for present study

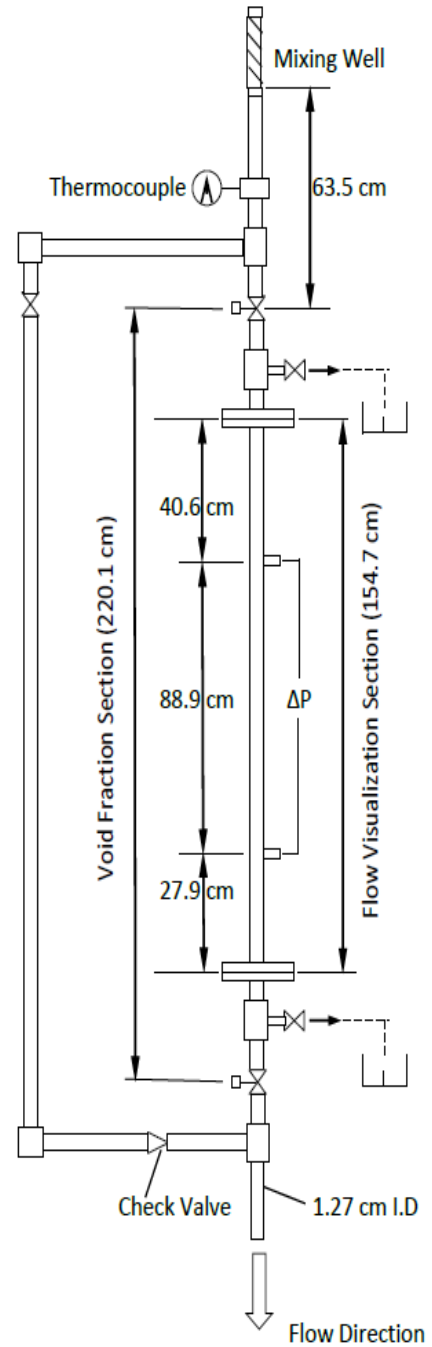


Figure 3.3 Schematics of flow visualization and void fraction section

Flow Visualization and Calming Length Section: A 154.7 mm long central pipe portion of void fraction section was used to observe flow patterns. The dimensional details of the flow visualization and void fraction section are given in Figure 3.3 shown below. The flow patterns were determined by visual observations, videos and still photographs.

For a void fraction profile to achieve fully developed condition it was necessary to provide sufficient calming length. A calming length is similar to hydrodynamic entry length for a pipe flow and as reported by Usui and Sato (1989) it is necessary to provide fully developed void fraction profile. It can be concluded that calming length problem should not affect the void fraction value since the present study deals with cross section averaged void fraction values and not the local void fraction across the pipe cross section. Calming length had been an issue of discussion since different investigators used different L/D ratios for experimentation. The values of L/D ratios used in downward two phase flow studies are listed in Table 3.1,

Table 3.1 Calming Length used in investigation of downward two phase flow

Author	Pipe Diameter D(mm)	Calming Length (L)
Present Study	12.67	50D
Crawford and Weinberger (1985)	25	50D
Oshinowo (1971)	25	60D
Golan (1968)	38	40D
Yamazaki and Yamaguchi (1979)	25	50D
Nguyen (1975)	45	44D
Usui and Sato (1989)	16	100D

The comparison of calming length as shown in Table 3.1 indicates that the calming length used in the present study experimental setup is in good agreement with other investigations. Moreover, the flow patterns observed in the present study were in concurrence with those of Oshinowo (1971), Golan (1968), Yamazaki and Yamaguchi (1979) and Usui and Sato (1989). This proved the ability of our experimental setup to identify different flow regimes.

Void Fraction Section: Void fraction measurement was one of the major objectives of the present study. It essentially consisted of three solenoid valves and a collecting tank to trap two phase flow mixture and collect the residual liquid in test section. The two solenoid valves were installed at inlet and outlet of the test section. When solenoid valves were triggered two normally open valves closed and closed valves opened thus trapping a volume of two phase mixture inside the test section. The third solenoid valve served as a bypass valve for two phase mixture during void fraction measurement. The two quick closing solenoid valves used were W.E. Anderson model ABV1DA101 pneumatically operated ball valves. The ball valves for solenoid controllers were manufactured by Dynaquip controls with a designation of 14570.01. An 8 lit tank of high density polyethylene material was used to collect the residual water in the test section. The liquid was evacuated through the test section using clear PVC tubes connected to 3.175 mm diameter ball valves. Compressed air was used to ensure maximum removal of liquid from the test section. Length of void fraction section between two solenoid valves was 220.09 cm which accounts to a volume of 277.5 cc and 276.9 g by weight of water. A check valve was used to prevent back flow of two phase mixture into the exit line.

Water Flow Circuit: The liquid phase used in this study was purified distilled water stored in a 208.2 liter capacity tank. The water was pumped by a centrifugal pump of Bell and Gosset (series 1535, model number 3445 D10) and filtered through an Aqua-Pure AP12-T purifier. It was then passed through a shell and tube heat exchanger (ITT model BCF 4063) to maintain it at room temperature. Before the water was mixed with air in the static mixer, water flow rate was measured by passing it through Emerson (Micro Motion Elite Series model number CMF 100) Coriolis mass flow meter. Water mass flow rate was controlled by a gate valve placed after the flow meter. The Coriolis water mass flow meter is shown in Figure 3.4.

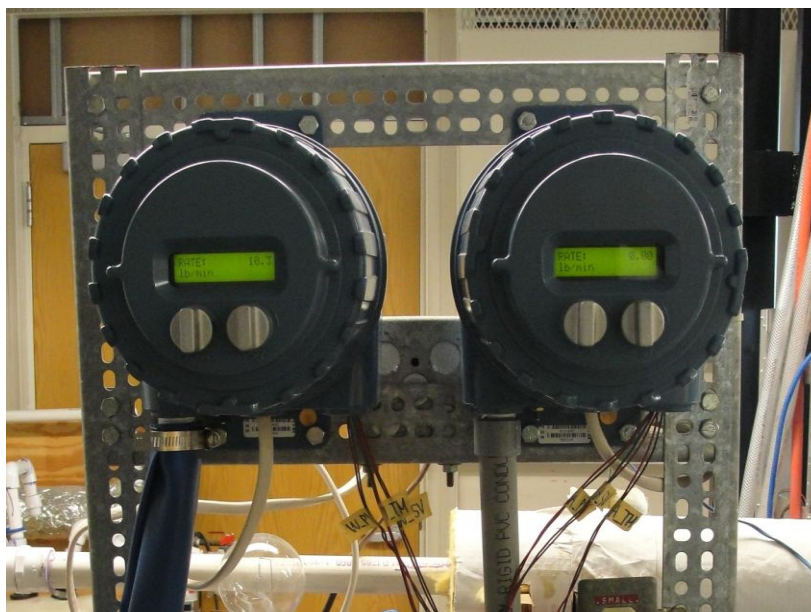


Figure 3.4 Water mass flow meters

Air Flow Circuit: The gas phase used in the present study was the compressed air supplied by Ingersoll-Rand T30 Model 2545 air compressor. It was then fetched through a filter and pressure regulator circuit followed by copper coil submerged heat

exchanger to maintain the supply air at room temperature. After passing through heat exchanger it was again introduced to a filter and dried before it was regulated through a Parker (24NS 82(A)-8LN-SS) needle valve. Emerson flow meters (Micro Motion Elite Series Model number LMF 3M and CMF 025) as shown in Figure 3.5 were used as low and high air mass flow meters. The air was then led to a mixing section where it was mixed thoroughly with distilled water. The range and accuracy of equipments used in water and air flow circuit are tabulated in Table 3.2.

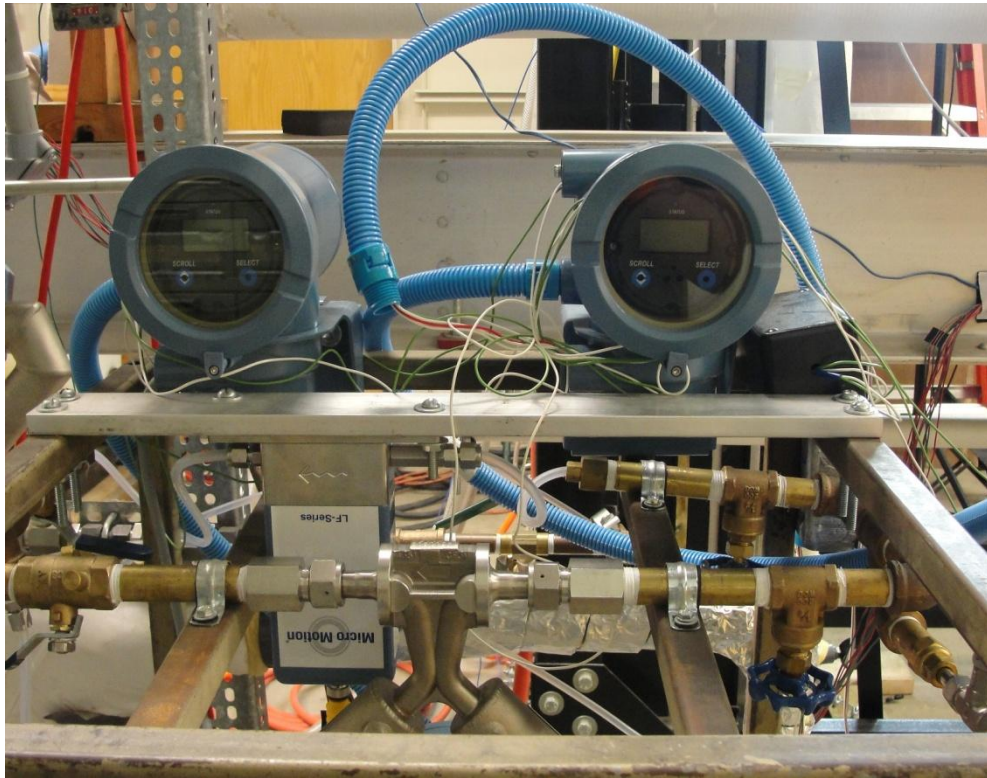


Figure 3.5 Air mass flow meters

Table 3.2 Range and Accuracies of Equipments and Instrumentations

Equipment/Instrument	Range	Accuracy
Bell and Gosset Series 1535 centrifugal pump (model3545D10)	0 - 0.226 kg/s	--
ITT model BCF 4063 shell and tube heat exchanger	0 - 19.7 KW	--
Ingersoll-Rand T30 model 2545 air compressor	0 - 125 psi 0-0.0042 kg/s	--
Micro motion coriolis flow meter for water (model CMF 100)	0-7.5555 kg/s	$\pm 0.05\%$
Micro motion coriolis flow meter for air (model LF)	0.000029- 0.00101 kg/s	$\pm 0.5\%$
Micromotion corilois flow meter for air (model CMF 025)	0 - 0.6055 kg/s	$\pm 0.35\%$
Absolute pressure transducer	0 - 50 psia	0.25% BSFL
Thermocouple Probe (Omega model TMQSS-06U-6)	-250 - 350°C	$\pm 1^\circ\text{C}$

3.2 Data Acquisition System

Data acquisition system by National Instruments played a key role as a graphical interface program in recording data for inlet and outlet mixture temperatures, air and water mass flow rates and superficial Reynolds number for individual phases. The data acquisition system consisted of three major parts: chassis, module and terminal blocks. The functional details of these components are given in Cook (2008). The data acquisition LABVIEW program was originally developed for different setup by Jae-Yong Kim, a former PhD student. Modifications were done to this program to allow data acquisition in present setup by Clement Tang, current PhD candidate and a senior member of two phase flow research team.

3.3 Procedure for Flow Visualization

Flow patterns were defined and distinguished based on the criteria of visual observations, photographic and video evidence. Flow patterns were observed visually for every single input of air and water mass flow rate. These observations were repeated to ensure enough repeatability in the observed flow patterns. The visual observations were supplemented with aid of high resolution 3.8 megapixels SONY DCR-VX2100 digital video camera with a shutter speed of $1/10000^{\text{th}}$ of a second and a frame rate of $1/60^{\text{th}}$ of a second. Still photographs were taken using 6 megapixels Nikon D50 Digital SLR camera with a shutter speed of $1/4000^{\text{th}}$ of a second. Sometimes it was difficult to visually recognize the flow pattern, typically in the froth flow region video camera played a key role in determining flow pattern. Determining and describing a flow pattern on the verge of transition was a challenging task. The flow pattern observations were repeated specially at transition regions. Albeit, there exist a lot of defined flow patterns for downward two phase flow, five major flow patterns were distinguishably identified and their description is in general agreement with those given by other authors. The detail discussion about flow patterns is mentioned in the next chapter.

3.4 Procedure to Measure Void Fraction Data

A systematic procedure was followed to record void fraction data with adequate accuracy. The procedure was a contribution of four major steps; pre-operation checks, system warm-up, followed by data collection and finally safe shutdown of the setup. More details of this procedure can be obtained from Cook (2008).

When the fluid is trapped in a vertical pipe orientation, some of the water may get trapped in the fittings of a solenoid valve and result in inaccurate reading of void fraction data. Hence, the calibration of void fraction setup was necessary to ensure least error in calculating mass of water trapped in the test section. As mentioned earlier the volume of the test section was calculated as 277.5 cc or 276.9 g of water. By measuring the mass of water drained from completely filled test section and comparing it with the mass of water drained from the section ideally, it was possible to predict the mass of water trapped inside the test section fittings. This process was repeated to ensure consistency in measuring mass of trapped fluid. The mass of water trapped inside the section was calculated to be 12.5 g for vertical downward orientation of the test section. This mass was considered as a correction factor and added to the measured mass of water drained from the test section to calculate the void fraction. Thus for a given, air and water mass flow rates the void fraction was calculated using equation, $\alpha = 1 - \frac{m_{liq} + m_c}{m_{tot}}$, where m_{liq} , m_c and m_{tot} are the mass of water drained from the test section, mass of water trapped in fittings and total mass of water ideally drained from the test section. These measurements were repeated until a good consistency among consecutive readings was observed. Following criteria was used to decide upon the final values of void fraction to be considered.

- For lower range of void fraction typically from $\alpha = 0.02$ to 0.3 three or more readings were taken to measure liquid mass trapped in the test section. If the difference between maximum and minimum values were within $\pm 5\%$ these values were averaged to calculate the final void fraction reading. Consistent values of liquid mass within $\pm 3\%$ could be easily obtained for higher void fraction data ($\alpha = 0.7$ to 1.0), however, it should

be noted that this process was repeated several times for slug region ($\alpha = 0.3$ to 0.7) to get percentage difference within $\pm 5\%$ for maximum and minimum readings of liquid mass.. This could be attributed to its intermittent flow characteristics.

- Once the values of void fraction were decided they were cross checked for accuracy against the data set available in the literature. Knowing the trend of void fraction at constant water flow rate with varying air flow rate, the measured void fraction data was plotted against varying air mass flow rate. The graph followed anticipated trend line and is discussed in the next chapter. The verification of measured void fraction data is discussed in the following section.

3.5 Uncertainty Analysis of Void Fraction Data

- The accuracy of the measured void fraction data was of prime importance since it serves as an input data to calculate the two phase flow pressure drop and convective heat transfer coefficient. Hence, a void fraction measurement uncertainty analysis was performed to evaluate the performance of the experimental facility. The uncertainty associated with the void fraction measurement was calculated using Kline and McClintock (1953) method. The void fraction was measured as $\alpha = \frac{m_{liq}}{m_{tot}}$.
- Here, m_{liq} represents the mass of liquid trapped inside the test section and m_{tot} is the total mass of fluid that could be trapped ideally instead in the test section. The value of m_{tot} had an estimated uncertainty of $\pm 2.0\text{g}$. Considering the worst case scenario the uncertainty associated with the m_{liq} was calculated as $\pm 3.0\text{g}$. For more details about the estimation of these uncertainties refer to Cook (2008). The

uncertainty associated with void fraction measurement was calculated using the following relation,

$$w_{\alpha} = \sqrt{\left(\frac{w_{liq}}{m_{tot}}\right)^2 + \left(\frac{m_{liq}}{m_{tot}^2} w_{m_{tot}}\right)^2}$$

- Uncertainty calculated using this formula is dependent on the range of void fraction being measured. This means that the percentage uncertainty increases with decreasing values of void fraction. To take care of this dependency, void fraction measurement uncertainty was calculated at all values of void fraction measured in this experimental work. The maximum uncertainty associated for measured void fraction was 0.0114 or $\pm 5.40\%$ and the minimum was 0.0108 or $\pm 1.18\%$.

3.6 Accuracy of Flow Patterns and Void Fraction Data

- It was discussed earlier in the initial part of this chapter that the flow patterns are a function of experimental setup and fluid combination used. It is thus obvious that the flow pattern descriptions and classification for a given mass flow rate in the present study and that by different investigators need not be in consensus. However, the most commonly observed flow patterns viz. bubbly flow, slug flow, froth flow, falling film flow and annular flow were observed in the present study and were similar to those described by other investigators. The detailed discussion about these flow patterns is presented in the next chapter.
- Cook (2008) did not verify the ability of this setup to measure void fraction in downward flow. In order to confirm the accuracy of void fraction data collected in the present study it was compared against the data from other

researchers for given air and water superficial velocities. Though this comparison was for approximately same superficial phase velocities, it gave a good idea about accuracy of our own setup as compared against other data. The verification of void fraction data in the present study is given in Table 3.3. Due to difficulty in measuring the low values of void fraction the percentage error associated in comparison with other data was little high. As the flow pattern attained annular flow and void fraction approached its higher end the percentage error dropped down. From Figure 3.6 it is observed that the overall measured void fraction data was in good agreement and within $\pm 10\%$ error band.

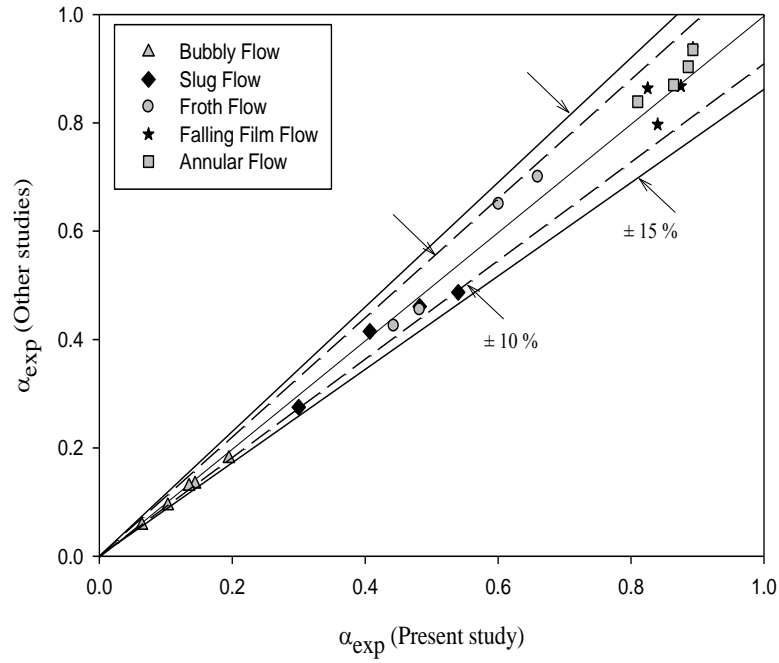


Figure 3.6 Comparison of void fraction data (present study) for different flow patterns against data from other researchers.

Table 3.3 Comparison of void fraction data (present study) for different flow patterns against data from other researchers

	Other Studies			Present Study		
Flow Pattern	Author	U_{sl} / U_{sg}	Void Fraction	U_{sl} / U_{sg}	Void Fraction	% error
Bubbly Flow	*	0.71 / 0.098	0.144	0.74 / 0.1	0.133	8.27
	Oshinowo (1971)*	1.43 / 0.21	0.135	1.49 / 0.22	0.129	4.65
	Paras (1982)*	1.72 / 0.4	0.195	1.74 / 0.38	0.1801	8.27
	Lorenzi and Stogia (1976)*	1.43 / 0.085	0.064	1.49 / 0.083	0.057	12.28
Slug Flow						
	Paras (1982)*	0.689 / 0.47	0.415	0.63 / 0.43	0.407	1.97
	Yijun and Rezkallah (1993)	0.33 / 0.438	0.487	0.37 / 0.45	0.54	-9.81
	Yijun and Rezkallah (1993)	0.99 / 0.82	0.461	0.98 / 0.87	0.482	-4.36
Froth Flow	Paras (1982)*	0.68 / 0.23	0.275	0.64 / 0.25	0.3	-8.33
	Paras (1982)*	1.38 / 1.38	0.425	1.39 / 1.34	0.443	-4.06
	Paras (1982)*	1.38 / 1.76	0.455	1.387 / 1.78	0.482	-5.60
Falling Film Flow	Oshinowo (1971)*	1.19 / 3.42	0.65	1.25 / 3.3	0.601	8.15
	Yijun and Rezkallah (1993)	0.99 / 2.66	0.7	0.943 / 2.73	0.66	6.06
	Yijun and Rezkallah (1993)	0.099 / 4.83	0.797	0.12 / 4.96	0.84	-5.12
Annular Flow	Yijun and Rezkallah (1993)	0.09 / 11	0.868	0.07 / 10.01	0.875	-0.80
	Oshinowo (1971)*	0.051 / 5.36	0.938	0.061 / 5.15	0.893	5.04
	Usui and Sato (1989)*	0.182 / 5.65	0.864	0.19 / 5.69	0.825	4.73
Annular Flow	Yijun and Rezkallah (1993)	0.10 / 11	0.87	0.12 / 11.18	0.864	0.69
	Oshinowo (1971)*	0.31 / 9.72	0.839	0.313 / 9.46	0.81	3.58
	Oshinowo (1971)*	0.13 / 13.3	0.9035	0.12 / 12.76	0.886	1.98
	Nguyen (1975)*	0.10 / 14.13	0.935	0.12 / 14.26	0.893	4.70

* Authors who have not reported the measured void fraction uncertainty.

All of the authors but one did not report the uncertainty of their measured void fraction data. Yijun and Rezkallah (1993) reported the uncertainty of measured void fraction data in a range of 1.8 to 5.0 %. The direct comparison of void fraction measured in present study at same superficial phase velocities, against the data of Yijun and Rezkallah (1993) was important since the pipe diameters, range of void fraction and the uncertainty associated with measured void fraction in both studies were comparable. The fluid combination and the method of void fraction measurement were same in both studies.

This comparison as shown in Figure 3.7 helped to confirm the accuracy of measured data in present study.

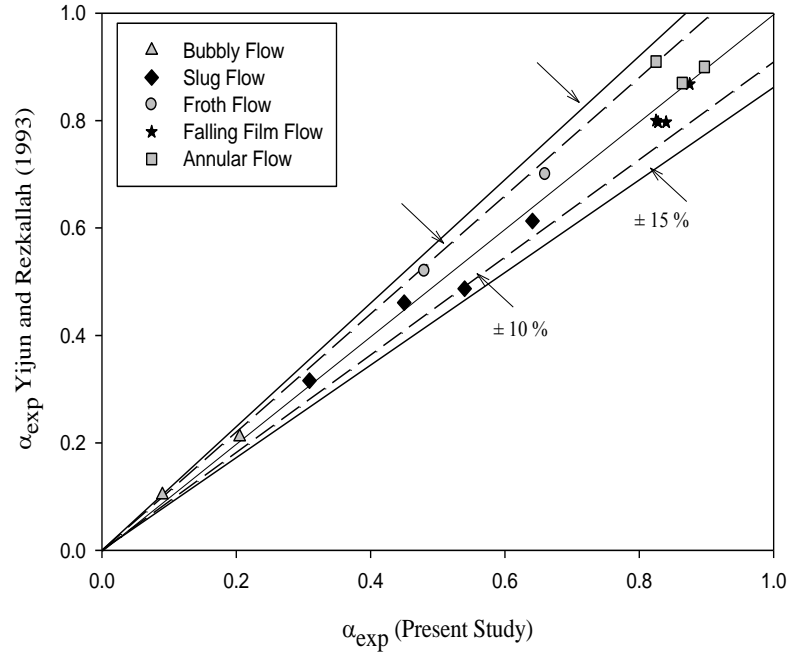


Figure 3.7 Comparison of measured void fraction in present study against that of Yijun and Rezkallah (1993)

To add more to this discussion on the accuracy of quick closing valve method to measure void fraction and other existing methods like radiation method, conductance probe method (tomography technique); investigation of other researchers on the effect of measurement technique on void fraction is presented here. Yijun and Rezkallah (1993) in their investigation measured void fraction data using quick closing valves and Gamma densitometer (radiation technique) methods. They found that both methods yield values of void fraction within $\pm 10\%$. Kawanishi et al. (1990) compared quick closing valve and electrical conductivity probe methods to measure void fraction and found the results to be within $\pm 15\%$ error band. The graphical representation of comparison between void

fraction measurement techniques as reported by Yijun and Rezkallah (1993) and Kawanishi et al. (1990) is shown in Figures 3.8 and 3.9, respectively

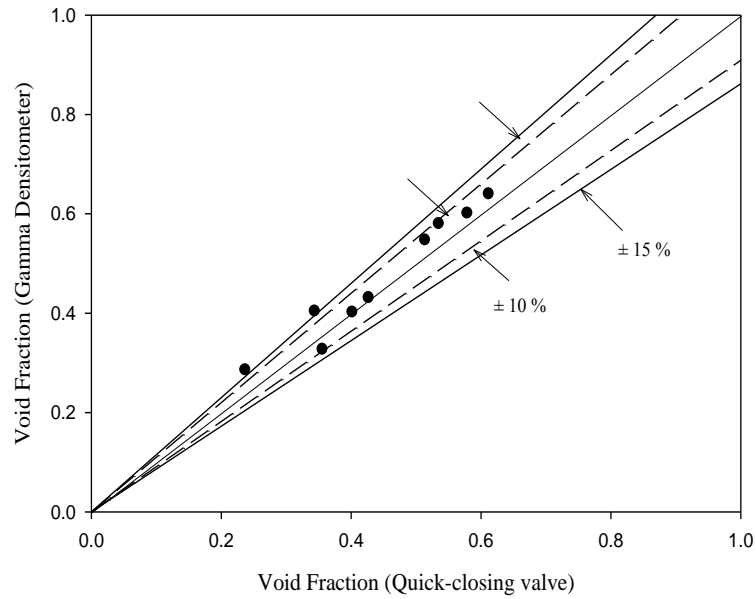


Figure 3.8 Comparison of void fraction measurement techniques adapted from Yijun and Rezkallah (1993)

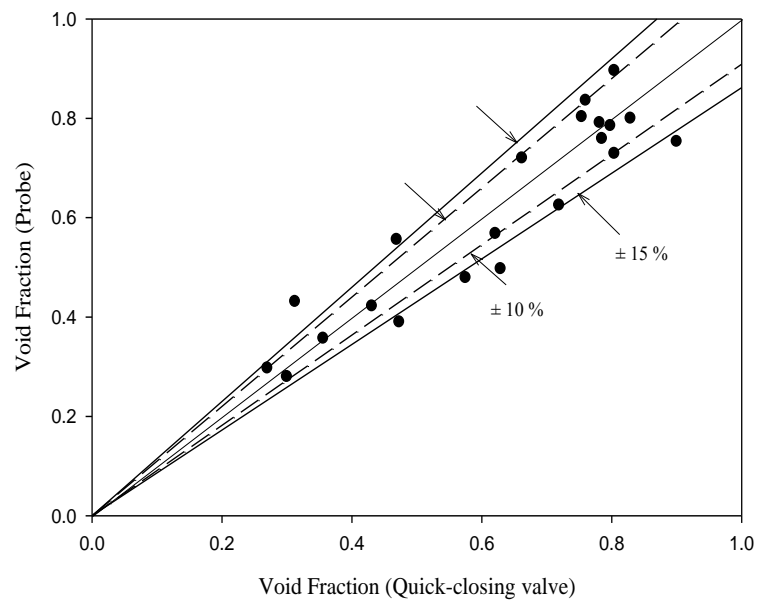


Figure 3.9 Comparison of void fraction measurement techniques adapted from Kawanishi et al. (1990)

Thus from the discussion so far it can be concluded that, the measured data is reasonable and comparable to other investigations for approximately same superficial phase velocities. The experimental setup in present study is competing and emulate with other experimental setup and yields void fraction data with excellent accuracy. Our work also overcomes the debate over using sufficient calming length and confirms the reliability of quick closing valve method to measure void fraction. The flow patterns and void fraction measurement obtained in the present study are summarized in Table 3.4.

Table 3.4 Summary of Flow Patterns and Void Fraction measurement in the present study

Flow Pattern	No. of data points	Void Fraction Range
Bubbly Flow	46	0.025 – 0.295
Slug Flow	38	0.255 – 0.660
Froth Flow	25	0.414 – 0.730
Falling Film Flow	31	0.706 – 0.897
Annular Flow	53	0.931 – 0.911
Total Data Points	193	0.025 – 0.911

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Flow Patterns and Flow Maps

The discussion about flow patterns in the literature review revealed that the existence of flow patterns in two phase flow highly depends upon the experimental setup and flow variables. Visual observation of flow patterns was necessary in the present study since the two phase flow parameters like void fraction, pressure drop and heat transfer coefficients are directly influenced by the flow patterns. Different flow patterns exist in downward two phase flow based on the distribution of individual phase across the pipe cross section. The present experimental study of flow patterns was carried out for constant liquid flow rates and starting from the low gas flow rates and then moving towards higher gas flow rates. Five distinct flow patterns were observed in the present study namely Bubbly, Slug, Froth, Falling Film and Annular flow. The flow patterns were identified on the basis of visual observation and still photographs. In this chapter the experimental observation of flow patterns in downward flow and the photographic evidences of the physical structure of flow patterns and their different appearances with changing phase flow rates are presented and discussed.

4.1.1 Flow Patterns

Bubbly Flow: The bubbly flow observed in the present experimental work could be subcategorized as bubbly and dispersed bubbly flow. The bubbly flow was observed at moderate liquid mass flow rates and low gas flow rates and consisted of large size and elongated shaped bubbles. As the liquid flow rate was increased the gas phase was dispersed as tiny and spherical shaped bubbles in the continuous liquid phase called as dispersed bubbly flow. The range of void fraction associated with bubbly flow in the present study is 0.025-0.293. In order to have deeper insight in the distinction between the bubbly and dispersed bubbly flow, still photographs were taken for different flow rates as shown in Figure 4.1. For better flow visualization and to point out the differences between bubbly and dispersed bubbly flow, the flow patterns were observed at constant gas flow rate and increasing liquid flow rate. As the liquid flow rate is increased as shown in Figure 4.1 (A) to (E), the large bubbles shear down to tiny bubbles and dispersed bubbly flow is observed. The mechanism of the transition from the bubbly to dispersed bubbly flow can be explained from Figure 4.1. The two phase bubbly flow is characterized by the balance between the gravitational, inertia, buoyancy and surface tension forces. When the two phase mixture flows in a pipe in the downward direction, at low gas flow rates the buoyancy effects dominate the inertia effects and the gas bubbles tend to rise in the upward direction. This rising tendency of the bubbles is opposed by the liquid flowing in the downward direction and exerts a shear stress on the bubbles surface. The inertia effects and hence the shear stress exerted by liquid phase increase with increasing liquid flow rate and this results into the disintegration of large bubbles into tiny size bubbles, finely dispersed and evenly distributed into the continuous liquid phase.

Ishii et al. (2004) observed a similar phenomenon with increasing superficial liquid flow rate and justified the disintegration of bubbles as a consequence of impact of turbulent eddies on discrete phase. It was observed that as the bubbles become really small in size, they assume spherical shape by virtue of increased surface tension force acting on the bubble surface. This distinction between the bubbly and dispersed bubbly flow can be of significant importance for studying the heat and mass transfer in two phase flow due to the large interfacial area available in the dispersed bubbly flow.

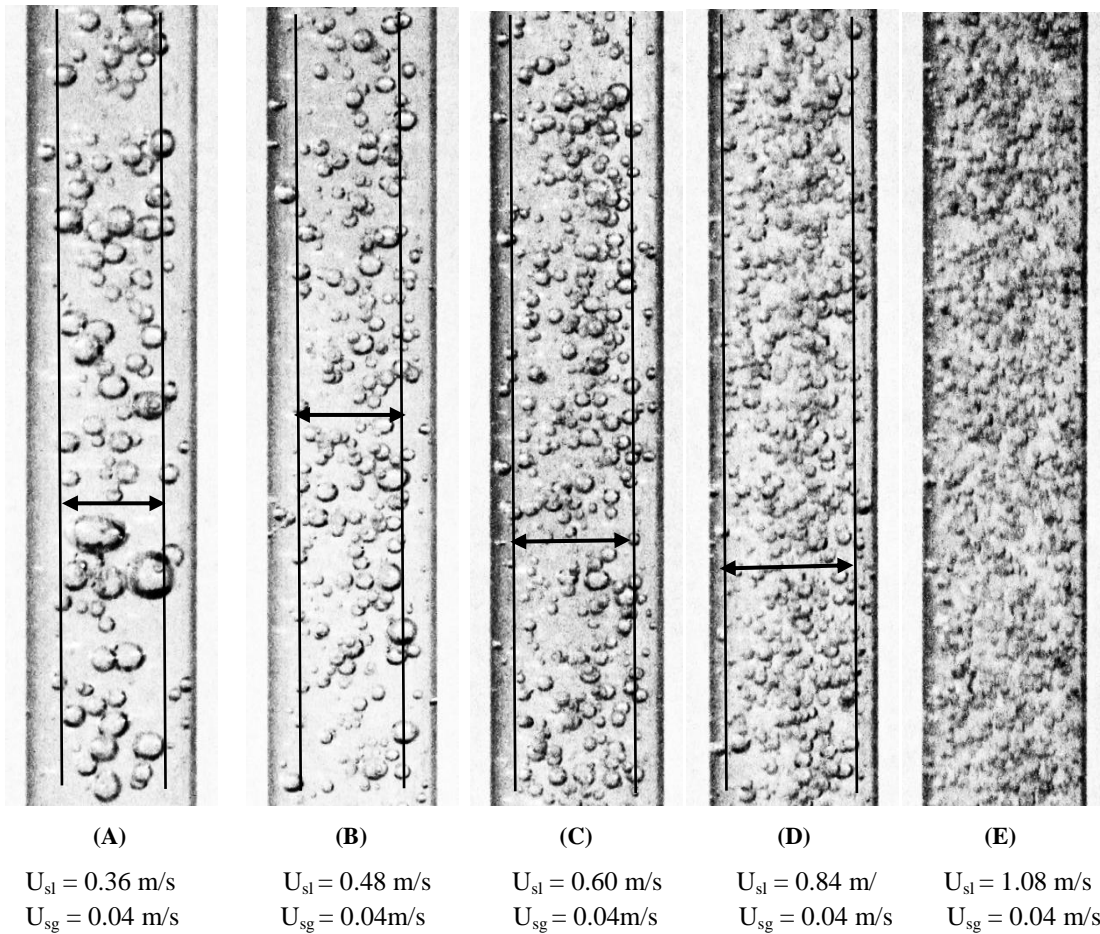


Figure 4.1 Effect of increasing liquid superficial velocity on bubble shape, size and distribution.

To study the effect of increasing gas flow rate on the shape and size of bubbles, the liquid flow rate was kept constant and the bubbly flow pattern was carefully observed for variable gas flow rate. As illustrated in Figure 4.2 (A) to (C), it was noticed that the gas bubbles gets elongated in the lateral direction and tend to agglomerate with increase in the gas flow rate. It can be anticipated that this agglomeration of bubbles with increasing gas flow rate and at constant liquid flow rate gives rise to slug flow. The other phenomenon observed in the bubbly flow was the zigzag and spiral motion of air bubbles. This can be attributed to the fact that, when bubbles tend to rise due to the dominant buoyancy effects they tend to follow the path of least resistance and are displaced slightly offset to the pipe axis. This zigzag motion of air bubbles is shown in Figure 4.2.D.

The other vital observation made in this experimental study was the distribution of bubbles across the pipe cross section. It was observed that the bubbles were concentrated in a region near pipe axis; whereas the region in the vicinity of the pipe wall consisted of continuous liquid phase. This phenomenon was referred to as coring bubbly flow by Oshinowo (1971). Usui and Sato (1989) and Crawford (1983) observed a similar distribution of the bubbles across pipe cross section. Oshinowo (1971) and Usui and Sato (1989) explained the mechanism behind occurrence of coring bubbly flow. They reported that the shear lift exerted due to the relative translational velocities of each phase give rise to coring phenomenon. This lift is in the direction of higher velocity region relative to the pipe wall. Oshinowo (1971) deduced that due to the opposite direction of motion of air bubbles and liquid flow, a rotational motion or spin is imparted to the air bubbles due to the difference in the velocity at the top and bottom of the bubbles. Thus rotational

motion coupled with translational motion of the bubbles and due to the velocity gradient of the liquid flowing in the downward direction, higher velocity is experienced on the top and comparatively lower velocity at the bottom of the air bubble. Thus velocity difference gives rise to the pressure gradients resulting in the action of lift force acting on the air bubbles in a direction normal to the flow, toward the pipe axis and away from the wall. This lift force is thus a consequence of well known Magnus effect or Spin effect and is shown in the Figure 4.3,

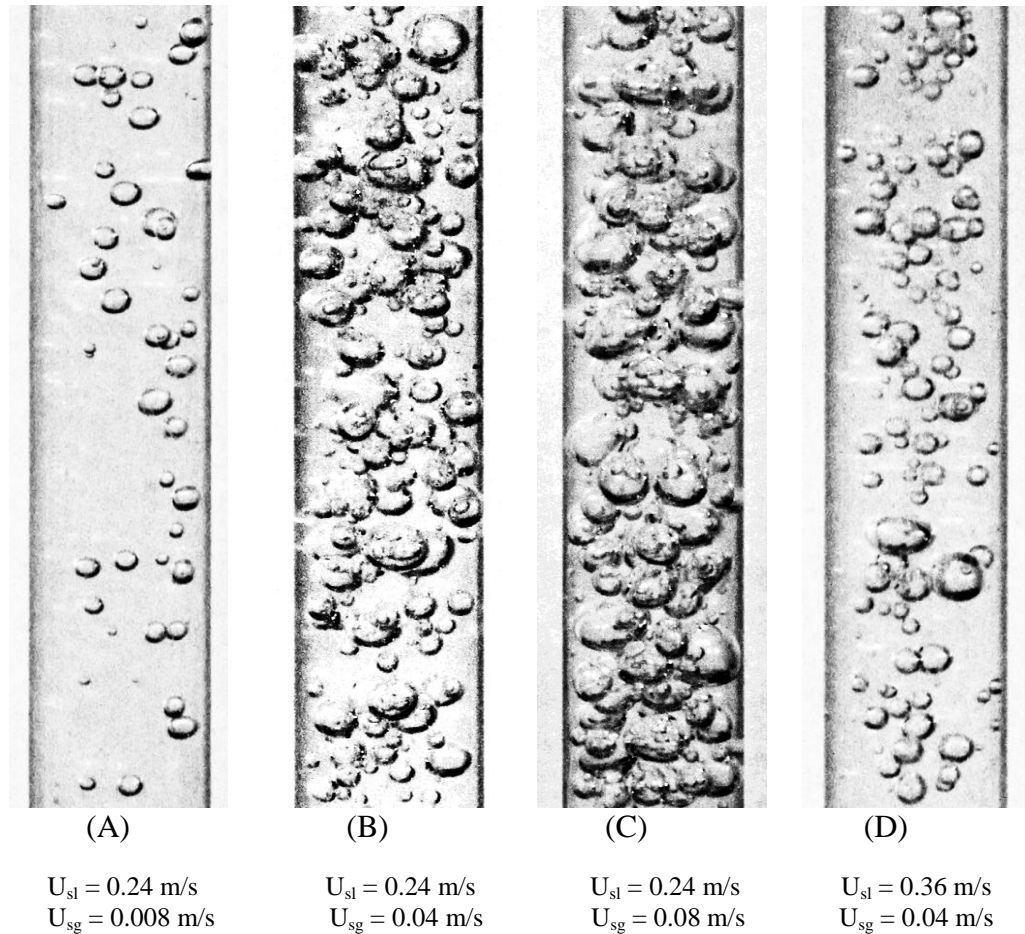


Figure 4.2 Effect of increasing gas superficial velocity on the bubbles size, shape and distribution.

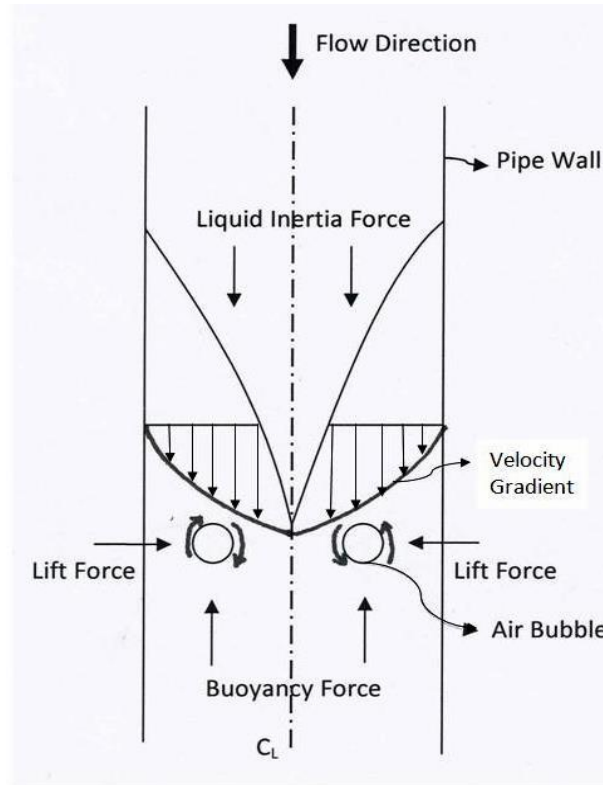


Figure 4.3 Coring phenomenon as a consequence of lift force

Kashinsky and Randin (1999) investigated the structure of cocurrent downward bubbly flow in a 0.043 m diameter pipe. They used electromechanical probes to measure the void fraction, velocity and shear stress distribution across the pipe cross section. It was inferred from the velocity and void fraction profiles that the effect of transverse lift force acting on the bubbles rising with relative velocity with respect to the liquid velocity and the wall repulsion force due to velocity gradients decide the distribution of the bubbles across the pipe cross section. Particularly for downward two phase bubbly flow the lateral lift force and the wall repulsion force act in the same direction and hence the bubbles stay in a region near pipe axis. Kashinsky and Randin (1999) reported that the downward bubbly flow is characterized by center peaked void fraction profile and the near wall region is almost free of bubbles. This conclusion was based on the void fraction

profile plotted against the distance from the pipe wall. Similar results were observed by Usui and Sato (1989) and Hibiki et al. (2004). The results of Kashinsky and Randin (1999) and Hibiki et al. (2004) are shown in Figure 4.4. The void distribution across the pipe cross section has zero value near the pipe wall; the local void fraction values gradually increase with the distance from the pipe wall and suddenly flatten out indicating the existence of the gas phase or bubbles. This void fraction distribution profile can be interpreted as the existence of coring phenomenon in downward two phase bubbly flow. The diameter of core region occupied by bubbles near pipe axis and surrounded by continuous liquid phase was recognized as core diameter. It was observed that the core diameter increases with increasing flow rate of either phase while the flow rate of another phase is kept constant. Oshinowo (1971) observed a similar phenomenon that the core diameter increases with increasing gas flow rate at constant liquid flow rate. However, he reported that the effect of increasing liquid flow rate on core diameter could not be inferred due to lack of data. The observations in the present experimental study about the increase in core diameter are consistent with the observations and conclusions of Oshinowo (1971). As illustrated in Figure 4.1, the effect of increasing liquid flow rate on bubbles size, shape and distribution was analyzed. From the Figure 4.1(A) to (E) it can be concluded that the core diameter definitely increases with increasing liquid flow rate.

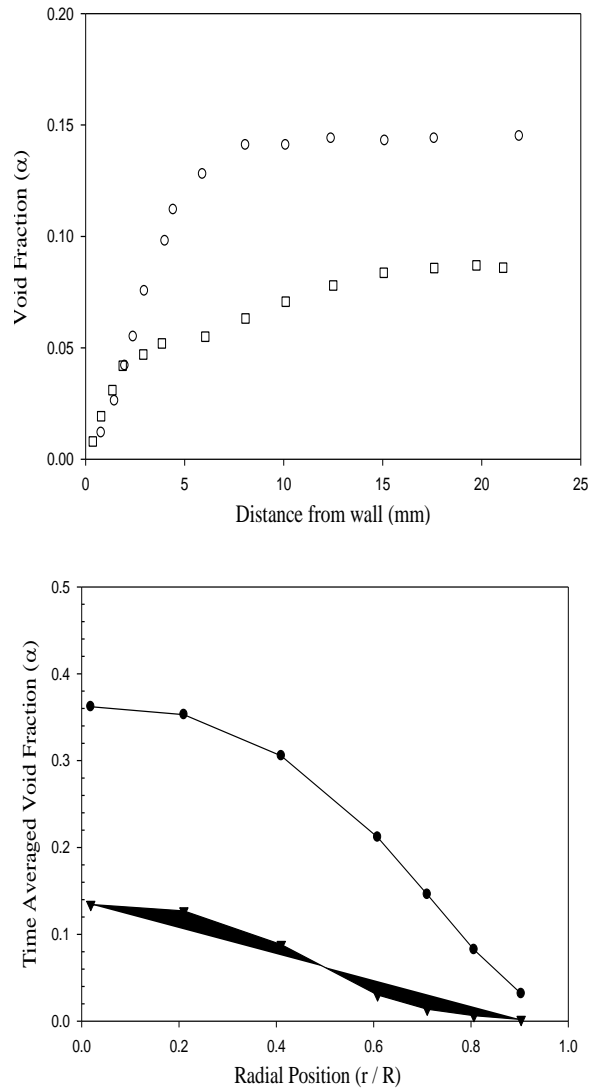


Figure 4.4 Void fraction distribution across the pipe cross section adopted from Kashinsky and Randin (1999) and Hibiki et al. (2004).

Slug Flow: The slug flow occurred at moderate gas and liquid flow rates. Prior to the transition of bubbly to the slug flow large diameter bubbles were observed. As discussed in the previous section the agglomeration of these bubbles established the slug flow. It was observed that the liquid slugs and gas bubbles followed each other in succession. The liquid slugs and gas bubbles occupied almost the entire pipe cross section

surrounded by thin liquid film adjacent to the wall. At the very beginning of slug flow, alternate slugs and large bubbles of irregular length were observed at indefinite intervals. The increase in gas flow rate resulted in the identical length slugs flowing at regular intervals. In order to understand the nature of slug flow still photographs were taken for three different gas-liquid flow rates. It was observed that the shape and direction of motion of a slug is greatly influenced by the change in liquid and gas flow rates. At low gas flow rates and moderate liquid flow rates a typical Taylor bubble was observed with its nose pointing upwards, a direction opposite to the direction of mean flow. It was noticed that though the liquid is flowing in the downward direction, the bullet shaped air slug tries to move upwards but eventually travels slowly in the downward direction with a velocity considerably lower than the liquid velocity. This can be due to the dominant nature of surface tension and the buoyancy force acting opposite to the inertia force of liquid phase. The increase in gas flow rate resulted into the flat head shaped slug with large number of small air bubbles entrained in the liquid slug as shown in Figure 4.5. Eventually with further increase of the gas and liquid flow rates, the bubble nose was found to be pointing downward in the same direction as that of the mean flow. The change in the slug shape can be acknowledged to the balance in the surface tension, buoyancy and inertia forces. It can be speculated that the relative velocity of the air slug with respect to the liquid velocity do not remain constant throughout the slug flow. The relative velocity of air slug can assume negative values for the Taylor shaped bubble. It increases with increasing flow rates of individual phases and gradually attains positive value when the bubble nose is pointing downwards and moving in the same direction of

the mean flow. Sekoguchi et al. (1996) reported that the gas slip velocity for the Taylor bubble like conditions was mostly negative.



(A)
 $U_{sl} = 0.314 \text{ m/s}$
 $U_{sg} = 0.096 \text{ m/s}$



(B)
 $U_{sl} = 0.748 \text{ m/s}$
 $U_{sg} = 0.251 \text{ m/s}$



(C)
 $U_{sl} = 0.779 \text{ m/s}$
 $U_{sg} = 1.655 \text{ m/s}$

Figure 4.5 Influence of the increasing phase flow rates over the shape of bubble nose and motion.

Fabre and Line (1992) presented a discussion on the motion of slug for horizontal and vertical pipes. They reported that in contrast to the vertical upward flow where bubbles remain centered, vertical downward flow causes the bubbles to move eccentrically, with the surface tension acting to restore the symmetry and as the pipe diameter increases, the surface tension forces weaken resulting into the issues of flow stability.

Martin (1976) carried detailed analysis of slug motion in downward two phase flow and reported that, a downward flow bubble may ascend or descend depending upon the relative magnitudes of gas and liquid velocities. He observed that the bubble shape resembles to a typical Taylor slug only for small liquid velocities and small diameter pipes and it was very difficult to obtain a stable Taylor slug in large diameter pipe. Martin (1976) and Usui and Sato (1989) reported the bubbles to be distorted and moving eccentric to the pipe axis and in the vicinity to the pipe wall, whereas in the present study the bubbles in slug flow were observed to be axially symmetric. This deviation from Martins observation can be credited to the small Eotvos number typically for $E_o < 90$, associated with the experimental setup in the present study and hence dominant surface tension acting on the bubble surface forcing it to retain its shape and maintain its symmetry across the pipe cross section. Sekoguchi et al. (1996) investigated the downward two phase slug flow in a 0.025 m diameter pipe and classified it into five subtypes. This classification was essentially based upon the physical appearance of the slug. The P_{LT} regime was identified as the one with low liquid and gas superficial velocities and the slug was observed to have a smooth and bullet shaped profile. The second subcategory was recognized as P_{LS} regime where the shape of gas slug at both upstream and downstream end was flat. The number of bubbles trapped in the liquid slug were large in number than the former. The slip or relative velocity in the region was observed to change its sign gradually from a negative to a positive value as small as 0.05 m/s. As mentioned in the literature review chapter, the P_{LU} and P_{LF} regimes reported by Sekoguchi et al. (1996) were not observed in the present study. The P_H regime was described as the one with leading edge of a slug round in shape and pointing downward

in the direction of the mean flow. The three slug flow regimes namely P_{LT} , P_{LS} and P_H are shown in Figure 4.6.

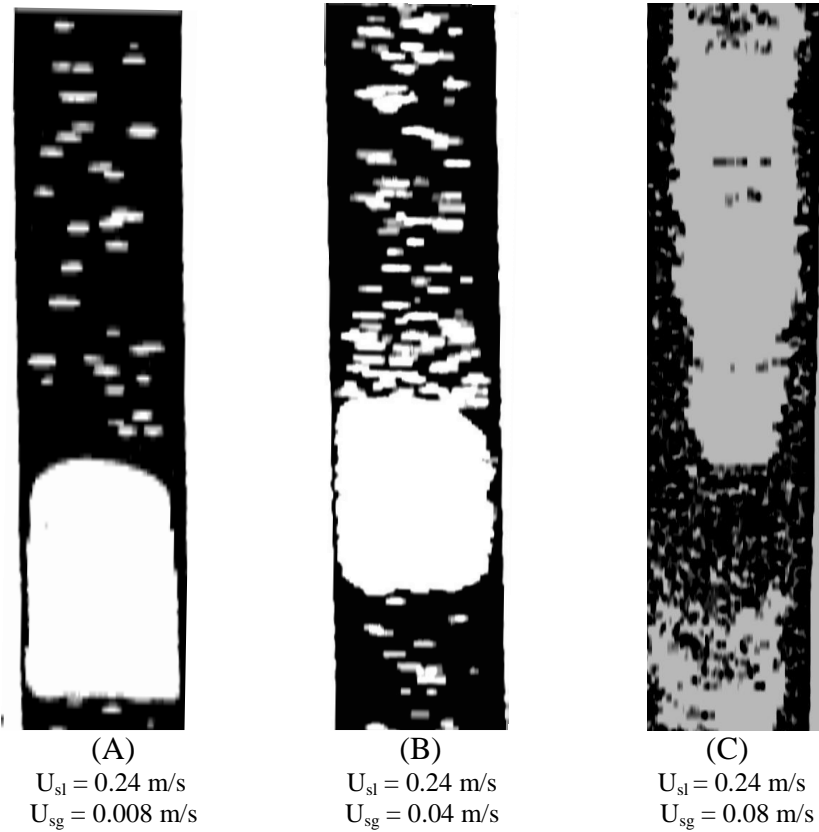


Figure 4.6 Influence of phase superficial velocities on the shape of bubble nose and its direction of motion reported by Sekoguchi et al. (1996)

The above discussion on downward two phase slug flow confirms that the physical structure of the air slug is a function of pipe diameter, depends upon the fluid properties to a considerable extent and the leading edge of the air slug can assume concave or convex shape depending upon the individual phase flow rates. The different types of air slugs observed in the present study with increasing flow rates are consistent with the findings of Sekoguchi et al. (1996). The conclusion is that the ascending, descending and eccentric motion of air slug and the direction and shape of the slug nose

affects the magnitude of relative velocity or alternatively the drift velocity and hence the void fraction values.

Froth Flow: This flow pattern was observed at high liquid and moderate gas flow rates. The onset of froth flow was marked by fast moving and distorted slugs. The froth flow could be distinguished from slug only on the basis of fast moving, distorted and short length slugs and the froth appearance to the flow mixture. The void fraction range associated with froth regime was 0.41-0.73. As discussed in the description of slug flow, the air slug nose in the froth regime was observed to point in the flow direction. With the increase in gas flow rate, the gas bubble appeared to be more distorted and eventually merged in the liquid phase giving frothy appearance to the flow. The fast moving slugs observed in the froth flow as shown in Figure 4.8 (C) were of considerably smaller length than those observed in slug flow regime. The transition to froth flow was achieved with increasing the gas flow rate in the slug regime and liquid flow rate in the falling film regime. Oshinowo (1971), Troniewski and Spisak (1987) and Yijun and Rezkallah (1993) reported the appearance of froth flow in downward two phase flow.

Falling Film Flow: The falling film flow appeared for very low liquid and moderate gas flow rates. The flow is characterized by a gaseous core surrounded by a thin liquid film moving along the pipe wall. This is a unique type of flow pattern observed only in vertical downward flow. Crawford (1983) mentioned that the falling film flow is essentially a separated flow in vertical downward pipes and recognized as stratified flow for declined pipes. At the onset of falling film flow the film appeared to be thin and wavy. Occasional dry spots were observed at the pipe surface. With the increase in liquid flow rates the film thickness increased and became wavy with air bubbles entrained in the

film. The bubbles in liquid film gradually vanished with increasing gas flow rates. This observation is consistent with that of the Oshinowo (1971) and Crawford (1983). The photographic evidence of the falling film shown in Figure 4.7 confirms the existence of a falling film flow with and without bubble entrainment. Oshinowo (1971) reported similar observations about the appearance of small bubbles in the falling film. He recognized it as falling bubbly film flow. Yamazaki and Yamaguchi (1979) observed a falling film type of flow pattern. They referred to it as a wetted wall flow or an annular flow with smooth gas liquid interface. Crawford (1983) observed the liquid film trickling downstream along the pipe wall primarily due to the influence of gravity and called it as low energy or lazy annular flow. The present study marked the transition from falling film to annular flow with increasing gas flow rate.

Annular Flow: Annular flow occurred at high values of gas and liquid flow rates. The distribution of two phases in the pipe was characterized by a gaseous core surrounded by a fast moving liquid along the pipe wall. The major difference between the falling film and the annular flow being the high flow rates of individual phases associated with the annular flow. Albeit there is not a big difference in the void fraction values associated with the two flow patterns, pressure drop and heat transfer coefficient values can be significantly different for the two flow regimes. Some investigators subcategorized the annular flow as mist, wispy annular flow or annular flow with droplets. In wispy or mist annular flow, liquid drops are entrained in the central gaseous core. This subtype of annular flow was not confirmed in the present study since it was very difficult to observe the liquid drop entrainment in the gaseous core. The annular flow was observed by most of the investigators and the description of annular flow

pattern observed in the present study is consistent to the observations of Golan (1968), Oshinowo (1971), Yamazaki and Yamaguchi (1979), Usui and Sato (1989) and other investigators.



$$\begin{aligned} U_{sl} &= 0.188 \text{ m/s} \\ U_{sg} &= 2.949 \text{ m/s} \end{aligned}$$



$$\begin{aligned} U_{sl} &= 0.063 \text{ m/s} \\ U_{sg} &= 3.056 \text{ m/s} \end{aligned}$$

Figure 4.7: Falling film flow with and without air bubble entrainment in the liquid film.

The five major flow patterns observed in the present study are shown in Figure 4.8. For constant water mass flow rate, the bubbly, slug, falling film and annular flow appear in sequence with increasing gas flow rate. Forth flow is added to the above flow patterns while falling film flow drops out when observed at constant high water mass flow rate and increasing gas flow rate. These flow patterns when plotted in terms of

superficial phase velocities or mass flow rate coordinates indicate the appearance and transition of one flow pattern to another. The flow map plotted with observations in present study is discussed in next section.

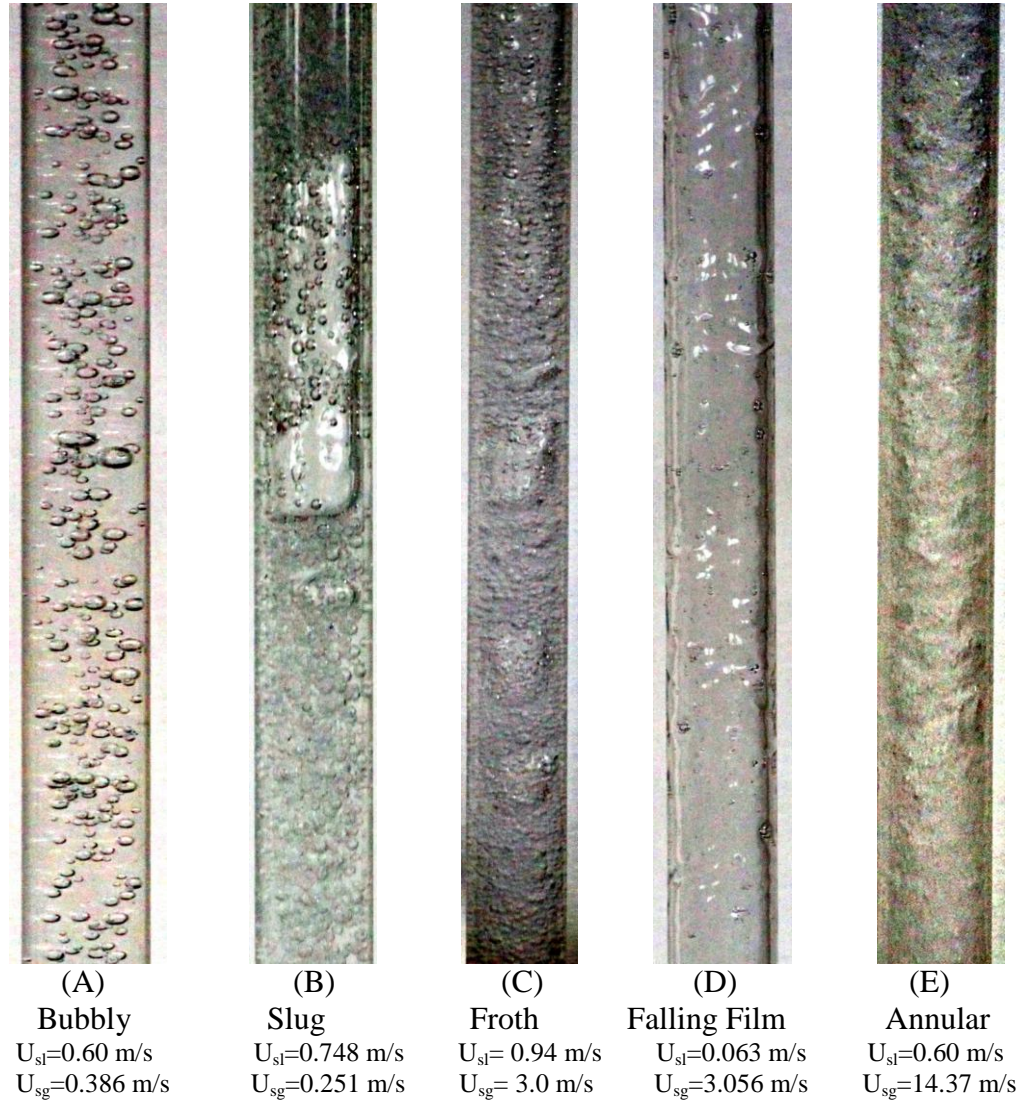


Figure 4.8 Flow patterns in downward two phase flow observed in the present study

4.1.2 Flow Maps

In the present study of downward two phase flow the flow patterns were observed at variable mass flow rates. It was observed that as the air mass flow rate is increased for constant water flow rate the flow pattern transition takes place. To represent these transitions graphically it was necessary to represent the flow patterns as a function of water and air mass flow rates. As discussed earlier in the literature review, there is no consistency in the flow maps proposed by different researchers regarding the transition lines between the flow patterns and the flow rates at which they occur. The flow maps available in the literature are based on dimensional (velocity, mass flow rate) or non-dimensional (Reynolds number, Froude number) coordinate system. The flow map for present study plotted for superficial air and water velocity coordinates is shown in Figure 4.9.

The analysis and comparison of flow pattern map against those available in the literature was not emphasized in the present study because it is difficult to represent a similar flow map in terms of transition of flow patterns as reported by other researchers due to its dependence on experimental setup and general understanding and description of flow patterns by an individual. However, the flow pattern map obtained in the present study was compared against the Oshinowo (1971) flow map for mass flow rate coordinates as shown in Figure 4.10.

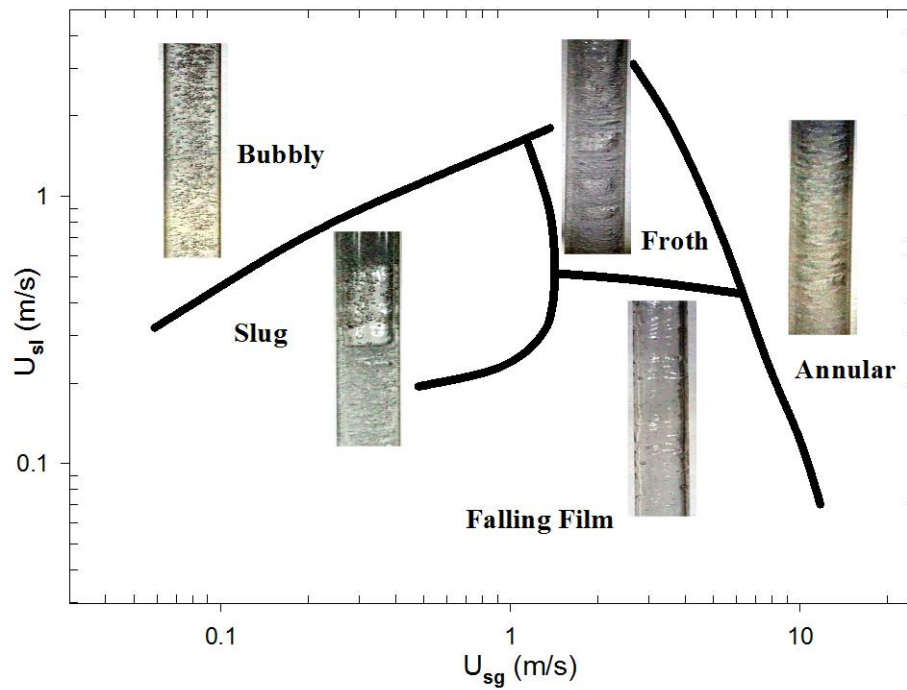


Figure 4.9 Flow pattern map for vertical downward two phase flow (present study)

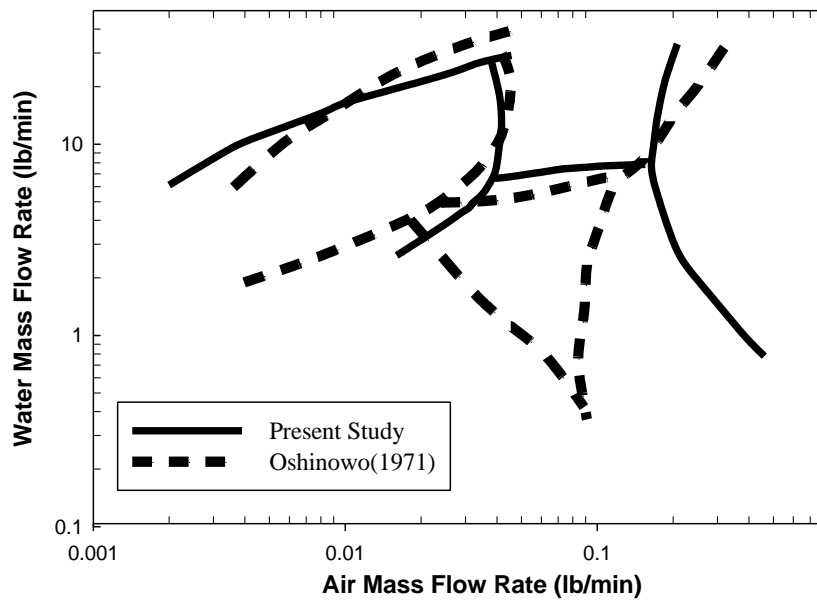


Figure 4.10 Comparison of flow pattern map of present study vs. Oshinowo (1971)

This comparison of flow pattern map of the present study against that of the Oshinowo (1971) concludes that the flow pattern transition between bubbly-slug, slug-froth, froth-falling film in the present study though not exact but are in good agreement with his flow pattern map. The transition between froth-annular and falling film-annular is observed to be entirely different than that of the Oshinowo (1971). This deviation can be interpreted as the consequence of differences in the description of the physical structure of the flow patterns defined by individual investigator.

Thus from the above discussion so far on flow patterns and flow map it is concluded that the major flow patterns observed in the present study are in consensus with the observations made by other investigators. The issues of coring phenomenon in the bubbly flow and the differences in the transition from bubbly to dispersed bubbly flow are addressed. The physical reasoning of different shapes of air slugs that can occur in vertical downward two phase flow is explained based on the photographic evidences. The comparison of the flow map against the one available in the literature inferred that the direct comparison of flow maps with respect to the transition of flow patterns is not recommendable due to broad definition of individual flow patterns. The flow map for observed flow patterns in the present study is presented in terms of superficial phase velocities as abscissa and ordinate to support the discussion of flow transitions and their physical structure. The measured void fraction associated with individual flow pattern increases with change in the phase superficial velocity or as the flow patterns shift from bubbly to annular. The variation of void fraction with transition of one flow pattern to another is illustrated in next section.

4.2 VOID FRACTION

It was seen in the literature review that a limited number of correlations are available to predict the void fraction in downward two phase flow with majority of them based on the concept of the drift flux model and developed for the bubbly and the slug flow regimes. The literature review also revealed that these correlations developed by investigators were based either on their own data or for the data with very limited range of operating conditions. In order to have a reliable performance analysis of the void fraction correlations, the accuracy of the available correlations was analyzed against an extensive experimentally measured void fraction data set of 909 points. This data set had a significant range of operating conditions in terms of the pipe diameter, system pressure and the fluid combination used for the two phase experimentation. This section of the chapter is a discussion about the variation of the void fraction with flow patterns or alternatively with the varying individual phase flow rates followed by the performance analysis of the available void fraction correlations and finally conclude with the recommendation of the best performing void fraction correlations for the downward two phase flow.

4.2.1 Variation of the void fraction with flow patterns

The literature review on the two phase flow and the experiments performed in the present study revealed that the void fraction is a function of the flow patterns and varies with respect to the individual phase mass flow rate and hence the flow patterns. For the major flow patterns appearing in the downward two phase flow it is observed that the void fraction is least for bubbly flow while it attains a maximum value as the flow regime transits to the annular flow pattern.

To verify this void fraction trend and the experimental work done in the present study, the variation of the void fraction was plotted against varying superficial gas velocity and at constant superficial liquid velocity as shown in Figure 4.11. It was observed that the void fraction initially increases rapidly with the introduction of the gas phase up to a certain value approximately $\alpha = 0.7$ and thereafter increases gradually with the increasing superficial gas velocity. This observation is consistent with the conclusions of Yijun and Rezkallah (1993), Usui and Sato (1989), Nguyen (1975) and Golan (1968). In the present experimental study it was found that the rapid increase in the void fraction occurs at liquid superficial velocities higher than 0.60 m/s. The tendency of accelerated growth in the void fraction against increasing superficial gas velocity is typically associated with the bubbly, slug and froth flow regimes while the gradual rise in the void fraction corresponds to the falling film and annular flow regimes. This phenomenon can be attributed to the fact that in the bubbly flow regime the small increase in the superficial gas velocity results in the laterally elongated and increased number of gas bubbles which try to coalesce and occupy almost the entire pipe cross section. This translates to the existence of the higher void fraction even for a small increment in the superficial gas velocity. The effect of increase in the superficial gas velocity on the bubbles size and distribution is already discussed in the previous section. The typical void fraction range associated with each flow pattern observed in the present study is reported in Table 4.1. It is observed that the range of void fraction associated with the slug and froth flow regimes overlap each other besides the overlapping void fraction range of the falling film and annular flow patterns.

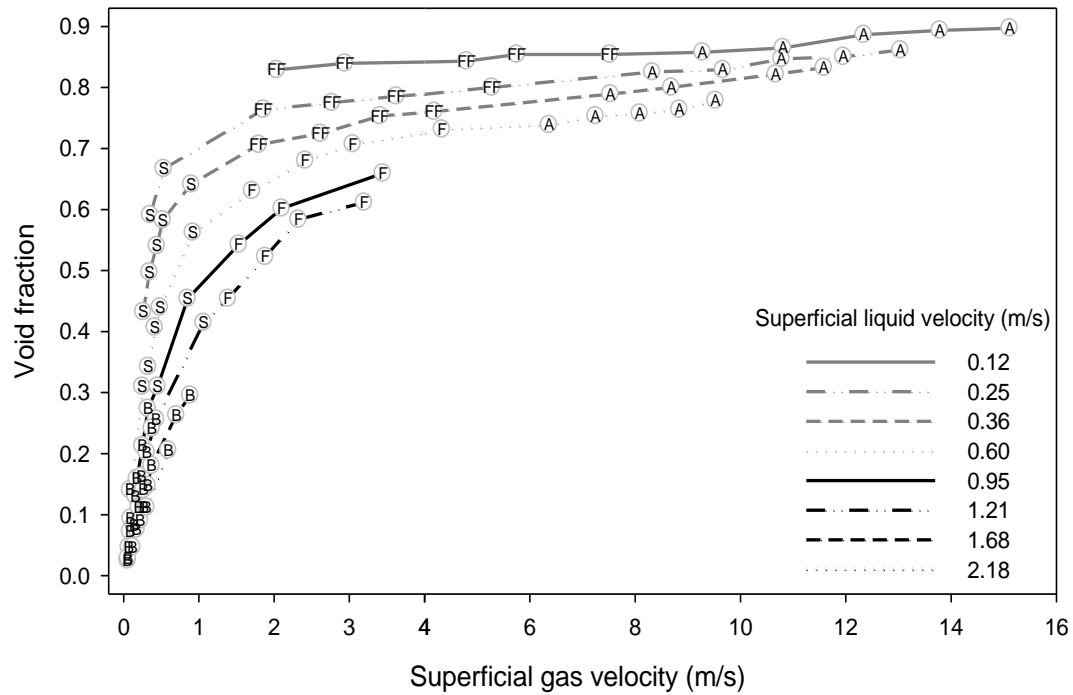


Figure 4.11 Variation of the void fraction with increasing superficial gas velocity and at constant superficial liquid velocity

Table 4.1 Range of void fraction for different flow patterns observed in the present study

Flow Pattern	Range of Void Fraction
Bubbly	0.025 – 0.295
Slug	0.255 – 0.666
Froth	0.414 – 0.731
Falling Film	0.706 – 0.897
Annular	0.731 – 0.911

In the falling film and annular flow regimes the increase in the void fraction with change in the superficial gas velocity is gradual and can be considered to remain virtually

constant even for increasing superficial gas velocity. In the present study this altered void fraction trend is observed for the liquid superficial velocities less than 0.36 m/s and the associated void fraction values are typically higher than 0.7. These remarks infer that since the void fraction in the bubbly flow regime is sensitive to the small change in the superficial gas velocity, accurate correlations must be used in the bubbly region to accommodate the rapid growth of the void fraction. The discussion on void fraction correlations and the dependency of void fraction on gas flow rate or superficial gas velocity is extended later in this chapter.

4.2.2 Performance analysis of the void fraction correlations

It was pointed out earlier in Chapter 2 that though some correlations are available in the literature to predict the void fraction in the downward two phase flow, majority of these correlations are developed for a particular data set and operating condition. Furthermore these correlations lack a detailed and reliable analysis of their performance to predict the void fraction in the downward two phase flow. This study attempts to analyze the available void fraction correlations in an unbiased manner and rank them based on the percentage accuracy and overall RMS (root mean square) associated with each of them in the prediction of the void fraction. This method of judging the correlations is consistent with that used in previous studies by other investigators. From the discussion in the chapter of literature review it is now apparent that the definition of a particular flow pattern is broad and to a greater extent depends upon an individual's perception. Hence instead of analyzing the flow dependent void fraction correlations for

the particular flow pattern, a two step scrutiny is used to appraise the performance of the void fraction correlations. In the very first step the results of the prediction of the void fraction correlations are analyzed for the individual data sets used in this investigation. It is then followed by the analysis of the correlations for the entire range of the void fraction. The second phase of assessment is divided into four intervals of 0.25 each, to be precise 0 - 0.25, 0.25 - 0.50, 0.50 - 0.75 and 0.75 - 1. The range of the void fraction preferred in the present study resembled the approximate range of the void fraction associated with the major flow patterns. For instance, the void fraction range of 0 - 0.25 approximated the bubbly flow, the next two ranges are approximately linked to the slug and froth flow combined together where as the 0.75 - 1 void fraction range is affiliated to the falling film and annular flow regimes. This approximation is within $\pm 15\%$ of the experimentally measured values of the void fraction in the present study as well as the investigations of Usui and Sato (1989), Yijun and Rezkallah (1993) and Oshinowo (1971). The two step analysis mentioned above gave a good idea of the performance of the void fraction correlations for individual data sets accounting for the pipe diameter and fluid properties and also worked to gauge their performance for the specified range of the void fraction.

This analysis was accompanied by the identification of the approximate range of the void fraction in which the correlations performed agreeably. In this section the void fraction correlations are evaluated in the same sequence as they are grouped in the Chapter 2, i.e. the correlations that are not and those that are based on the drift flux model. In order to have a thorough evaluation of the performance of the void fraction correlations a diverse data set of 909 points is used in the present study. This data set

consists of four different fluid combinations, nine pipe diameters and a range of system pressure and void fraction measurement techniques. The summary of the void fraction data set used in the present study is shown in Table 4.2.

Table 4.2 Experimental Data Sets used in the present study.

Source	Diameter (m)	Data Points	Fluids	Measurement Method	Pressure Range (MPa)	Temperature Range (°C)	Liquid Mass Flow Range (kg/min)	Gas Mass Flow Range (kg/min)	Void Fraction Range
Present Study	0.01267	193	Air-water	Quick Closing Valve	0.11 - 0.23	24.16 - 28.5	0.44 – 18.08	0.009 - 0.223	0.025 – 0.93
Hernandez (2002)	0.0545	39	Air-water	Quick Closing Valve	NA	NA	5.7 – 151.8	1.4 - 10.4	0.02 - 0.246
Yijun and Rezkallah (1993)	0.0095	81	Air-water	Gamma Ray Densitometer	NA	NA	0.14 – 13.9	0.0011 -0.24	0.02 - 0.99
Usui and Sato (1989)	0.016	25	Air-water	Conductance Probe	0.1	NA	1.09 – 17.8	0.0015 -0.30	0.07 – 0.89
Paras (1982)	0.01905	35	Air-water	Neutron Noise Analysis	NA	NA	5.86 – 29.3	0.0022-0.056	0.11 – 0.90
Mukherjee (1979)	0.0381	52	Air-kerosene	Capacitance Method	0.25 - 0.56	12.2 – 47.7	1.5 – 180.8	0.016 – 9.6	0.32- 0.99
		48	Air-oil		0.28 – 0.45	10.5 – 37.2	1.56 – 139	0.021 – 8.5	0.22 – 0.99
Lorenzi and Stogia (1976)	0.044	71	Air-water	Manometric Method	NA	NA	43.2 - 182.4	0.564 -32.22	0.011– 0.209
	0.090	44	Air-water		NA	NA	182.6 – 399.5	0.015-0.169	0.015- 0.169
	0.032 [#]	26	Air-water	NA	NA	NA	16.84 – 66.87	0.00087 – 0.0193	0.029 – 0.29
Nguyen (1975)	0.0455	79	Air-water	Closing Gate type valve manually	0.09 – 0.103	23.6 – 27.45	1.697 - 136.7	0.0155-6.36	0.11-0.988
Beggs (1972)	0.0381	13	Air-water	Quick Closing Valves	0.54-0.66	22.7 – 35.5	1.53 - 108.83	0.584-7.109	0.465-0.973
	0.0254	12			0.43-0.63	19.44- 30.5	0.730 - 74.31	0.0445-3.48	0.094-0.983
Oshinowo (1971)	0.0254	112	Air-water	Quick Closing Valve	0.13-0.205	17.78-26.39	9.5E-5 – 0.03	0.022-1.039	0.057-0.961
		78	Air-glycerin		0.14-0.203	23.06 – 26.8	7.4E-5 – 0.03	0.0086-8.86	0.047-0.964

[#]Data from De Raui (1976) as reported by Lorenzi and Stogia (1976)

4.2.3 Comparison of the void fraction correlations with the experimental database

One of the important objectives of the present study was to identify the best void fraction correlations for the downward vertical two phase flow that are independent of the flow patterns, fluid combination and the pipe diameter. In the literature there are very few flow pattern independent void fraction correlations available for vertical downward flow. In the present study, in addition to these correlations flow dependent correlations are also evaluated for the entire range of the void fraction incorporating all the flow patterns mainly for two reasons; the first reason being that the database in the literature lacks a clear definition and records of the flow patterns and the associated range of the void fraction with each flow pattern and the other reason being that the preliminary analysis of the correlations showed that these flow dependent void fraction correlations perform satisfactorily in the flow regimes they were not designed for. The criterion for satisfactory performance used in the present study is mentioned later in this section.

In the first step of the analysis, the performance of the void fraction correlations is analyzed for all the data set used in the present study as documented in the Table 4.3. This is followed by the comparison of the predictions of the void fraction correlations for individual data sets. This analysis gave a better understanding of the performance of the void fraction correlations when used for a range of operating conditions, pipe diameters and working fluids. The accuracy and hence the performance of the void fraction correlations is judged in terms of the percentage accuracy and overall RMS (root mean square) error method. Mathematically root mean square is expressed as,

$$\text{RMS error} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N \left[\frac{(\alpha_{calc})_i - (\alpha_{meas})_i}{(\alpha_{meas})_i} \right]^2} \times 100\%$$

Where N is the number of experimental data points.

A performance criterion based on the void fraction range with an interval of 0.25 each is used to analyze the accuracy of the correlations. It was observed that irrespective of the data set, the percentage error associated with the prediction of the void fraction correlations in the lower range of void fraction typically for a range of 0 – 0.25 was higher than that observed in a range of 0.75 – 1.

Table 4.3 Comparison of prediction of void fraction correlations for all data (909) points

Correlation	Percentage of data points predicted within				RMS error %
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	44.7	66.7	81.9	92.2	16.4
Armand (1946), Chisholm (1983)	65.6	77.9	87.4	92.5	14.7
Beggs (1972)	32.7	43.7	52.2	60.8	483.7
Chisholm (1973)	65.9	77.8	87.4	92.5	14.7
Mukherjee (1979)	38.6	57.1	61.8	65.6	190.7
Usui and Sato (1989) ^{FF}	24.6	46.8	56.7	63.0	693.0
Yamazaki and Yamaguchi (1979)	70.4	82.1	88.9	94.6	13.9
Bonnecaze et al. (1971)	67.9	87.5	94.4	99.0	15.7
Cai et al. (1997) ^B	72.0	86.8	94.2	99.0	19.2
Cai et al. (1997) ^S	79.2	90.1	95.8	99.6	13.6
Clark and Flemmer (1985)	73.2	87.1	94.4	98.9	17.7
Dix (1971)	50.8	60.5	69.3	80.3	29.1
Goda et al. (2003)	65.8	78.9	85.6	91.4	17.0
Gomez et al. (2000)	79.1	90.3	96.2	99.3	9.2
Hasan (1995)	78.6	90.1	95.3	98.8	13.2
Huq and Loath (1992)	55.4	68.0	80.1	91.0	16.7
Kawanishi et al. (1990)	43.0	54.8	62.3	76.2	29.2
Kokal and Stainslav (1989)	67.9	87.3	94.0	98.9	16.5
Nicklin et al. (1962)	67.9	87.5	94.4	99.0	15.3
Rouhani and Axelsson (1970) ¹	76.3	86.7	90.9	96.6	11.4
Sun et al. (1981)	65.5	84.0	91.6	98.7	92.4
Usui and Sato (1989) ^S	23.4	36.7	49.2	76.1	38.6
Woldesemayat and Ghajar (2007)	57.9	63.5	67.1	70.8	104.1
Zuber and Findlay (1964)	67.3	85.7	94	98.9	21.5

^B - Bubbly, ^S - Slug, ^{FF} - Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The equations of all the correlations used in the performance analysis in the present study are enlisted in the Appendix. It can be seen from Table 4.3 that most of the correlations based on the drift flux model are able to predict 90% or more points well within $\pm 30\%$ error bands whereas none of the correlations excels in a more stringent error bands of $\pm 10\%$. The correlations based on the concept of drift flux model are here onwards abbreviated as DFM correlations. The correlations developed exclusively for

bubbly and slug flow regime are found to be able to predict more than 85% of the data points in the error bands of $\pm 15\%$ with Gomez et al. (2000) having a maximum accuracy of 90.3% and RMS error of 9.2% in these error bands.

However since the number of data points in each range of the void fraction, flow patterns and the fluid combinations are not equally distributed, this analysis could result into a biased and misleading comparison and build a wrong impression about the performance of the void fraction correlations. To overcome this issue the void fraction correlations are also compared against the individual data set to analyze their performance and an attempt is made to figure out the approximate range of the void fraction for satisfactory performance of the correlations. The comparison of the void fraction correlations against the void fraction data measured in the present study is shown in Table 4.4. It is apparent from this table that among the non DFM correlations only Yamazaki and Yamaguchi (1979) performs satisfactorily whereas most of the DFM correlations predict 90% of the void fraction data well within $\pm 15\%$ error bands with the RMS error of 10.4%, the exceptions being Dix (1971) and Kawanishi et al. (1990).

Table 4.4 Comparison of prediction of void fraction correlations for present study, air water fluid combination, (193) points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	34.2	57.0	83.5	98.5	14.2
Armand (1946), Chisholm (1983)	73.6	88.6	99.0	99.0	8.6
Beggs (1972)	26.4	34.7	45.9	62.1	507.3
Chisholm (1973)	73.6	88.1	99.0	99.0	8.6
Mukherjee (1979)	28.5	66.3	68.6	72.3	92.8
Usui and Sato (1989) ^{FF}	17.1	35.2	53.6	65.1	237.4
Yamazaki and Yamaguchi (1979)	82.4	90.7	92.8	95.4	10.4
Bonnecaze et al. (1971)	81.9	92.7	98.5	99.0	7.5
Cai et al. (1997) ^B	88.1	94.4	96.9	97.9	8.6
Cai et al. (1997) ^S	90.2	97.4	98.5	99.0	6.6
Clark and Flemmer (1985)	83.4	93.3	96.4	97.9	9.4
Dix (1971)	49.7	61.7	73.2	82.1	27.2
Goda et al. (2003)	83.4	90.7	95.9	98.5	8.1
Gomez et al. (2000)	93.8	97.9	99.0	99.5	6.6
Hasan (1995)	81.3	98.4	99.5	100	7.5
Huq and Loath (1992)	53.9	73.6	88.1	100	12.2
Kawanishi et al. (1990)	43.5	44.0	51.8	63.2	33.0
Kokal and Stainslav (1989)	81.9	91.7	97.9	100	7.5
Nicklin et al. (1962)	81.9	92.7	99.0	100	7.4
Rouhani and Axelsson (1970) ¹	94.8	99.5	99.5	100	4.9
Sun et al. (1981)	89.6	95.9	97.9	99.5	7.0
Usui and Sato (1989) ^S	65.8	97.4	99.5	100	8.8
Woldesemayat and Ghajar (2007)	62.7	67.4	71.0	74.1	69.7
Zuber and Findlay (1964)	87.56	94.30	97.40	99.48	7.9

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The data set of Hernandez (2002) was saturated in the higher region of the void fraction. As can be seen in Table 4.5 most of the correlations both DFM and non DFM predict more than 90% of data points within the $\pm 20\%$ tolerance. This is due to the fact that the higher values of measured void fraction results into the smaller values of percentage error. Hasan (1995), Rouhani and Axelsson (1970)¹, Cai et al. (1997)^S and

Gomez et al. (2000) were the top performers in the narrow error bands of $\pm 10\%$ yielding accuracy of 97.4%, 94.9%, 94.9% and 89.7%, respectively.

Table 4.5 Comparison of prediction of void fraction correlations for Hernandez (2002) air-water fluid combination, (39) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	89.7	100	100	100	6.8
Armand (1946), Chisholm (1983)	59.0	71.8	94.9	100	12.3
Beggs (1972)	48.7	79.5	92.3	100	11.9
Chisholm (1973)	61.5	74.4	94.9	100	11.6
Mukherjee (1979)	82.1	94.9	97.4	100	7.1
Usui and Sato (1989) ^{FF}	30.8	92.3	97.4	100	11.9
Yamazaki and Yamaguchi (1979)	59.0	84.6	94.9	100	10.7
Bonnecaze et al. (1971)	69.2	94.9	97.4	100	9.9
Cai et al. (1997) ^B	79.5	97.4	100	100	8.7
Cai et al. (1997) ^S	94.9	97.4	100	100	6.2
Clark and Flemmer (1985)	84.6	97.4	100	100	7.6
Dix (1971)	53.8	69.2	76.9	100	14.4
Goda et al. (2003)	46.2	92.3	97.4	100	11.2
Gomez et al. (2000)	89.7	97.4	100	100	8.2
Hasan (1995)	97.4	100	100	100	4.4
Huq and Loath (1992)	61.5	71.8	87.2	97.4	13.0
Kawanishi et al. (1990)	69.2	89.7	94.9	97.4	11.1
Kokal and Stainslav (1989)	69.2	94.9	97.4	100	9.9
Nicklin et al. (1962)	69.2	94.9	97.4	100	9.9
Rouhani and Axelsson (1970) ¹	84.6	94.9	97.4	100	8.2
Sun et al. (1981)	48.7	94.9	97.4	100	11.0
Usui and Sato (1989) ^S	2.6	2.6	10.3	84.6	26.5
Woldesemayat and Ghajar (2007)	79.5	94.9	100	100	7.2
Zuber and Findlay (1964)	69.23	94.87	97.43	100	9.7

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Table 4.6 Comparison of prediction of void fraction correlations for Yijun and Rezkallah (1993) air-water fluid combination (81) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	56.8	79.0	90.1	97.5	12.9
Armand (1946), Chisholm (1983)	55.6	67.9	80.2	100	14.1
Beggs (1972)	28.4	39.5	43.2	54.3	259.7
Chisholm (1973)	54.3	67.9	80.2	100	14.1
Mukherjee (1979)	44.4	65.4	76.5	81.5	49.4
Usui and Sato (1989) ^{FF}	19.8	32.1	39.5	50.6	63.7
Yamazaki and Yamaguchi (1979)	55.6	74.1	88.9	97.5	13.1
Bonnecaze et al. (1971)	43.2	74.1	82.7	98.8	13.6
Cai et al. (1997) ^B	50.6	71.6	92.6	98.8	12.9
Cai et al. (1997) ^S	64.2	75.3	95.1	100	11.6
Clark and Flemmer (1985)	54.3	69.1	93.8	98.8	12.7
Dix (1971)	37.0	48.1	66.7	87.7	28.3
Goda et al. (2003)	46.9	70.4	84.0	98.8	13.9
Gomez et al. (2000)	66.7	76.5	93.8	100	11.3
Hasan (1995)	66.7	77.8	95.1	100	11.0
Huq and Loath (1992)	42.0	55.6	67.9	93.8	17.2
Kawanishi et al. (1990)	43.2	67.9	77.8	85.2	23.6
Kokal and Stainslav (1989)	43.2	72.8	82.7	98.8	13.6
Nicklin et al. (1962)	43.2	74.1	82.7	98.8	13.6
Rouhani and Axelsson (1970) ¹	51.9	77.8	91.4	100	12.2
Sun et al. (1981)	39.5	71.6	85.2	100	13.6
Usui and Sato (1989) ^S	65.4	77.8	95.1	100	11.4
Woldesemayat and Ghajar (2007)	49.4	67.9	74.1	84	44.2
Zuber and Findlay (1964)	48.14	72.83	90.12	98.76	13.2

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The performance of the void fraction correlations for the data of Yijun and Rezkallah (1993) and Usui and Sato (1989) is shown in Tables 4.6 and 4.7, respectively. It is observed that none of the DFM models were able to predict more than 90 % of the void fraction data in the error bands of $\pm 20\%$ whereas in the category of DFM correlations Cai et al. (1997)^S, Gomez et al. (2000), Hasan (1995), Rouhani and Axelsson (1970)¹ and Usui and Sato (1989)^S give impressive results with accurate prediction of more than 90%

of the data set of Yijun and Rezkallah (1993) within the $\pm 20\%$ error bands and RMS error less than 15%. A comparatively low performance of these correlations for the data set of Usui and Sato (1989) is unexpected. Since the accuracy of this experimentally measured void fraction data is not known; the comparison and hence the performance of the void fraction correlations cannot be concluded. It is speculated that the correlations of Usui and Sato (1989) for falling film and slug flow do not perform well because these correlations are flow pattern dependent and performance of the correlations shown in Table 4.7 is for the entire range of the void fraction data by Usui and Sato (1989).

Table 4.7 Comparison of prediction of void fraction correlations for Usui and Sato (1989) air-water fluid combination (25) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	36	60	68	76	21.7
Armand (1946), Chisholm (1983)	60	72	80	88	18.5
Beggs (1972)	8.0	24	32	44	306.9
Chisholm (1973)	60	72	80	88	18.5
Mukherjee (1979)	20	36	60	72	73
Usui and Sato (1989) ^{FF}	16	68	76	76	186.7
Yamazaki and Yamaguchi (1979)	36	60	72	92	18.9
Bonnecaze et al. (1971)	52	76	92	100	13.1
Cai et al. (1997) ^B	72	76	92	100	10.8
Cai et al. (1997) ^S	52	76	88	100	12.9
Clark and Flemmer (1985)	68	76	84	100	11.8
Dix (1971)	44	52	60	64.0	32.6
Goda et al. (2003)	44	68	80	88	19.0
Gomez et al. (2000)	52	76	80	100	12.8
Hasan (1995)	68	72	80	100	13.5
Huq and Loath (1992)	56	68	76	80	20.3
Kawanishi et al. (1990)	24	36	40	52	39
Kokal and Stainslav (1989)	52	72	88	100	13.2
Nicklin et al. (1962)	52	76	92	100	13.1
Rouhani and Axelsson (1970) ¹	56	88	96	100	10.3
Sun et al. (1981)	76	84	96	100	9.5
Usui and Sato (1989) ^S	56	72	76	88	17.9
Woldesemayat and Ghajar (2007)	32	44	56	68	63.9
Zuber and Findlay (1964)	68	84	96	100	9.9

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Table 4.8 Comparison of prediction of void fraction correlations for Paras (1982) air-water fluid combination (35) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	48.6	57.1	65.7	88.6	18.3
Armand (1946), Chisholm (1983)	68.6	91.4	100	100	9.4
Beggs (1972)	22.9	37.1	40	40	195.8
Chisholm (1973)	68.6	91.4	100	100	9.3
Mukherjee (1979)	11.4	22.9	48.6	68.6	46.9
Usui and Sato (1989) ^{FF}	2.9	14.3	22.9	42.9	120.9
Yamazaki and Yamaguchi (1979)	71.4	94.3	100	100	8.6
Bonnecaze et al. (1971)	65.7	82.9	91.4	100	10.9
Cai et al. (1997) ^B	62.9	82.9	85.7	100	12.5
Cai et al. (1997) ^S	62.9	80	88.6	100	12.1
Clark and Flemmer (1985)	57.1	82.9	82.9	97.1	13.4
Dix (1971)	60.0	77.1	85.7	97.1	13.8
Goda et al. (2003)	62.9	74.3	91.4	100	12.3
Gomez et al. (2000)	60	82.9	85.7	100	11.8
Hasan (1995)	51.4	80	85.7	94.3	13.7
Huq and Loath (1992)	40	65.7	91.4	100	13.5
Kawanishi et al. (1990)	2.9	8.6	17.1	40.0	39.6
Kokal and Stainslav (1989)	65.7	82.9	91.4	100	10.9
Nicklin et al. (1962)	65.7	82.9	91.4	100	10.9
Rouhani and Axelsson (1970) ¹	80.0	85.7	91.4	100	10.1
Sun et al. (1981)	71.4	82.9	91.4	100	11.0
Usui and Sato (1989) ^S	17.1	40	54.3	82.9	24.2
Woldesemayat and Ghajar (2007)	11.4	31.4	51.4	68.6	41.8
Zuber and Findlay (1964)	68.57	80	85.71	100	15.37

^B - Bubbly, ^S - Slug, ^{FF} - Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The majority of the Paras (1982) data was concentrated in the void fraction range of $0.3 < \alpha < 0.75$. As listed in Table 4.8, among all the correlations evaluated for this dataset Yamazaki and Yamaguchi (1979) gave the outstanding performance by predicting more than 94% of the data within $\pm 15\%$ and 100% of the data in $\pm 20\%$ error bands. The non DFM correlations of Chisholm (1983), Armand (1946) and Chisholm (1983) were also among the top performers. This was the only data set in which the non DFM models

outweighed the DFM correlations. In the category of DFM correlations with a slightly relaxed tolerance of $\pm 20\%$ seven correlations were able to forecast more than 90% of the data accurately.

Table 4.9 Comparison of prediction of void fraction correlations for Mukherjee (1979) air-oil fluid combination (48) data points

Correlation	Percentage of data points predicted within				RMS error %
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	25.0	72.9	91.7	95.8	15.2
Armand (1946), Chisholm (1983)	75.0	89.6	91.7	93.8	12.8
Beggs (1972)	56.3	66.7	83.3	87.5	36.7
Chisholm (1973)	77.1	89.6	91.7	93.8	12.7
Mukherjee (1979)	0	0	0	4.2	583.8
Usui and Sato (1989) ^{FF}	58.3	64.6	72.9	85.4	43.1
Yamazaki and Yamaguchi (1979)	81.3	91.7	93.8	95.8	10.6
Bonnecaze et al. (1971)	79.2	83.3	91.7	95.8	11.3
Cai et al. (1997) ^B	77.1	83.3	93.8	95.8	11.3
Cai et al. (1997) ^S	79.2	91.7	95.8	97.9	11.4
Clark and Flemmer (1985)	77.1	91.7	93.8	95.8	11.3
Dix (1971)	66.7	81.3	87.5	89.6	17.1
Goda et al. (2003)	89.6	91.7	93.8	93.8	11.9
Gomez et al. (2000)	79.2	93.8	95.8	97.9	8.5
Hasan (1995)	75.0	91.7	95.8	97.9	12.4
Huq and Loath (1992)	72.9	83.3	89.6	93.8	14.8
Kawanishi et al. (1990)	58.3	66.7	77.1	85.4	24.7
Kokal and Stainslav (1989)	79.2	83.3	91.7	95.8	11.3
Nicklin et al. (1962)	79.2	83.3	91.7	95.8	11.3
Rouhani and Axelsson (1970) ¹	77.1	91.7	91.7	97.9	10.8
Sun et al. (1981)	79.2	83.3	91.7	95.8	11.0
Usui and Sato (1989) ^S	2.1	10.4	16.7	27.1	40.8
Woldesemayat and Ghajar (2007)	87.5	87.5	91.7	95.8	10.5
Zuber and Findlay (1964)	79.16	83.33	93.75	95.83	11.4

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The performance of all the correlations analyzed in the present study for air-oil and air-kerosene data set of Mukherjee (1979) as shown in Tables 4.9 and 4.10, was of

real interest due to the different fluid combination used in the experimentation. In the category of non DFM models Yamazaki and Yamaguchi (1979) was the only correlation to be able to predict more than 90% of the void fraction data for both fluid combinations and within the error tolerance of $\pm 15\%$. In the group of DFM, quite a few correlations performed satisfactorily with predicting more than 90% of the void fraction data within $\pm 15\%$ error bands. The Gomez et al. (2000) was the most successful correlation satisfying the criteria with accuracy of 93.8% and 90.6% within $\pm 15\%$ error bands and the %RMS error of 8.5% and 10.6% for each dataset, respectively.

Table 4.10 Comparison of prediction of void fraction correlations for Mukherjee (1979) air-kerosene fluid combination (52) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	54.7	86.8	94.3	94.3	17.2
Armand (1946), Chisholm (1983)	79.2	90.6	90.6	92.5	17.8
Beggs (1972)	56.6	73.6	81.1	83.0	41.7
Chisholm (1973)	81.1	90.6	90.6	92.5	17.6
Mukherjee (1979)	73.6	86.8	88.7	94.3	15.1
Usui and Sato (1989) ^{FF}	43.4	69.8	83.0	96.2	20.9
Yamazaki and Yamaguchi (1979)	84.9	90.6	92.5	94.3	16.5
Bonnecaze et al. (1971)	66	90.6	96.2	96.2	50.3
Cai et al. (1997) ^B	83.0	92.5	96.2	96.2	68.2
Cai et al. (1997) ^S	83.0	88.7	92.5	98.1	43.2
Clark and Flemmer (1985)	84.9	92.5	94.3	96.2	60.8
Dix (1971)	71.7	84.9	88.7	92.5	22.8
Goda et al. (2003)	71.7	86.8	92.5	94.3	20.1
Gomez et al. (2000)	83.0	90.6	96.2	96.2	10.6
Hasan (1995)	84.9	90.6	90.6	96.2	39.2
Huq and Loath (1992)	67.9	84.9	90.6	92.5	19.0
Kawanishi et al. (1990)	73.6	84.9	86.8	90.6	39.6
Kokal and Stainslav (1989)	67.9	90.6	96.2	96.2	54.5
Nicklin et al. (1962)	66.0	90.6	96.2	96.2	48.4
Rouhani and Axelsson (1970) ¹	83.0	92.5	94.3	96.2	13.8
Sun et al. (1981)	77.4	90.6	96.2	96.2	383.6
Usui and Sato (1989) ^S	0	1.9	7.5	54.7	81.0
Woldesemayat and Ghajar (2007)	84.9	86.8	88.7	94.3	15.0
Zuber and Findlay (1964)	67.73	90.56	96.22	96.22	78.5

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The Cai et al. (1997) correlations for the bubbly and the slug flow were expected to perform really well for the air-oil data set as documented in Table 4.9, since the distribution parameters (C_o) in these two equations were proposed based on the air-oil data.

Table 4.11 Comparison of prediction of void fraction correlations for Lorenzi and Stogia (1976) air-water fluid combination (71) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	42.3	52.1	60.6	74.6	22.4
Armand (1946), Chisholm (1983)	33.8	45.1	54.9	74.6	24.1
Beggs (1972)	0	0	1.4	2.8	1286.8
Chisholm (1973)	33.8	45.1	54.9	74.6	24.1
Mukherjee (1979)	0	0	0	0	324.1
Usui and Sato (1989) ^{FF}	0	0	0	0	1605.5
Yamazaki and Yamaguchi (1979)	31.0	47.9	63.4	81.7	22.8
Bonnecaze et al. (1971)	25.4	56.3	77.5	97.2	16.7
Cai et al. (1997) ^B	47.9	70.4	85.9	100	13.6
Cai et al. (1997) ^S	52.1	71.8	88.7	100	12.9
Clark and Flemmer (1985)	56.3	76.1	93.0	100	12.4
Dix (1971)	5.6	7	12.6	31.0	57.8
Goda et al. (2003)	22.9	39.4	49.3	66.2	30.1
Gomez et al. (2000)	62.0	80.3	93.0	100	11.5
Hasan (1995) ^I	69.0	83.1	94.4	100	10.5
Huq and Loath (1992)	22.5	39.4	49.9	69.0	25.7
Kawanishi et al. (1990)	5.6	16.9	35.2	83.1	24.5
Kokal and Stainslav (1989)	25.4	56.3	76.1	95.8	17.0
Nicklin et al. (1962)	25.4	56.3	77.5	97.2	16.7
Rouhani and Axelsson (1970) ^I	39.4	53.4	66.2	87.3	18.6
Sun et al. (1981)	15.5	49.3	71.8	94.4	17.7
Usui and Sato (1989) ^S	4.2	12.7	26.8	77.5	26.7
Woldesemayat and Ghajar (2007)	0	0	0	0	246.5
Zuber and Findlay (1964)	30.98	67.60	83.09	98.59	14.8

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ^I reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The two data set of Lorenzi and Stogia (1976) for pipe diameter of 0.09 and 0.044 m, respectively, consisted the lower range of the void fraction typically from 0 – 0.25. Mukherjee (1979) and Woldesemayat and Ghajar (2007) failed in predicting even a single data point within $\pm 30\%$ error bands. The reason for the bad performance of the Woldesemayat and Ghajar (2007) correlation could be attributed to the fact that this

correlation was essentially developed for the horizontal, inclined and vertical upward two phase flow and the drift velocity term used in this equation approach a zero value for the vertical downward inclination resulting in the higher percentage error in the lower range of the void fraction. The bad performance of the Usui and Sato (1989)^{FF} correlation was expected since this equation was derived for the falling film regime or alternatively the higher range of the void fraction. This consequence can be inferred as that the Usui and Sato (1989)^{FF} correlation is a flow pattern specific and cannot be applied outside the void fraction range it is designed for. For this low range of the void fraction data Gomez et al. (2000) proved to be the most competent correlation with accuracy of 93% and 95.5% within $\pm 20\%$ error bands and the %RMS error of 11.5% and 13.4% for the 0.09 and 0.044 m diameter pipes, respectively. The performances of all the correlations used for the two data sets of Lorenzi and Stogia (1976) are shown in Tables 4.11 and 4.12, respectively. The results of the void fraction correlation for the data set of Nguyen (1975) and Oshinowo (1971) for air-water fluid combination are shown in Tables 4.13 and 4.14, respectively. Most of the correlations performed satisfactorily predicting more than 90% of the void fraction data within $\pm 15\%$ error bands and % RMS error of less than 10%. Undoubtedly Gomez et al. (2000) was among the top performers.

Another fluid combination that was used to verify the void fraction correlations in this study was air-glycerin combination with 78 void fraction data points available in the data of Oshinowo (1971). This was the only data set available in the literature in which the liquid phase density was higher than that of the water. Most of the DFM correlations gave excellent results for this data with once again Gomez et al. (2000) correlation being

one of the top performers. The comparison of the predictions of the void fraction correlations against the air-glycerin data of Oshinowo (1971) are shown in Table 4.15.

Table 4.12 Comparison of prediction of void fraction correlations for Lorenzi and Stogia (1976) air-water fluid combination (44) data points

Correlation	Percentage of data points predicted within				RMS error %
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	4.5	13.6	27.3	40.9	32.4
Armand (1946), Chisholm (1983)	0.0	9.1	22.7	36.4	33.7
Beggs (1972)	0.0	0.0	0.0	2.3	388.2
Chisholm (1973)	0.0	9.1	22.7	36.4	33.7
Mukherjee (1979)	0.0	0.0	0.0	0.0	352.6
Usui and Sato (1989) ^{FF}	0.0	0.0	0.0	0.0	2239.2
Yamazaki and Yamaguchi (1979)	31.8	70.5	93.2	95.5	14.6
Bonnecaze et al. (1971)	79.5	88.6	97.7	100.0	9.0
Cai et al. (1997) ^B	18.2	54.5	81.8	100	16.0
Cai et al. (1997) ^S	61.4	79.5	86.4	100	11.5
Clark and Flemmer (1985)	25.0	56.8	93.2	100	14.5
Dix (1971)	2.3	9.1	18.2	40.9	36.8
Goda et al. (2003)	0.0	2.3	11.4	27.3	42.7
Gomez et al. (2000)	36.4	68.2	95.5	100	13.4
Hasan (1995)	59.1	63.6	75.0	93.2	15.8
Huq and Loath (1992)	0.0	0.0	20.5	31.8	34.9
Kawanishi et al. (1990)	6.8	9.1	29.5	79.5	26.2
Kokal and Stainslav (1989)	79.5	90.5	97.7	100.0	8.8
Nicklin et al. (1962)	79.5	88.6	97.7	100	9.0
Rouhani and Axelsson (1970) ¹	2.3	11.4	25.0	61.4	28.7
Sun et al. (1981)	2.3	15.9	45.5	97.7	21.4
Usui and Sato (1989) ^S	0.0	0.0	2.3	4.5	114.3
Woldesemayat and Ghajar (2007)	0.0	0.0	0.0	0.0	254.1
Zuber and Findlay (1964)	13.63	43.18	77.27	97.72	17.2

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Table 4.13 Comparison of prediction of void fraction correlations for Nguyen (1975) air-water fluid combination (79) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	57.0	78.5	91.1	97.5	12.9
Armand (1946), Chisholm (1983)	93.7	93.7	97.5	97.5	8.7
Beggs (1972)	53.2	72.2	83.5	92.4	59.1
Chisholm (1973)	93.7	93.7	97.5	97.5	8.6
Mukherjee (1979)	81.0	94.9	94.9	96.2	26.9
Usui and Sato (1989) ^{FF}	34.2	82.3	93.7	93.7	89.6
Yamazaki and Yamaguchi (1979)	92.4	93.7	96.2	97.5	7.8
Bonnecaze et al. (1971)	54.4	92.4	97.5	97.5	11.7
Cai et al. (1997) ^B	67.1	97.5	97.5	97.5	10.8
Cai et al. (1997) ^S	83.5	97.5	97.5	97.5	9.4
Clark and Flemmer (1985)	72.2	97.5	97.5	97.5	10.1
Dix (1971)	89.9	92.4	93.7	96.2	10.0
Goda et al. (2003)	86.1	94.9	97.5	97.5	10.0
Gomez et al. (2000)	79.7	97.5	97.5	97.5	9.7
Hasan (1995)	91.1	96.2	97.5	97.5	8.7
Huq and Loath (1992)	91.1	93.7	93.7	97.6	9.5
Kawanishi et al. (1990)	59.5	93.7	94.9	97.5	12.0
Kokal and Stainslav (1989)	54.4	92.4	97.5	97.5	11.7
Nicklin et al. (1962)	54.4	92.4	97.5	97.5	11.7
Rouhani and Axelsson (1970) ¹	92.4	97.5	97.5	97.5	9.6
Sun et al. (1981)	49.4	87.3	97.5	97.5	12.4
Usui and Sato (1989) ^S	0.0	2.5	27.8	73.4	27.3
Woldesemayat and Ghajar (2007)	92.4	94.9	96.2	96.2	23.4
Zuber and Findlay (1964)	55.69	93.67	97.46	97.46	11.5

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Table 4.14 Comparison of prediction of void fraction correlations for Oshinowo (1971) air-water fluid combination (112) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	43.8	72.3	88.4	98.2	14.0
Armand (1946), Chisholm (1983)	79.5	91.1	97.3	99.1	8.3
Beggs (1972)	29.5	40.2	52.7	63.4	302.6
Chisholm (1973)	80.4	91.1	97.3	99.1	8.3
Mukherjee (1979)	46.4	73.2	79.5	82.1	72.5
Usui and Sato (1989) ^{FF}	17.0	55.4	72.3	75.0	206.8
Yamazaki and Yamaguchi (1979)	85.7	87.5	89.3	93.8	12.5
Bonnecaze et al. (1971)	81.3	96.4	98.2	100	7.8
Cai et al. (1997) ^B	91.1	98.2	99.1	100	6.6
Cai et al. (1997) ^S	89.3	96.4	99.1	100	6.7
Clark and Flemmer (1985)	92.0	98.2	99.1	100	6.5
Dix (1971)	69.6	75.9	83.0	89.3	22.7
Goda et al. (2003)	85.7	96.4	98.2	100.0	6.9
Gomez et al. (2000)	92.0	97.3	99.1	100	6.9
Hasan (1995)	83.9	97.3	99.1	99.1	7.4
Huq and Loath (1992)	67.0	79.5	92.0	99.1	11.0
Kawanishi et al. (1990)	58.9	74.1	75.0	83.9	18.1
Kokal and Stainslav (1989)	81.3	96.4	98.2	100	7.8
Nicklin et al. (1962)	81.3	96.4	98.2	100	7.8
Rouhani and Axelsson (1970) ¹	91.1	98.2	99.1	100	6.4
Sun et al. (1981)	84.8	97.3	98.2	100	7.4
Usui and Sato (1989) ^S	3.6	17	44.6	84.8	23.4
Woldesemayat and Ghajar (2007)	70.5	76.8	79.5	82.1	57.8
Zuber and Findlay (1964)	89.28	97.32	98.21	99.10	6.9

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Table 4.15 Comparison of prediction of void fraction correlations for Oshinowo (1971) air-glycerin fluid combination (78) data points

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	52.6	74.4	91.0	100	12.9
Armand (1946), Chisholm (1983)	79.5	91.0	98.7	100	7.9
Beggs (1972)	52.6	66.7	70.5	78.2	334.4
Chisholm (1973)	79.5	91.0	98.7	100	8.0
Mukherjee (1979)	53.8	75.6	79.5	80.8	67.9
Usui and Sato (1989) ^{FF}	61.5	75.6	75.6	75.6	239.3
Yamazaki and Yamaguchi (1979)	87.2	89.7	92.3	96.2	10.1
Bonnecaze et al. (1971)	80.8	94.9	97.7	100	7.9
Cai et al. (1997) ^B	82.1	96.2	100	100	7.2
Cai et al. (1997) ^S	84.6	97.4	100	100	7.0
Clark and Flemmer (1985)	80.8	94.9	100	100	7.2
Dix (1971)	53.8	67.9	74.4	87.2	22.2
Goda et al. (2003)	82.1	96.2	98.7	100	7.1
Gomez et al. (2000)	91.0	97.4	100	100	5.9
Hasan (1995)	82.1	91.0	100	100	7.8
Huq and Loath (1992)	75.6	82.1	92.3	100	10.5
Kawanishi et al. (1990)	50.0	55.1	65.4	76.9	23.1
Kokal and Stainslav (1989)	79.5	94.9	97.4	100	8.0
Nicklin et al. (1962)	80.8	94.9	97.4	100	7.9
Rouhani and Axelsson (1970) ¹	92.3	97.4	100	100	5.5
Sun et al. (1981)	78.2	97.4	98.7	100	7.7
Usui and Sato (1989) ^S	2.6	10.3	25.6	73.1	26.8
Woldesemayat and Ghajar (2007)	79.5	79.5	79.5	79.5	61.3
Zuber and Findlay (1964)	82.05	97.43	98.71	100	7.3

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

This comparison of the performance of the void fraction correlations against the individual data set revealed that the non DFM models were of no use with the exception of Yamazaki and Yamaguchi (1979) correlation. It was also observed that some of the DFM correlations available in the literature consistently performed satisfactorily for every database and can be considered as the nominees for the selection and ranking of the

best correlation for the downward two phase flow. The next step of performance gauging of the void fraction correlations is focused on the different ranges of the void fraction approximating the flow regimes.

4.2.4 Performance of the correlations for different ranges of the void fraction

As justified earlier in this section the selected ranges of the void fraction for performance evaluation approximate the flow patterns in the downward two phase flow. The analysis calculated values of the void fraction correlations in the range of 0 – 0.25, 0.25 – 0.5, 0.5 – 0.75 and 0.75 – 1 are presented below.

For the performance evaluation of the correlations it was necessary to set the criterion in terms of the acceptable error or desired accuracy in the prediction of the void fraction. In the literature there is no well defined or universal definition to evaluate the performance of the correlations. The criteria set for this evaluation is based on the prediction results of the correlations in the present study for different ranges of the void fraction. The dialogue in the previous chapters concludes that the void fraction in the lower range of 0 – 0.25 is very sensitive to the increase in the gas flow rate and yields higher percentage error due to the smaller values of the void fraction. Hence the acceptable error associated with the void fraction range is relaxed to a higher limit. For the higher values of the void fraction 0.75 – 1, the percentage error between the predicted and measured void fraction was found to be less in comparison to the void fraction range of 0 – 0.25 and hence a more stringent criteria was set to determine the satisfactory performance of the void fraction correlations. The criteria used in the present study to determine the performance of the void fraction correlations is listed in Table 4.16.

Table 4.16 Criteria to determine the performance of the void fraction correlations

Void Fraction Range	Criteria
0.0-1.0	At least more than 85% of points are within $\pm 10\%$ and more than 90% of points within $\pm 15\%$ and RMS error $< 15\%$
0 – 0.25	At least more than 85 % of points are within $\pm 20\%$ and RMS error $< 15\%$
0.25 – 0.50	At least more than 80 % of points are within $\pm 15\%$ and RMS error $< 15\%$
0.50 – 0.75	At least more than 80 % of points are within $\pm 15\%$ and RMS error $< 15\%$
0.75 – 1.0	At least more than 90% of points are within $\pm 15\%$ and RMS error $< 10\%$

Performance of the correlations for $0 < \alpha \leq 0.25$

For the void fraction range of $0 < \alpha \leq 0.25$, all the correlations available in the literature and documented in the present study were evaluated against a data set of 237 data points. As expected very little accuracy was achieved in narrow error bands of $\pm 10\%$ due to lower values of the void fraction. Hence for a relaxed criterion as mentioned in Table 4.16, the non DFM correlations did not work satisfactorily at all in this low range of the void fraction. The accuracy of the non DFM correlations in this low range is reported in Table 4.17.

Table 4.17 Performance evaluation of the correlations for $0 < \alpha \leq 0.25$

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	46	61.2	69.2	78.5	20.7
Armand (1946), Chisholm (1983)	37.6	54.4	67.5	76.8	22.1
Beggs (1972)	2.1	2.5	3.8	5.5	745.2
Chisholm (1973)	37.6	54.4	67.5	76.8	22.1
Mukherjee (1979)	0	0	0	0.4	267.8
Usui and Sato (1989) ^{FF}	0.4	0.4	0.8	1.3	1359.2
Yamazaki and Yamaguchi (1979)	33.8	51.9	68.4	83.1	22.4

^{FF}- Falling Film, indicate two or more flow pattern specific correlations given by same author

In the class of the DFM correlations, eight correlations were found to predict the void fraction satisfactorily with Gomez et al. (2000) having a maximum accuracy of 62.9%, 79.3 %, and 93.7% in $\pm 10\%$, $\pm 15\%$ and $\pm 20\%$ error bands, respectively. As documented in Table 4.18 this correlation is followed by Cai et al. (1997)^S and Clark and Flemmer (1985) correlations. It should be noted that Gomez et al. (2000) and Clark and Flemmer (1985) correlations are proposed for the bubbly flow and are based on the concept of the drift flux model. Among the other top eight performers were Bonnecaze et al. (1971), Nicklin et al. (1962) and Kokal and Stainslav (1989) giving an accuracy of 88.2%, 88.2% and 86.9% in error bands of $\pm 20\%$, respectively. The RMS error associated with these correlations was less than 15%.

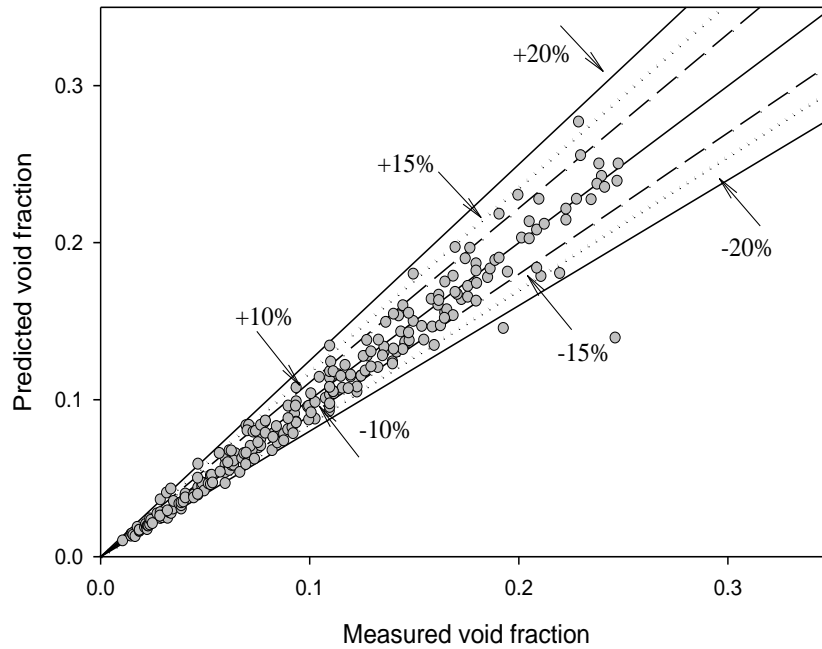


Figure 4.12 Performance of Gomez et al. (2000) correlation for $0 < \alpha \leq 0.25$

The Cai et al. (1997)^S and Clark and Flemmer (1985) gave competitive results with accuracy of 91.6% and 90.7% in the error bands of $\pm 15\%$ and $\pm 20\%$, respectively. Both of the correlations were based on the drift flux concept with only slight modification in the distribution parameter (C_o) while keeping other terms in the model intact. These results conclude that the DFM correlations are most suitable to calculate the void fraction in the lower region of void fraction or alternately in the bubbly flow regime. This is by the virtue of the drift velocity term in DFM that accounts for the interaction between the two phases. For this lower range of the void fraction $0 < \alpha \leq 0.25$, Gomez et al. (2000) correlation is recommended. The performance of the Gomez et al. (2000) correlation is shown in Figure 4.12.

Table 4.18 Performance evaluation of the DFM correlations for $0 < \alpha \leq 0.25$

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Bonnecaze et al. (1971)	48.5	73.5	88.2	98.3	13.5
Cai et al. (1997) ^B	54	73	87.8	99.6	12.9
Cai et al. (1997) ^S	62	80.2	91.6	99.6	11.5
Clark and Flemmer (1985)	57	74.7	90.7	99.6	12.4
Dix (1971)	8.9	14.3	23.2	40.1	50.8
Goda et al. (2003)	31.2	46.8	59.1	72.6	27.8
Gomez et al. (2000)	62.9	79.3	93.7	99.6	11.4
Hasan (1995)	70.9	81	91.6	98.3	11.5
Huq and Loath (1992)	24.5	42.2	61.6	74.3	23.8
Kawanishi et al. (1990)	8	13.5	25.7	60.3	35.6
Kokal and Stainslav (1989)	48.1	73.4	86.9	97.9	13.6
Nicklin et al. (1962)	48.5	73.4	88.2	98.3	13.5
Rouhani and Axelsson (1970) ¹	48.9	65	73.8	88.6	17.5
Sun et al. (1981)	40.9	61.6	77.2	97.5	15.4
Usui and Sato (1989) ^S	21.1	29.2	40.7	64.4	54.1
Woldesemayat and Ghajar (2007)	0	0.4	0.4	0.8	203.3
Zuber and Findlay (1964)	46.4	68.8	87.3	98.7	13.6

^B- Bubbly, ^S- Slug, indicate two or more flow pattern specific correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Performance of the correlations for $0.25 < \alpha \leq 0.5$

This range of the void fraction approximated the slug flow regime with 107 data points from the entire dataset and due to higher values of the void fraction, the performance criteria used for satisfactory performance was stricter than the earlier range. The top performing correlations are shortlisted if they predict more than 80% of points in error bands of $\pm 15\%$. It is evident from Table 4.19 that among the non DFM models only Yamazaki and Yamaguchi (1979) satisfied the criteria with percentage accuracy of 92.4% within error bands of $\pm 15\%$ and RMS error of 10.4%. Yamazaki and Yamaguchi (1979) claimed their correlation to predict the void fraction data within $\pm 20\%$ error bands but did

not mention the percentage of the data points to be within the criterion. Though this correlation failed in the lower range of $0 < \alpha \leq 0.25$, it successfully predicted more than 95% data points for next higher ranges of the void fraction and within the $\pm 20\%$ error restriction criterion.

Table 4.19 Performance evaluation of the correlations for $0.25 < \alpha \leq 0.5$

Correlation	Percentage of data points predicted within				RMS error %
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	50.5	73.3	84.8	95.2	14.2
Armand (1946), Chisholm (1983)	52.4	72.4	94.3	96.2	13.9
Beggs (1972)	29.5	38.1	40	41.0	121.5
Chisholm (1973)	53.3	72.4	94.3	96.2	13.9
Mukherjee (1979)	18.1	33.3	50.5	71.4	27.9
Usui and Sato (1989) ^{FF}	9.5	17.3	23.1	31.7	66.8
Yamazaki and Yamaguchi (1979)	75.2	92.4	94.3	97.1	10.4

^{FF} - Falling Film, indicate two or more flow pattern specific correlations given by same author

A dozen of DFM correlations as shown in Table 4.20 were successful in satisfying the criteria set for this void fraction range. Bonnecaze et al. (1971), Nicklin et al. (1962), Rouhani and Axelsson (1970)^a were the top performers predicting 91.4% of data points each within error bands of $\pm 15\%$ with RMS error of 10.2%, respectively. The high accuracy of the first two correlations was anticipated since they were developed exclusively for the slug flow. Cai et al. (1997)^S, Kokal and Stainslav (1989) and Gomez et al. (2000) were among the other competent correlations. Gomez et al. (2000) successfully predicted 89.5% of the data points within the restricted $\pm 15\%$ error bands. The prediction of the void fraction in this range is difficult due to intermittent nature of the two phase flow. The DFM correlations by Nicklin et al. (1962) and Bonnecaze et al. (1971) considers the terminal velocity of a single bubble which is essentially the drift velocity of a single bubble through a stagnant liquid column. The Bonnecaze et al. (1971) correlation is same as that of the Nicklin et al. (1962) equation with the terminal velocity

of the bubble expressed in terms of non dimensional velocity or the Froude number. The performance of the Yamazaki and Yamaguchi (1979) and Gomez et al. (2000) correlations is presented graphically in Figures 4.13 and 4.14, respectively.

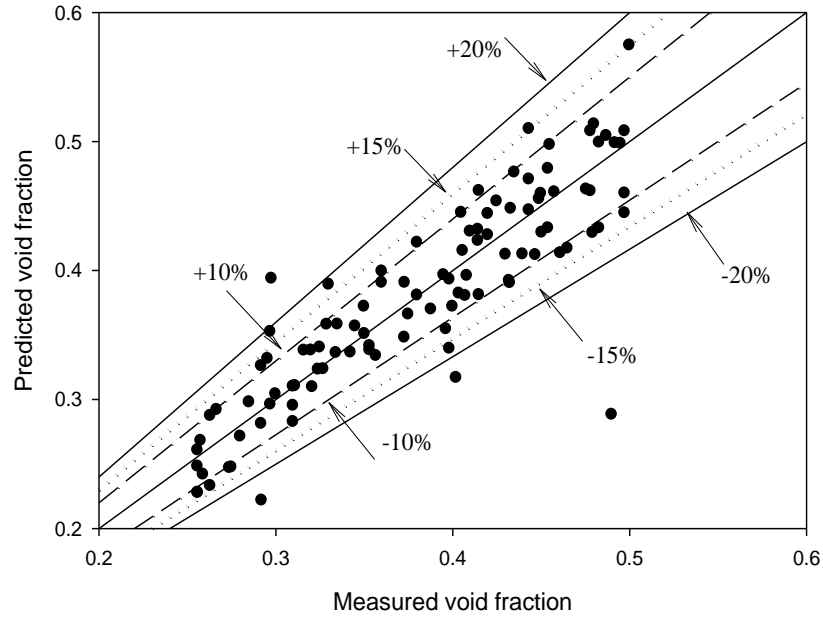


Figure 4.13 Performance of Yamazaki and Yamaguchi (1979) correlation for $0.25 < \alpha \leq 0.5$

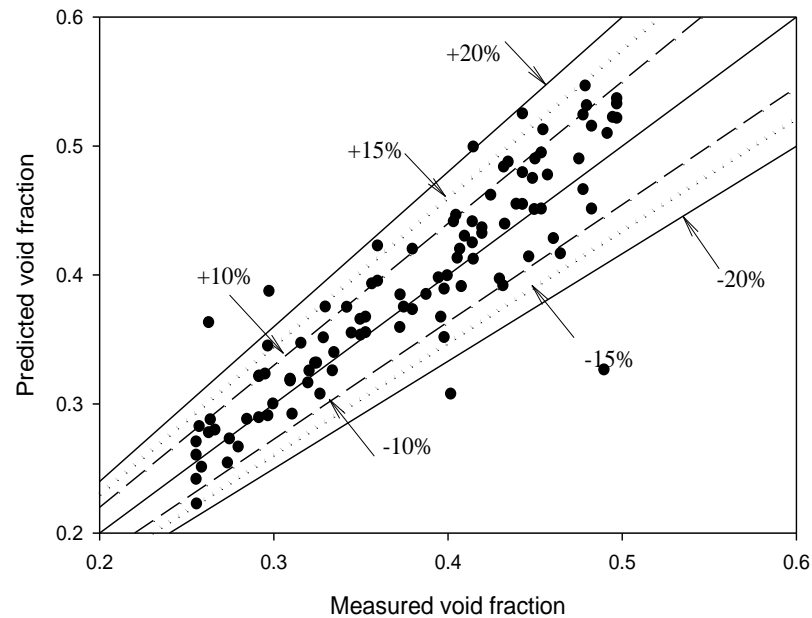


Figure 4.14 Performance of Gomez et al. (2000) correlation for $0.25 < \alpha \leq 0.5$

Table 4.20 Performance evaluation of the DFM correlations for $0.25 < \alpha \leq 0.50$

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Bonnecaze et al. (1971)	75.2	91.4	96.2	98.1	10.2
Cai et al. (1997) ^B	74.3	84.8	90.5	95.2	12.8
Cai et al. (1997) ^S	82.9	90.5	95.2	99.0	9.5
Clark and Flemmer (1985)	70.5	81.9	86.7	95.2	13.6
Dix (1971)	47.6	59.0	75.2	86.7	19.7
Goda et al. (2003)	71.4	82.9	92.4	95.2	13.3
Gomez et al. (2000)	78.1	89.5	92.4	97.1	10.7
Hasan (1995) ¹	77.1	89.5	92.4	98.1	10.1
Huq and Loath (1992)	17.1	44.8	67.6	95.2	18.9
Kawanishi et al. (1990)	12.4	22.9	31.4	46.7	42.1
Kokal and Stainslav (1989)	75.2	90.5	96.2	98.1	10.2
Nicklin et al. (1962)	75.2	91.4	96.2	98.1	10.2
Rouhani and Axelsson (1970) ¹	77.1	91.4	94.3	98.1	9.9
Sun et al. (1981)	75.2	89.5	93.3	97.1	10.8
Usui and Sato (1989) ^S	41	59.6	72.1	88.5	21.0
Woldesemayat and Ghajar (2007)	21.9	39.0	55.2	75.2	23.8
Zuber and Findlay (1964)	76.2	84.8	91.4	96.2	12.2

^B- Bubbly, ^S- Slug, indicate two or more flow pattern specific correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Performance of the correlations for $0.5 < \alpha \leq 0.75$

The next higher range of the void fraction approximated partially the slug flow and the froth flow regimes and consisted of 126 data points from the entire data set. The satisfactory performance criteria set for this range is similar to the previous range of the void fraction. Among the non DFM correlations Mukherjee (1979) and Yamazaki and Yamaguchi (1979) were found to predict 82.5% and 87.3% of the data points within the tolerance of $\pm 15\%$, respectively. This is the only range where Mukherjee (1979) performs within the set criterion but with considerable high RMS error of 18.9%. The reason may be that the Mukherjee (1979) correlation was developed using a regression tool without

much emphasizing the physical interaction of the two phases and was based only on his own data set. The prediction of the non DFM correlations for the range of $0.5 < \alpha \leq 0.75$ are presented in Table 4.21. The performance of the Mukherjee (1979) and Yamazaki and Yamaguchi (1979) is depicted graphically in Figures 4.15 and 4.16, respectively.

Table 4.21 Performance evaluation of the correlations for $0.5 < \alpha \leq 0.75$

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	31.7	46.0	67.5	91.3	18.7
Armand (1946), Chisholm (1983)	56.3	75.4	88.1	98.4	12.8
Beggs (1972)	40.5	49.2	54.8	54.8	36.3
Chisholm (1973)	56.3	75.4	88.1	98.4	12.7
Mukherjee (1979)	67.5	82.5	89.7	92.1	18.9
Usui and Sato (1989) ^{FF}	45.2	67.2	81.6	88.8	19.3
Yamazaki and Yamaguchi (1979)	73.8	87.3	96.8	99.2	9.7

^{FF} - Falling Film, indicate two or more flow pattern specific correlations given by same author

In the category of DFM a total of thirteen correlations qualified the set criteria. Woldesemayat and Ghajar (2007) emerged as the most successful candidate with an accuracy of 92.1% within $\pm 15\%$ error bands and RMS error of 8.2%. It was followed by Gomez et al. (2000) and Rouhani and Axelsson (1970)¹ with a maximum accuracy of 86.5% each within the tolerance of $\pm 15\%$ but with an RMS error of 10.3% and 9.7%, respectively. The other top performing correlations were those appeared in the previous ranges of the void fraction with an addition of Sun et al. (1981) to the list. The performance of all the successful DFM correlations for the range of $0.5 - 0.75$ is presented in Table 4.22. The graphical illustration of the prediction of the two best DFM correlations namely Gomez et al. (2000) and Woldesemayat and Ghajar (2007) in the range of $0.5 < \alpha \leq 0.75$ is illustrated in Figures 4.17 and 4.18, correspondingly.

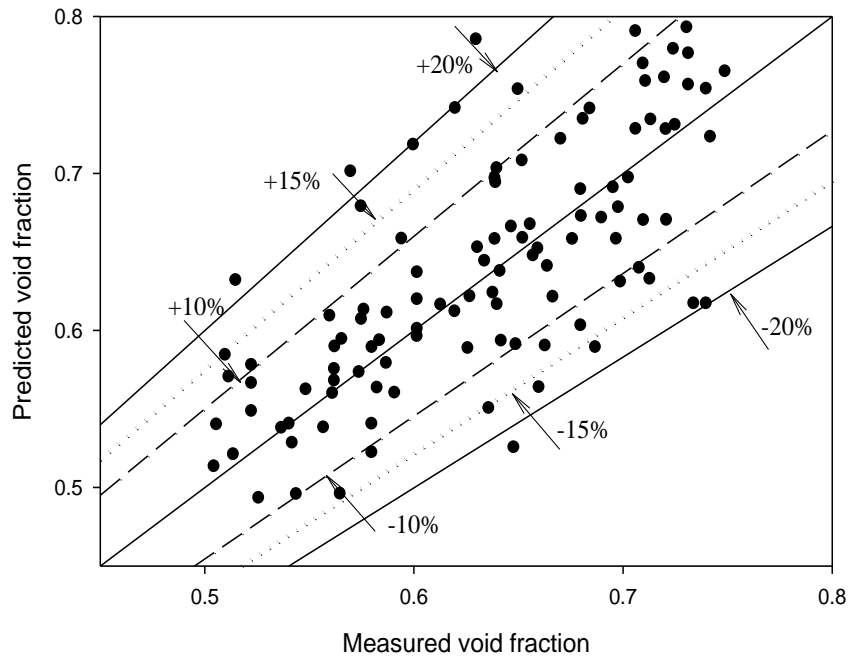


Figure 4.15 Performance of Mukherjee (1979) correlation for $0.5 < \alpha \leq 0.75$

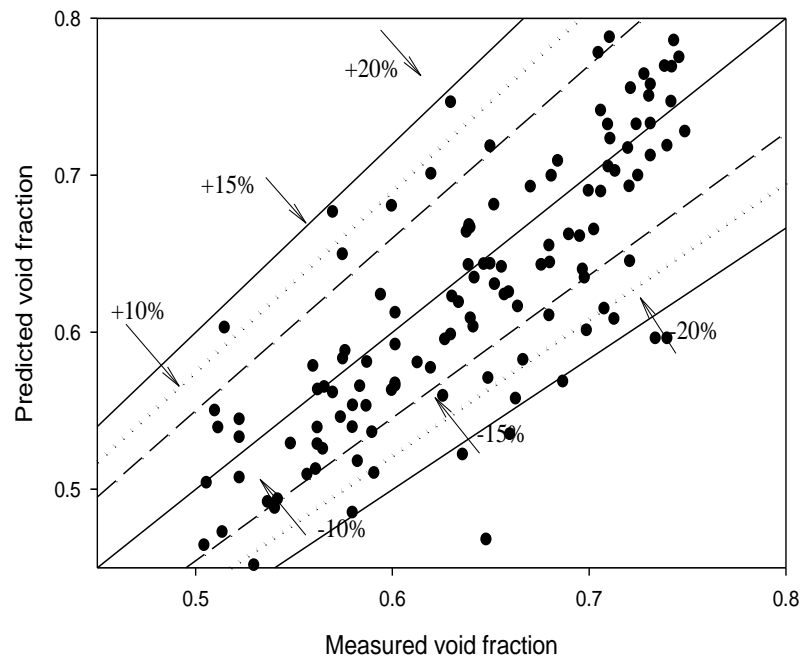


Figure 4.16 Performance of the Yamazaki and Yamaguchi (1979) correlation $0.5 < \alpha \leq 0.75$

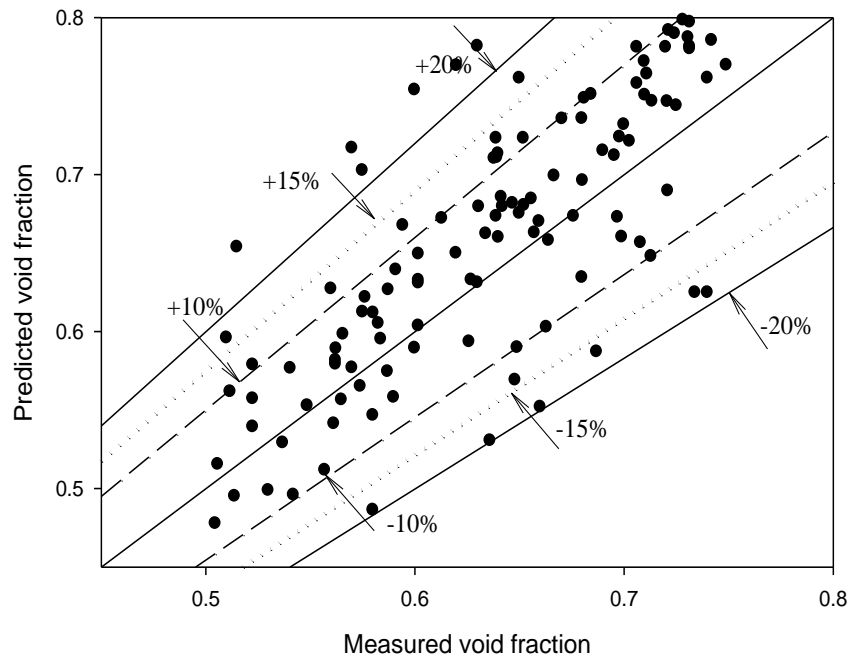


Figure 4.17 Performance of Gomez et al. (2000) correlation for $0.5 < \alpha \leq 0.75$

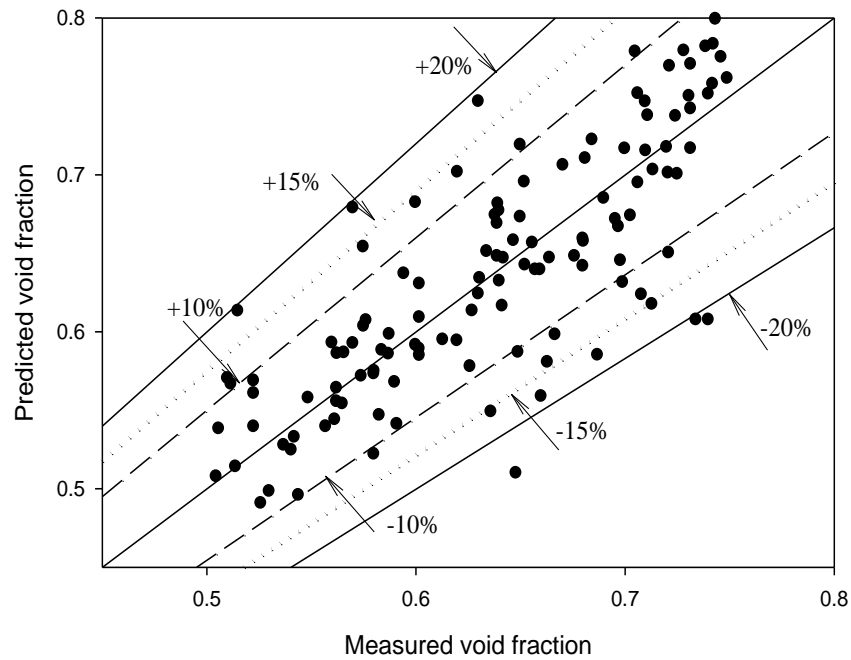


Figure 4.18 Performance of Woldeesemayat and Ghajar (2007) correlation for $0.5 < \alpha \leq 0.75$

Table 4.22 Performance evaluation of the DFM correlations for $0.5 < \alpha \leq 0.75$

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Bonnecaze et al. (1971)	77	85.7	92.1	100	9.3
Cai et al. (1997) ^B	68.3	81.7	92.1	100	10.8
Cai et al. (1997) ^S	72.2	83.3	93.7	100	10.4
Clark and Flemmer (1985)	63.5	81.0	90.5	99.2	11.6
Dix (1971)	48.4	65.9	80.2	92.9	16.8
Goda et al. (2003)	71.4	82.5	88.1	97.6	11.7
Gomez et al. (2000)	75.4	86.5	92.9	100	10.3
Hasan (1995)	57.1	82.5	92.9	98.4	12.0
Huq and Loath (1992)	38.1	57.9	76.2	96.8	16.5
Kawanishi et al. (1990)	46.0	55.6	65.9	74.6	28.6
Kokal and Stainslav (1989)	77	85.7	91.3	100	9.4
Nicklin et al. (1962)	77	85.7	92.1	100	9.3
Rouhani and Axelsson (1970) ¹	75.4	86.5	95.2	100	9.7
Sun et al. (1981)	76.2	85.7	94.4	100	9.6
Usui and Sato (1989) ^S	26.2	40.0	49.6	68.0	25.5
Woldesemayat and Ghajar (2007)	80.2	92.1	97.6	100	8.2
Zuber and Findlay (1964)	71.4	83.3	93.7	100	10.4

^B- Bubbly, ^S- Slug, indicate two or more flow pattern specific correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Performance of the correlations for $0.75 < \alpha \leq 1$

This is the most reliable category of the void fraction in a sense that the measurement of the void fraction is less prone to errors and the percentage error between the calculated and measured values are less due to the higher values of the void fraction. Due to ease in the measurement of the void fraction data in this range most of the data sets available in the literature consist of the void fraction values higher than 0.75. Among all the data set used in the present study 441 data points qualified within a range of $0.75 < \alpha \leq 1$. This higher range of the void fraction essentially approximated the falling film and annular flow regimes. The criterion set for the satisfactory performance of the

correlations was more stringent as mentioned in Table 4.16. In the category of non DFM correlations Chen (1986) and Smith (1969) correlations were included to the list since they proved prominent in successfully predicting the void fraction in this range. Chen (1986) predicted the void fraction with maximum accuracy of 90.2% in the error bands of $\pm 10\%$ followed by Yamazaki and Yamaguchi (1979) and Chisholm (1983) with an accuracy of 88.2% and 87.1% in $\pm 10\%$ error bands, respectively. The other successful correlations in non DFM category were Smith (1969) and Minami and Brill (1987). The outcome of this analysis is shown in Table 4.23. The RMS error associated with these correlations was less than 10%.

Table 4.23 Performance evaluation of the correlations for $0.75 < \alpha \leq 1$

Correlation	Percentage of data points predicted within				RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Homogeneous	46.1	74.1	92.3	99.3	13.0
Armand (1946), Chisholm (1983)	86.6	92.7	96.4	98.6	9.0
Beggs (1972)	47.8	65.8	80.5	97.1	15.3
Chen (1986)	90.2	93.9	95.9	98.6	8.3
Chisholm (1973)	87.1	92.5	96.4	98.6	9.0
Minami and Brill (1987)	83.9	92.1	96.4	98.0	10.8
Mukherjee (1979)	56.0	86.4	89.8	91.8	190.7
Smith (1969)	86.8	92.1	95.5	98.6	9.4
Usui and Sato (1989) ^{FF}	35.8	73.4	88.2	97.0	15.1
Yamazaki and Yamaguchi (1979)	88.2	94.6	96.6	99.1	8.2

^{FF}- Falling Film, indicate two or more flow pattern specific correlations given by same author

In this range it was difficult to rank the correlation for their performance since majority of the DFM correlations were successful in agreeably predicting the void fraction in the specified tolerance. Gomez et al. (2000) was the most successful correlation predicting 97.7% of the data points within $\pm 15\%$ error bands and RMS error of 7%. This performance was competed by five other correlations predicting more than

95% data points within the set criterion. For a more restricted tolerance of $\pm 10\%$ Woldesemayat and Ghajar (2007) was observed to be a better correlation than Gomez et al. (2000) giving a prediction of 91.4% and 95.2% data points in $\pm 10\%$ and $\pm 15\%$ error bands, respectively. The other good performing correlations are listed in Table 4.24 and the performance of the Chen (1986), Yamazaki and Yamaguchi (1979), Gomez et al. (2000) and Woldesemayat and Ghajar (2007) is presented graphically in the Figures 4.19, 4.20, 4.21 and 4.22, respectively.

Table 4.24 Performance evaluation of the DFM correlations for $0.75 < \alpha \leq 1.0$

Correlation	Percentage of data points predicted within				RMS error %
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	$\pm 30\%$	
Bonnecaze et al. (1971)	74.1	94.8	98.2	99.5	8.6
Cai et al. (1997) ^B	82.3	96.4	99.3	99.5	7.9
Cai et al. (1997) ^S	89.8	97.5	99.1	99.8	7.0
Clark and Flemmer (1985)	85.5	97.1	99.5	99.5	7.5
Dix (1971)	74.8	84.4	89.8	97.1	13.1
Goda et al. (2003)	81.6	94.3	97.7	99.1	9.3
Gomez et al. (2000)	89.3	97.7	99.3	99.5	7.0
Hasan (1995)	89.3	97.5	98.9	99.5	7.2
Huq and Loath (1992)	86.2	90.5	94.3	97.5	9.9
Kawanishi et al. (1990)	68.3	84.6	88.4	92.3	17.7
Kokal and Stainslav (1989)	74.4	94.6	98.2	99.5	8.6
Nicklin et al. (1962)	74.1	94.8	98.2	99.5	8.6
Rouhani and Axelsson (1970) ^I	91.2	97.5	98.2	99.8	6.8
Sun et al. (1981)	73.5	94.3	98.4	99.5	8.7
Usui and Sato (1989) ^S	20.4	35.5	49.1	82.5	33.9
Woldesemayat and Ghajar (2007)	91.4	95.2	97.3	99.1	7.4
Zuber and Findlay (1964)	75.3	95.9	98.4	99.5	8.4

^B - Bubbly, ^S - Slug, indicate two or more flow pattern specific correlations given by same author, ^I reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

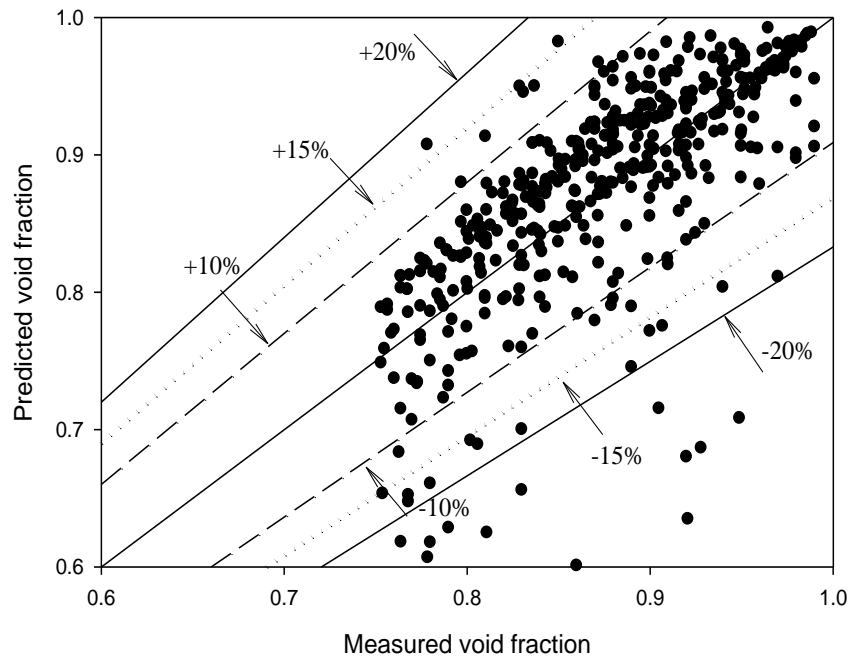


Figure 4.19 Performance of Chen (1986) correlation for $0.75 < \alpha \leq 1.0$

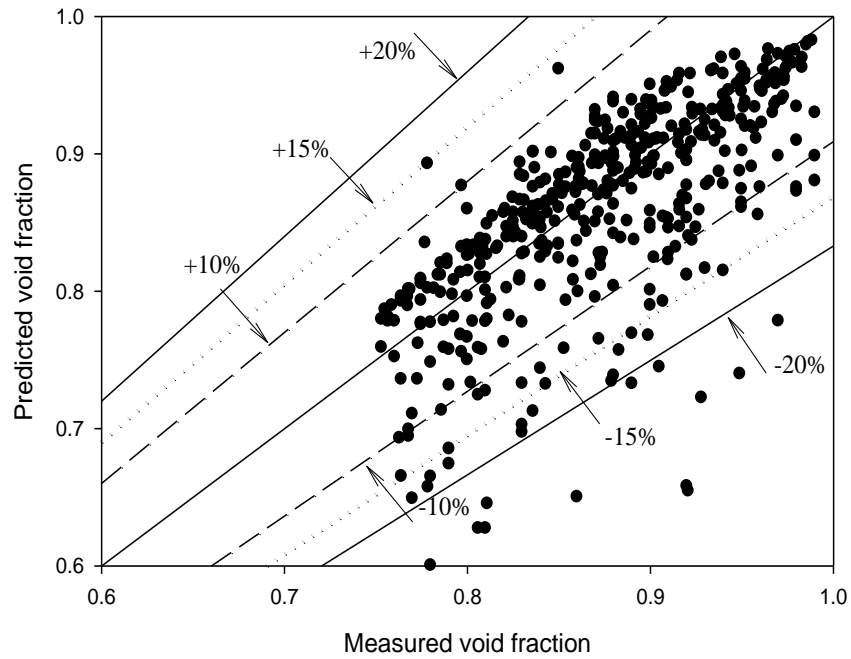


Figure 4.20 Performance of Yamazaki and Yamaguchi (1979) correlation for $0.75 < \alpha \leq 1.0$

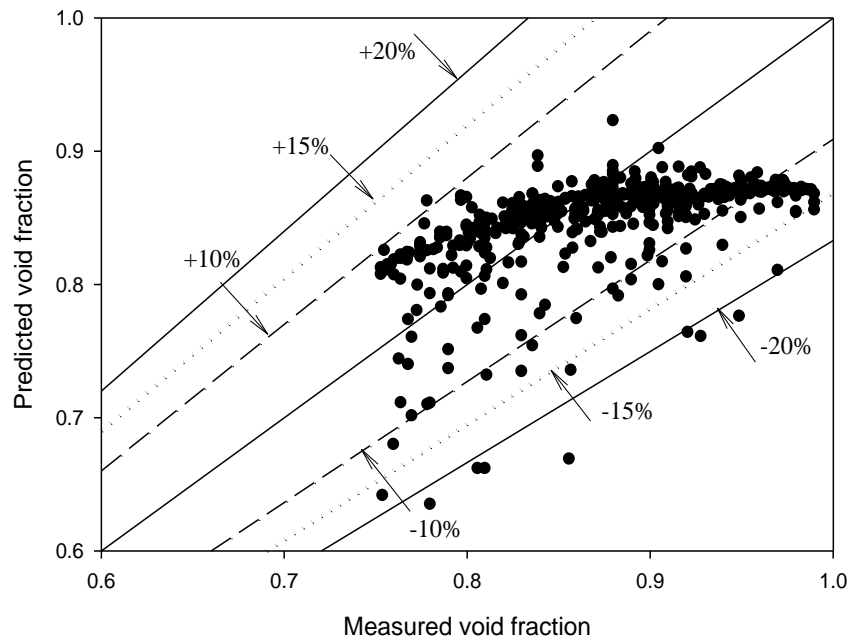


Figure 4.21 Performance of Gomez et al. (2000) correlation for $0.75 < \alpha \leq 1.0$

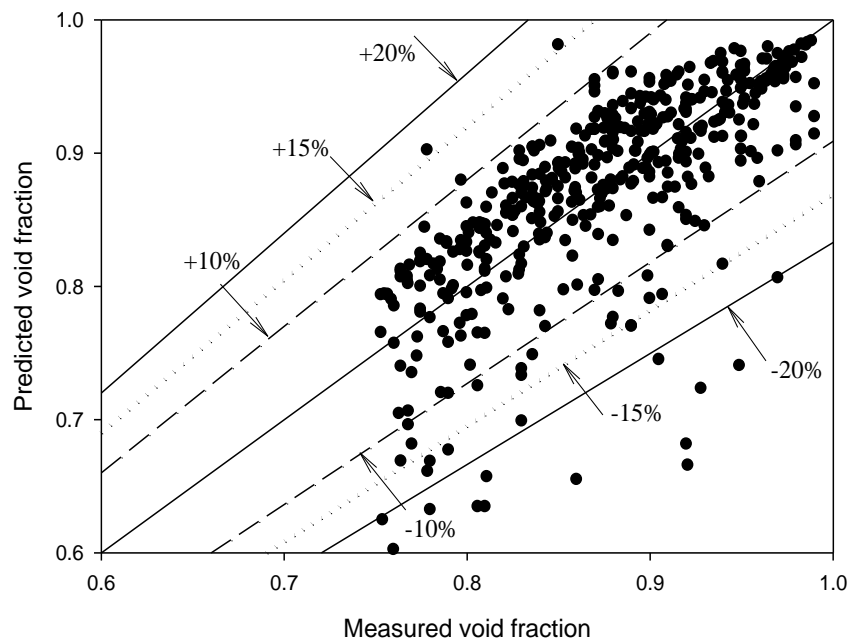


Figure 4.22 Performance of Woldeesemayat and Ghajar (2007) correlation for $0.75 < \alpha \leq 1.0$

This investigation of the performance of the void fraction correlations could be summarized on a qualitative basis such as satisfactory or unsatisfactory performance in the framework of the chosen criterion. The qualitative analysis as documented in Table 4.25 unveils that, only DFM correlations are able to perform reasonably according to the set measures for satisfactory performance.

Table 4.25 Qualitative performance of the void fraction correlations in the four specified ranges of the void fraction

Correlation	Range of the void fraction			
	0 – 0.25	0.25 – 0.50	0.50 – 0.75	0.75- 1
Homogeneous	NS	NS	NS	NS
Armand (1946), Chisholm (1983)	NS	NS	NS	S
Beggs (1972)	NS	NS	NS	NS
Chisholm (1973)	NS	NS	NS	S
Mukherjee (1979)	NS	NS	S	NS
Usui and Sato (1989) ^{FF}	NS	NS	NS	NS
Yamazaki and Yamaguchi (1979)	NS	S	S	S
Bonnecaze et al. (1971)	S	S	S	S
Cai et al. (1997) ^B	S	S	S	S
Cai et al. (1997) ^S	S	S	S	S
Clark and Flemmer (1985)	S	S	S	S
Dix (1971)	NS	NS	NS	NS
Goda et al. (2003)	NS	S	S	S
Gomez et al. (2000)	S	S	S	S
Hasan (1995)	S	S	S	S
Huq and Loath (1992)	NS	NS	NS	S
Kawanishi et al. (1990)	NS	NS	NS	NS
Kokal and Stainslav (1989)	S	S	S	S
Nicklin et al. (1962)	S	S	S	S
Rouhani and Axelsson (1970) ^I	NS	S	S	S
Sun et al. (1981)	NS	S	S	S
Usui and Sato (1989) ^S	NS	NS	NS	NS
Woldesemayat and Ghajar (2007)	NS	NS	S	S
Zuber and Findlay (1964)	S	S	S	NS

^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more flow pattern specific correlations given by same author, ^I reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007). NS-Not Satisfactory, S- Satisfactory

The performance evaluation and the comparison between the correlations demonstrated that the among these eight DFM correlations Gomez et al. (2000) offered a quantitatively consistent performance in all the four specified ranges of the void fraction and fulfilled the criteria for satisfactory performance. This correlation also gave competitive result when compared against the individual data set. The outcome of the Gomez et al. (2000) correlation for a range of pipe diameters and the fluid combination is plotted against the measured void fraction data and illustrated in Figure 4.23. In the category of non DFM model the predictions of the Yamazaki and Yamaguchi (1979) correlation against the measured void fraction data for different fluid combination and pipe diameters is plotted in Figure 4.24.

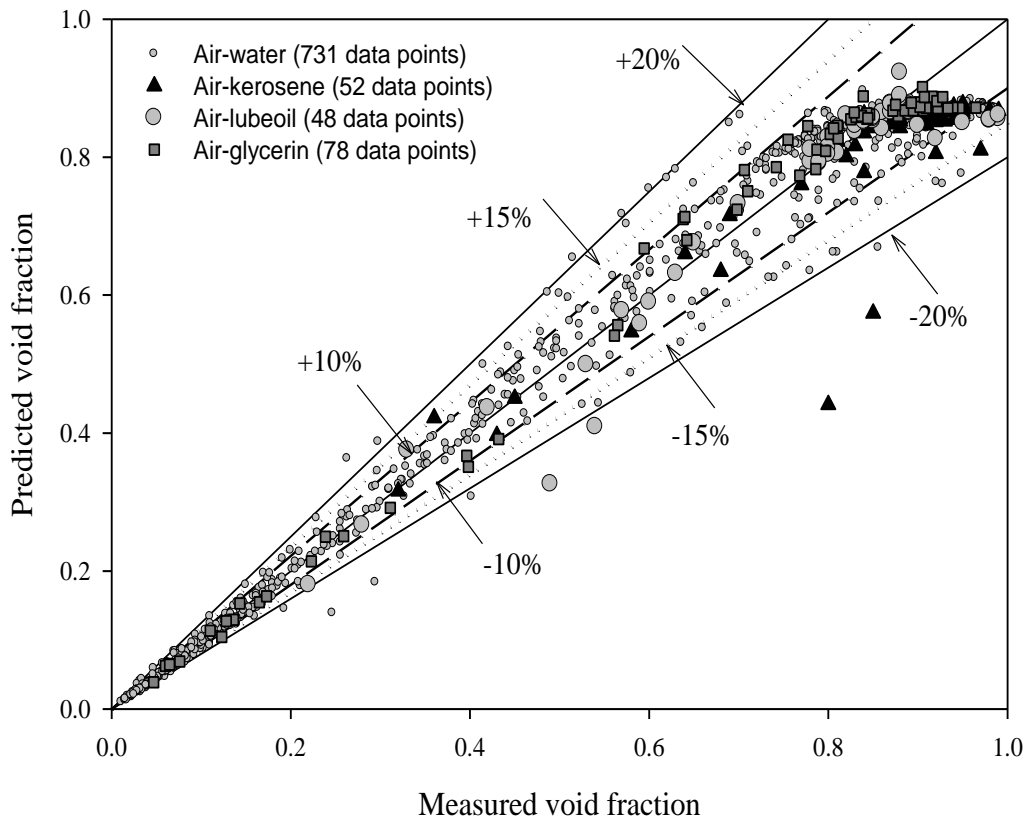


Figure 4.23 Performance of Gomez et al. (2000) correlation for different fluid combination

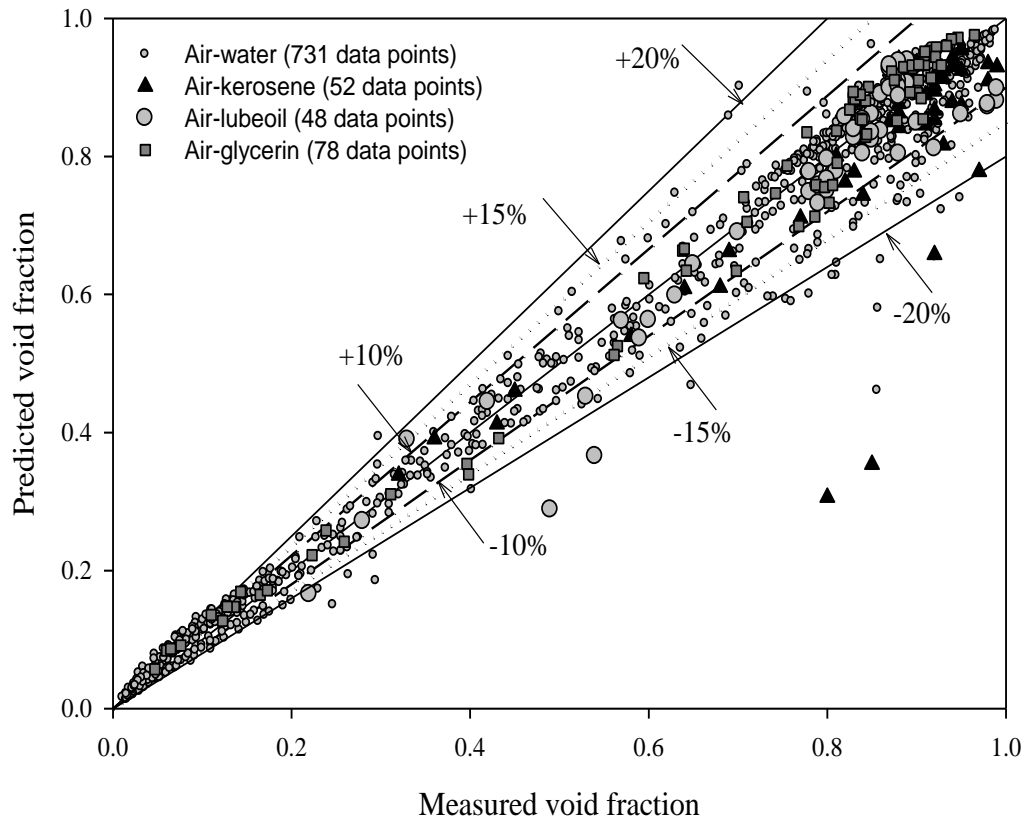


Figure 4.24 Performance of Yamazaki and Yamaguchi (1979) correlation for different fluid combination

It was observed in the present study that the correlations of Yamazaki and Yamaguchi (1979) and Chisholm (1983) did not perform well in the lower range of 0 – 0.25. Chisholm (1983) claimed his correlation to hold good only for $\alpha > 0.2$ and as a consequence fails to take care of the $\alpha - \beta$ relationship (void fraction vs. gas volumetric flow fraction) in the lower region of the void fraction. It should be noted that these correlations are based on $\alpha - \beta$ relationship and Yamazaki and Yamaguchi (1979) reported that this relationship varies for two different regions of the void fraction, $\alpha \leq 0.2$ and $\alpha > 0.2$, respectively. They observed that for $\alpha < 0.2$, the average gas velocity is less than the average liquid velocity or in other words the slip ratio is less than unity while for

homogeneous void fraction or alternatively the volumetric gas flow fraction, the average velocities of the gas and liquid phases are assumed to be the same; and hence $\alpha < \beta$. Whereas for $\alpha > 0.2$, the converse is true i.e. the gas average velocity is higher than the liquid average velocity and the slip ratio is greater than unity, thus resulting into a relationship, $\alpha < \beta$. Yamazaki and Yamaguchi (1979) proposed two separate equations to toggle between these two regions of the void fraction but did not perform satisfactorily in the lower region of 0 – 0.2.

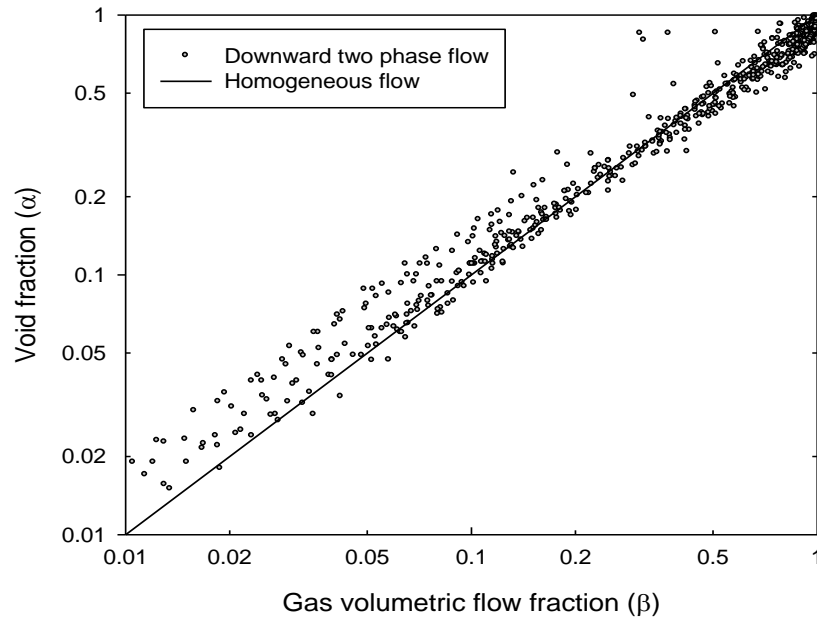


Figure 4.25 Variation of the void fraction with gas volumetric flow fraction

The void fraction data used in the present study is analyzed for $\alpha - \beta$ relationship and is found to be in accordance with the conclusions of Yamazaki and Yamaguchi (1979). The plot of void fraction vs. gas volumetric flow fraction is shown in Figure 4.25 and it can be clearly seen that the void fraction (α) is greater than the gas volumetric flow fraction (β), approximately for $\alpha < 0.2$, and after which the converse is true. This also

concludes that the homogeneous void fraction model ($\alpha = \beta$) in general fails over the entire range of the void fraction since it assumes that both phases move at the same velocity while the two phase flow is essentially characterized by the difference in the velocities of the two phases. They also reported that this relationship between the two parameters α and β is different for upward and downward two phase flow. This also concludes that the correlations based on $\alpha - \beta$ relationship not only rely on the void fraction values but are also influenced by the flow direction and the pipe orientation.

With the aid of quantitative and qualitative analysis so far the top five performing correlations in all four specified ranges of the void fraction are listed in an alphabetical order as shown in Table 4.26. The RMS error associated with each of these correlations is also considered in this analysis. As listed in this table, Gomez et al. (2000) is found to be among the top five performing correlations for the void fraction ranges of $0 - 0.25$, $0.5 - 0.75$ and $0.75 - 1.0$, respectively. Though the Gomez et al. (2000) does not appear in top five performers in a range of $0.25 < \alpha \leq 0.5$ it attains the criteria of satisfactory performance for this range. In the lower range of $0 < \alpha \leq 0.25$, Hasan (1995) and Gomez et al. (2000) give excellent performance and are recommended for prediction of the void fraction in this range. For the next two consecutive ranges of the void fraction $0.25 < \alpha \leq 0.5$ and $0.5 < \alpha \leq 0.75$ the outstanding results of the Nicklin et al. (1962) and Bonnecaze et al. (1971) are expected since these correlations were developed for the slug flow which broadly translates to the range of void fraction selected in the present study. For the last range of $0.75 < \alpha \leq 1.0$ the Gomez et al. (2000), Rouhani and Axelsson (1970)¹ and Woldesemayat and Ghajar (2007) prove to be the most prominent correlations. The reason behind the good performance of these three correlations is reported later in this

chapter. It should be noted that the all the top performing correlations in the void fraction range of 0 – 0.25, 0.25 – 0.5, 0.5- 0.75 and 0.75 – 1 are based on the concept of the drift flux model with the exception of Yamazaki and Yamaguchi (1979).

Table 4.26 Results of the top five performing correlations for the four specific ranges of the void fraction

Void fraction range	Percentage of data points predicted within			RMS error
	$\pm 10\%$	$\pm 15\%$	$\pm 20\%$	
$0 < \alpha \leq 0.25$				%
Cai et al. (1997) ^S	62	80.2	91.6	11.5
Clark and Flemmer (1985)	57	74.7	90.7	12.4
Gomez et al. (2000)	62.9	79.3	93.7	11.4
Hasan (1995)	70.9	81	91.6	11.5
Nicklin et al. (1962) [#]	48.5	73.5	88.2	13.5
$0.25 < \alpha \leq 0.50$				
Cai et al. (1997) ^S	82.9	90.5	95.2	9.5
Gomez et al. (2000)	78.1	89.5	92.4	10.7
Nicklin et al. (1962) [#]	75.2	91.4	96.2	10.2
Rouhani and Axelsson (1970) ¹	77.1	91.4	94.3	9.9
Yamazaki and Yamaguchi (1979)	75.2	92.4	94.3	10.4
$0.50 < \alpha \leq 0.75$[*]				
Gomez et al. (2000)	75.4	86.5	92.9	10.3
Nicklin et al. (1962) [#]	77	85.7	92.1	9.3
Rouhani and Axelsson (1970) ¹	75.4	86.5	95.2	9.7
Sun et al. (1981)	76.2	85.7	94.4	9.6
Woldesemayat and Ghajar (2007)	80.2	92.1	97.6	8.2
$0.75 < \alpha \leq 1$				
Cai et al. (1997) ^S	89.8	97.5	99.1	7.0
Chen (1986)	90.2	93.9	95.9	8.3
Gomez et al. (2000)	89.3	97.5	98.9	7.2
Rouhani and Axelsson (1970) ¹	91.2	97.5	98.2	6.8
Woldesemayat and Ghajar (2007)	91.4	95.2	97.3	7.4

[#] Similar performance given by Bonnecaze et al. (1971). ^S- Slug, indicate two or more flow pattern specific correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

It should be noted that the top performing correlations of Bonnecaze et al. (1971), Nicklin et al. (1962), Rouhani and Axelsson (1970)¹, Gomez et al. (2000), Kokal and Stainslav (1989) and Woldesemayat and Ghajar (2007) are reported to be developed for the upward two phase flow but these correlations acquire a top position for the downward flow as well. The performance of these correlations can be credited to the negative values of the drift velocity. If the drift velocity (U_{GM}) in the drift flux model is switched to take a negative value while assuming the velocities in the flow direction to be positive, the DFM correlations calculate the void fraction within satisfactory limits. The $\sin\theta$ term employed in the Gomez et al. (2000) and Woldesemayat and Ghajar (2007) correlation takes care of flipping the sign of the drift velocity from positive to negative. In order to have a better feel for this concept, the outcome of the Gomez et al. (2000) correlation is presented graphically in Figure 4.26 using the positive and negative sign conventions for the drift velocity term.

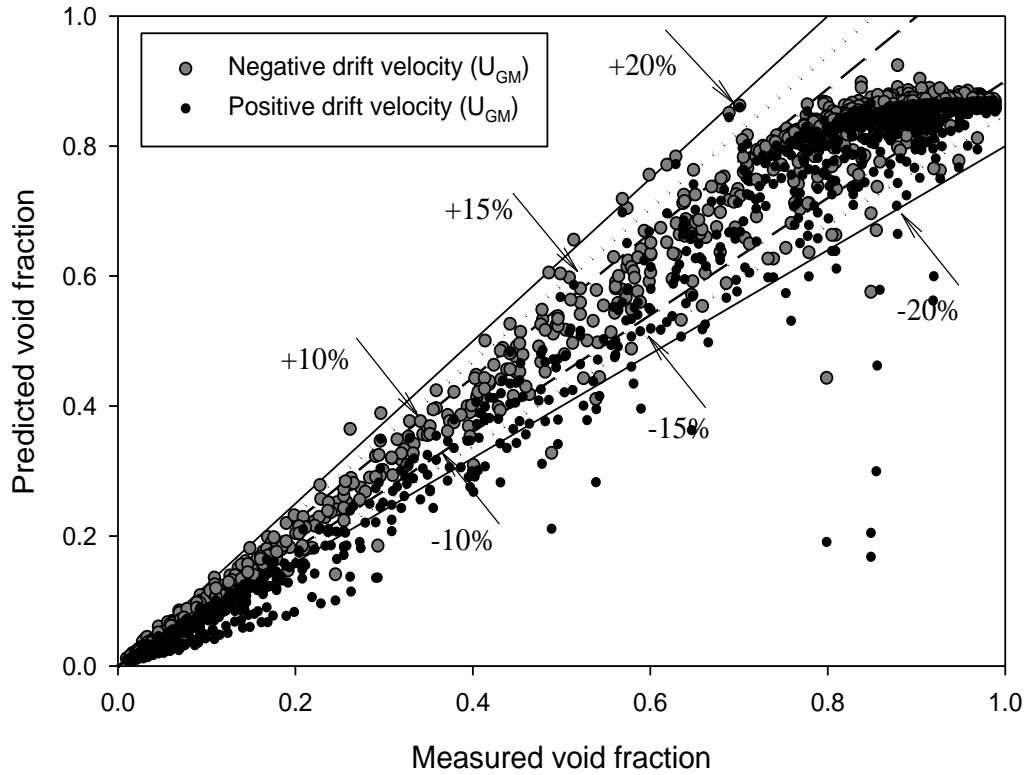


Figure 4.26 Performance of the Gomez et al. (2000) correlation using positive and negative values of the drift velocity (U_{GM})

A careful observation of the Figure 4.26 reveals that the positive and negative sign of the drift velocity makes a big difference in the prediction of the void fraction in a lower range typically for $0 < \alpha \leq 0.3$. On the other hand the variance in the predicted void fraction using the positive and negative drift velocity diminishes for the higher range of the void fraction in general for $0.75 < \alpha \leq 1$. To have a better view of the disparity and confirmation within the void fraction values for lower and higher region of the void fraction using positive and negative drift velocity, the plots for region $0 - 0.25$ and $0.75 - 1$ are presented in Figures 4.27 and 4.28, respectively.

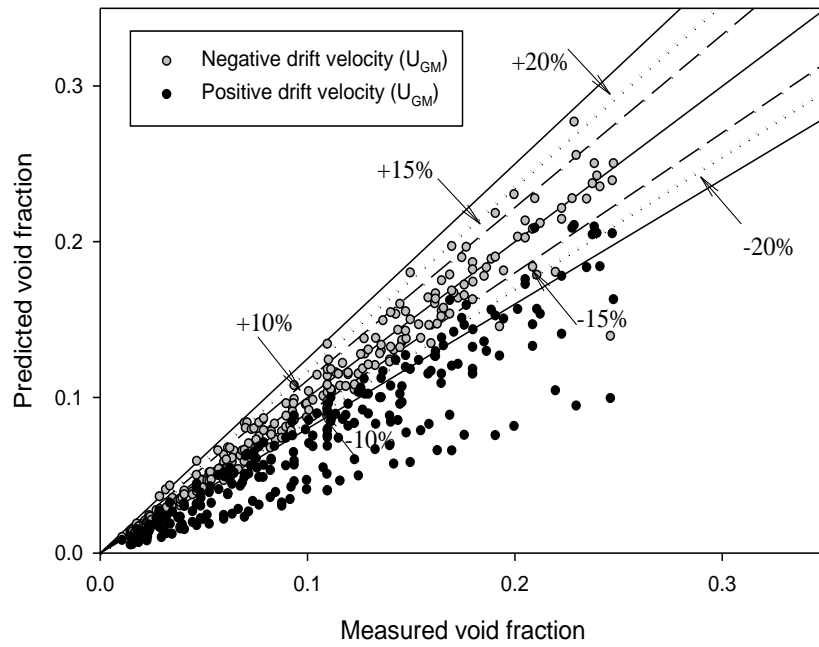


Figure 4.27 Performance of the Gomez et al. (2000) correlation using positive and negative values of the drift velocity (U_{GM}) for $0 < \alpha \leq 0.25$

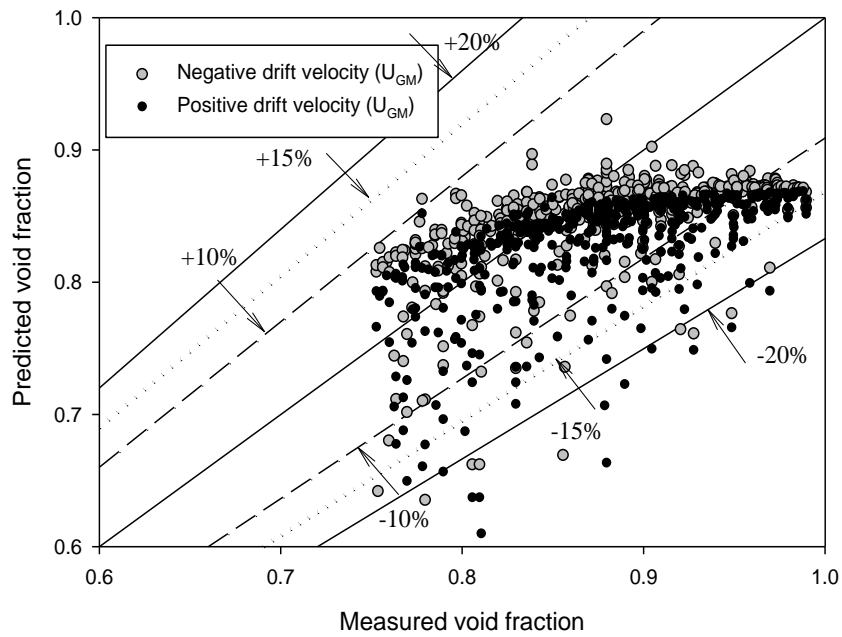


Figure 4.28 Performance of the Gomez et al. (2000) correlation using positive and negative values of the drift velocity (U_{GM}) for $0.75 < \alpha \leq 1$

A better discussion on the sign of the drift velocity and its impact in the lower and higher region of the void fraction can be presented in context of the flow pattern description and the flow visualization done in the first half of this chapter. The drift velocity is defined as the velocity of the gas phase with respect to the mixture velocity at the center of the pipe. In case of the bubbly flow it is evident that due to buoyancy effects the gas phase i.e. the bubbles try to rise in a direction opposite to the mean flow. Thus it implicitly means that the relative velocity of the bubbles with respect to the two phase mixture or to be more precise the drift velocity for downward two phase flow is negative. The drift velocity is positive for upward flow since the buoyancy force acts in a direction of the mean flow. At the higher end of the void fraction occupied by the falling film and annular flow patterns, the relative velocity of the gas phase with respect to the mixture at the pipe center is negligible and hence the drift velocity term becomes really small. As a consequence, the higher end of the void fraction is virtually independent of the drift velocity and this justifies the confirmation within the void fraction values while employing positive and negative signs to the drift velocity at the higher end.

4.2.5 Identification of the approximate range of the void fraction correlations

The analysis of the correlations in the range of $0 - 0.25$, $0.25 - 0.50$, $0.50 - 0.75$ and $0.75 - 1.0$ was useful in determining the performance of the correlations in the respective ranges but was incomplete in a sense that the actual range for satisfactory performance associated with individual correlation could be different than that specified in this study, probably the intermediate values of the two ranges. Hence in addition to the comparison of the void fraction correlations for the specified range, an attempt was made to figure out the approximate range of the void fraction in which the correlations

performed satisfactorily. The performance approval of the correlations is subject to the criteria that at least 80% of the points should lie in a tolerance of $\pm 20\%$. This assessment of the correlations was necessary to make sure that the performance ranking of the correlations is unbiased. Table 4.27 reports the approximate range of the void fraction associated with an individual correlation for satisfactory performance. In the group of non DFM correlations none of the correlations except Yamazaki and Yamaguchi (1979) could predict the void fraction satisfactorily in the range of $0.2 < \alpha \leq 1$. The Usui and Sato (1989) correlation for falling film performed well for the range of $0.7 - 0.85$, a typical range associated with the falling film regime. This concludes that though the Usui and Sato (1989) falling film correlation failed in performing for the overall data and for the specified void fraction range but it definitely gives satisfactory performance for the approximate void fraction range of $0.7 \leq \alpha \leq 0.85$.

Table 4.27 Approximate range of the void fraction in which the correlations perform satisfactorily

Correlation	Approximate range of void fraction
Homogeneous	0.2 – 0.3
Armand (1946), Chisholm (1983)	0.6 – 1.0
Beggs (1972)	0.85 – 1.0
Chisholm (1973)	0.6 – 1.0
Mukherjee (1979)	0.45 – 1.0
Usui and Sato (1989) ^{FF#}	0.7 – 0.85
Yamazaki and Yamaguchi (1979)	0.2 – 1.0
Bonnecaze et al. (1971)	0.1 – 0.9
Cai et al. (1997) ^B	0.1 – 1.0
Cai et al. (1997) ^S	0.0 – 1.0
Clark and Flemmer (1985)	0.1 – 1.0
Dix (1971)	0.8 – 1.0
Goda et al. (2003)	0.6 – 1.0
Gomez et al. (2000)	0.0 – 1.0
Hasan (1995)	0.0 – 1.0
Huq and Loath (1992)	0.65 – 1.0
Kawanishi et al. (1990)	0.65 – 0.9
Kokal and Stainslav (1989)	0.1 – 0.9
Nicklin et al. (1962)	0.1 – 0.9
Rouhani and Axelsson (1970) ¹	0.1 – 1.0
Sun et al. (1981)	0.1 – 0.9
Usui and Sato (1989) ^S	0.3 – 0.6
Woldesemayat and Ghajar (2007)	0.45 – 1.0
Zuber and Findlay (1964)	0.1 – 1.0

[#] Performance limited to $D < 0.025\text{m}$ ^B- Bubbly, ^S- Slug, ^{FF}- Falling Film, indicate two or more flow pattern specific correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

The correlations of Bonnecaze et al. (1971), Cai et al. (1997)^B, Kokal and Stainslav (1989), Sun et al. (1981), Rouhani and Axelsson (1970)¹ were found to calculate the void fraction satisfactorily for the range of $0.1 < \alpha \leq 1.0$. It is obvious from this result that the low performance of these correlations in the range of $0 < \alpha \leq 0.25$ is due to their inability to perform for void fraction less than 0.1. However the Gomez et al. (2000), Cai et al. (1997)^S and Hasan (1995) were able to predict the data better than these correlations for the void fraction range of $0 < \alpha \leq 0.1$. To find out this discrepancy in

results of the correlations for $\alpha \leq 0.1$, these correlations were analyzed for 121 void fraction data points scattered in the range of 0 – 0.1. This performance for subcategory of 0 – 0.25 range was considered necessary since half of the points scattered in this region were within 0 – 0.1. The numerical outcome of these correlations for $0 < \alpha \leq 0.1$ are presented in Table 4.28. The percentage accuracy in this table addresses that the deteriorated performance of the Rouhani and Axelsson (1970)¹, Sun et al. (1981), Bonnecaze et al. (1971) and Nicklin et al. (1962) in the region of $0 < \alpha \leq 0.1$, creates a wrong impression about their performance in the range of $0 < \alpha \leq 0.25$.

Table 4.28 Performance of the correlations for $0 < \alpha \leq 0.1$

Correlation	% of points within $\pm 15\%$ error band	Correlation	% of points within $\pm 15\%$ error band
Gomez et al. (2000)	71.38	Rouhani and Axelsson (1970) ¹	52.54
Cai et al. (1997) ^S	68.90	Clark and Flemmer (1985)	66.42
Hasan (1995)	68.07	Kokal and Stainslav (1989)	65.0
Bonnecaze et al. (1971)	63.11	Sun et al. (1981)	43.14
Nicklin et al. (1962)	63.11	Zuber and Findlay (1964)	44.62

^S - Slug, indicate two or more flow pattern specific correlations given by same author, ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldeamayrat and Ghajar (2007).

The identification of the approximate range of the void fraction correlations thus gives an option of choosing one particular correlation over the other correlations in the industrial applications where a particular range of the void fraction is encountered.

The physical structure of the drift flux model based correlation of Gomez et al. (2000) which emerged as one of the successful correlations was analyzed to justify its better performance over others. As cited earlier, the DFM correlations are based on the

concept of interaction between the two phases. The two variables that significantly influence the performance of the DFM correlations are namely the distribution parameter (C_o) and the drift velocity (U_{GM}). The development of the drift flux model by Zuber and Findlay (1964) was devoted to the prediction of the void fraction in bubbly flow assuming constant values of the distribution parameter and the drift velocity. However, the DFM correlations were observed to predict the void fraction for other flow patterns without significant loss of accuracy. The validity of using these constants is confirmed since the best performing correlations for $0 < \alpha \leq 0.25$, are based on DFM approach and has fixed values of both C_o and U_{GM} . The Gomez et al. (2000) correlation was essentially developed for the upward bubbly flow but is found to be equally applicable for other flow patterns in the upward and the downward two phase flow and the rationale is already justified earlier in this section on the grounds of the drift velocity. The work of Wallis (1969) compares the drift flux model proposed by Zuber and Findlay (1964) with the experimental data to demonstrate that the distribution parameter for the bubbly flow should assume a value of 1.2 and the drift velocity is expressed by the equation proposed by Haramathy (1960). The Gomez et al. (2000) correlation assigns the value of 1.15 to the distribution parameter and uses Haramathy (1960) equation to calculate the drift velocity. It is perceived in the literature review that most of the void fraction correlations based on the concept of the drift flux incorporate the distribution parameter and the drift velocity terms as a constant with the exceptions of Rouhani and Axelsson (1970) and Woldesemayat and Ghajar (2007). The former expresses the drift velocity term as a function of the mixture mass flow rate while the later uses the phase superficial velocities in the expression of distribution parameter. As documented by Goda et al. (2003) the

void fraction profile assumes a flat profile for the higher values of the void fraction typically for the falling film and annular regimes and hence the value of the distribution parameter should approach unity. In addition to this the present study concludes on the basis of the photographic evidence of the bubbly and the slug flow that the drift velocity term in DFM is not a constant but varies with respect to the mass flow rates or the velocities of the two phases. The distribution parameter in the Gomez et al. (2000) correlation has a value of 1.15 which is intermediate to the values recommended for the bubbly and annular flow regimes. Moreover the drift velocity expression is composed of the term $(1 - \alpha)^{0.5}$ which makes the drift velocity value really small in the higher region of the void fraction. Thus the better performance of the Gomez et al. (2000) over other correlations can be attributed to its physical structure based upon the two phase flow mechanism. On the same note it is observed that the Woldeesemayat and Ghajar (2007) correlation gives outstanding results for the higher range of the void fraction since the drift velocity term used in their equation assumes a zero value for vertical downward orientation. The important observation from Figures 4.23 and 4.26, is that the plot of predicted vs. measured void fraction has a flat appearance at higher end of the void fraction. In the view of the framework of the drift flux model this flat profile is expected because, for the higher values of the void fraction the superficial gas velocity (U_{sg}) is comparable to that of the two phase mixture velocity (U_m) while the drift velocity (U_{GM}) is negligible. This makes the void fraction, $\left(\alpha = \frac{U_{sg}}{C_o U_m - U_{GM}} \right)$ virtually constant resulting into the flat profile for higher values of the void fraction. This discussion is in conjunction with the earlier section on the variation of the void fraction with flow patterns where we observed that, in a higher region of the void fraction typically $\alpha > 0.7$,

the void fraction is independent of the superficial gas velocity and remains approximately constant. Thus the results and discussion of the void fraction presented in this section highlights the variation of the void fraction with respect to the flow rates of the individual phases or alternatively the flow patterns. This variation is found to be in accord with those investigations done in the past and thus confirms the authenticity and accuracy of our data. This variation of the void fraction with flow rates was also useful in assigning the approximate range of the void fraction associated with an individual flow pattern. The next focus of this section analyzed the available void fraction correlations against an extensive data bank collected from literature including the experimental work done in the present study. This systematic investigation was done against the entire data, individual data sets and for the specified ranges of the void fraction. The flow pattern dependent correlations were verified against the entire range of the void fraction data to identify the approximate range of the void fraction they can perform satisfactorily. The concept of using negative values of the drift velocity or using the negative sign convention for the downward flow worked well and the correlations that were designed for vertical upward flow were verified and found to work satisfactorily for the downward void fraction data. To give a closure to this analysis the performance of the correlations was studied meticulously to identify the approximate range of the void fraction in which these correlations perform satisfactorily. Finally this section concludes with a discussion to justify the performance of the correlations in a certain range of the void fraction. The requirements for the design of an ideal correlation based on the drift flux model and accounting for the interaction between the two phases is presented next in conclusions and recommendations.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The present work was dedicated to the extensive study of the flow patterns and the void fraction correlations for downward two phase flow. The experimental component of this investigation was marked by successful observation of the flow patterns and accurate measurement of the void fraction data. The experimentation was carried out for a 0.0127 m diameter tube using air-water fluid combination. The major flow patterns observed in this study were consistent with the observations of other investigators. The discernible features of the flow visualization were the still photographs and videos that were helpful in rationalizing the mechanism of motion, shape and distribution of air bubbles in the two phase flow and the study of the drift flux model. The analysis of the void fraction correlations resulted into recognition of the best performing flow pattern independent void fraction correlations. The conclusions of experimental study and analysis of flow visualization and void fraction are summarized in this chapter.

5.1 Conclusions of flow visualization

- Five flow patterns were observed in the downward two phase flow namely bubbly, slug, froth, falling film and annular flow. The appearances of the flow patterns were consistent with those reported in the literature.

- The bubbly and dispersed bubbly flows were distinctly observed and the mechanism governing this transition could be elucidated. This study also proved helpful in reasoning the change in bubble shape, motion and distribution across the pipe cross section for varying phase flow rates. A coring bubbly phenomenon consistent to that of Oshinowo (1971), and the effect of increasing gas mass flow rate on the core diameter was observed. The lateral elongation of bubbles resulting into the transition of bubbly to the slug flow was noticed.
- The slug flow was carefully monitored to identify the change in slug shape and size with increasing air and water mass flow rates. The three different shapes of the slug nose namely upward pointing, flat and downward pointing were useful in the discussion of the drift velocity and direction of the slug travel in two phase flow. This observation of the slug shape was in accordance with the investigations of Sekoguchi et al. (1996). From the pictorial evidences of the bubbles and slug motion it was deduced that by the virtue of the buoyancy effect acting on the lighter phase, the bubbles and slug tries to move in a direction opposite to the mean flow and as a consequence, the drift velocity in downward two phase flow especially for bubbly and slug flow regimes is negative.

5.2 Conclusions of the void fraction measurement and analysis

- The experimental study of void fraction carried out in a 0.0127 m diameter pipe using air-water fluid combination as working fluids, resulted into 193 accurate measurements of the void fraction data ranging over a span of 0 – 1. The uncertainty of this measured data using a quick closing valve technique was

determined using a method proposed by Kline and McClintock (1953). The confirmation of the measured void fraction with other investigators at comparable superficial liquid and gas velocities and within $\pm 10\%$ error band verified the capabilities of existing setup to do flow visualization and measure the void fraction data. The measurement of the void fraction data also served to contribute to the assembly of a comprehensive void fraction data set.

- The variation of the void fraction with respect to the flow patterns was observed to be in accordance with the literature records. The void fraction was observed to be sensitive to the increasing gas flow rate and at constant liquid flow rates for bubbly and slug flow regimes. This trend also justified the need of accurate correlations to calculate the void fraction in bubbly and slug flow regimes or approximately for $0 < \alpha \leq 0.7$. To avoid the discrepancy in the definition of flow patterns and their corresponding void fraction range, this observation in addition to the records available in the literature was useful in assigning the approximate range of the void fraction to each flow pattern.
- The experimental component of this study was followed by the two step performance evaluation of the void fraction correlations. This scrutiny was done against individual data set to identify any effects of the pipe diameter and the fluid combination on the void fraction. The second step consisted of the testing the correlations for the specified ranges of the void fraction divided equally over a span of $0 < \alpha \leq 1$. This performance evaluation was completed by identification of the approximate range of the void fraction in which the correlations perform satisfactorily. The criterion for satisfactory performance was user defined and

based on the outcomes of the correlations. The outcome of this analysis in conjunction with the results of Godbole (2009) showed that the drift flux model based correlations are most suitable to calculate the void fraction in the downward and the upward two phase flow. The Gomez et al. (2000) correlation emerged as the most successful correlation followed by decent performances of the Cai et al. (1997), Nicklin et al. (1962), Bonnecaze et al. (1971), Rouhani and Axelsson (1970) and Sun et al. (1981) correlations. The outstanding performance of Woldesemayat and Ghajar (2007) and Gomez et al. (2000) correlation in the higher range of the void fraction is noteworthy and is justified based on the arrangement of physical parameters in the equations.

- By merely flipping the sign of the drift velocity, the void fraction correlations developed for the upward two phase flow were applied against the downward void fraction data and were found to predict the void fraction data successfully within the satisfactory criterion set in the present study. It was observed that the change in the sign of drift velocity significantly alters the void fraction values in the lower range, typically for $0 < \alpha \leq 0.3$ whereas the higher end of the void fraction remains virtually unaffected. This also confirms our conclusion that the drift velocity in downward two phase flow is negative especially for the bubbly and slug flows.

5.3 Recommendations for flow visualization

The literature review revealed that very few experimental investigations have been done for the pipe diameters typically greater than 0.05 m and rare research focused

on the slug and froth flow regimes. Research of Martin (1976) showed that for large pipe diameters the typical slug flow do not exist and observed slugs are agitated, distorted and travels off the pipe axis. It is also anticipated that the slug flow is strongly influenced by the fluid thermo physical properties and system pressure. Hence a detailed analysis of the slug flow and its rise velocity in large diameter tubes and variable fluid combinations is highly recommended. The efforts should be put in experimentally determining the bubble (slug) rise velocity in the downward two phase flow to aid the development of the void fraction correlation. This study will help to confirm the idea proposed in the present study that, the drift velocity is negative at the onset of the slug flow and gradually attains a negligibly small value with increasing flow rates.

5.4 Recommendations of the void fraction correlations analysis

Based on the performance evaluation of the void fraction correlations in the present study following correlations are recommended in Table 5.1, for the specified ranges of the void fraction namely for 0 – 0.25, 0.25 – 0.5, 0.5 – 0.75 and 0.75 – 1. The drift flux model based correlations were found to perform satisfactorily for $0 < \alpha \leq 1$ and the recommended top five flow pattern independent correlations are listed in Table 5.2.

Table 5.1 Recommendation of the best performing void fraction correlations for specified ranges of the void fraction

Void Fraction Range	Correlation
0 – 0.25	Gomez et al. (2000)
0.25 – 0.50	Rouhani and Axelsson (1970) ¹
0.50 – 0.75	Woldesemayat and Ghajar (2007)
0.75 – 1	Rouhani and Axelsson (1970) ¹

¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

Table 5.2 Recommendation of the flow pattern independent void fraction correlations

No.	Void fraction correlation
1	Cai et al. (1997) ^S
2	Gomez et al. (2000)
3	Hasan (1995)
4	Nicklin et al. (1962) [#]
5	Rouhani and Axelsson (1970) ¹

^S Slug Flow, indicate the flow specific correlation given by the author, [#] similar performance to that of the Bonnecaze et al. (1971), ¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by Woldesemayat and Ghajar (2007).

5.5 Recommendations for the ideal design of a void fraction correlation

The detailed study of the two phase flow features and the drift flux model revealed the requirements of a correlation to be satisfied to predict the void fraction accurately. The drift flux model can be thought of as a prospective candidate for the development of the accurate void fraction correlation for the downward two phase flow. The requirements of such a model taking into account the physics of individual flow pattern are mentioned below.

- The void fraction in the bubbly flow regime is very sensitive to the gas flow rate and hence accurate prediction of the void fraction is required in this flow regime. It is shown in the literature that for bubbly flow, the void fraction profile appears similar to the liquid velocity profile in a turbulent flow. For turbulent flow the ratio of the maximum to the cross sectional average velocity is approximately equal to 1.2 and hence it can be speculated that the distribution parameter (C_o) defining the distribution of the gas phase across the pipe cross section relative to

the pipe axis should approach the value of 1.2. With increasing flow rates as the flow regime transits to the annular flow regime the velocity as well as the void fraction profile becomes flat and hence the value of the distribution parameter should gradually attain unity.

- The drift velocity is defined as the actual velocity of the gas phase relative to the mixture velocity at the centerline. Thus for the upward two phase flow the drift velocity adds to the centerline mixture velocity while it is taken off from the centerline mixture velocity for the downward flow. This is due to the buoyancy force acting in and opposite to the direction of the mean flow. The drift velocity is significant in the lower region of the void fraction as defined by Haramathy (1960) but for the higher region of the void fraction or alternatively for the falling film and annular flow regimes the relative velocity between the gas phase and the centerline mixture velocity becomes negligible and hence the drift velocity should approach a negligibly small value at high flow rates.
- It is anticipated that by adjusting these two important variables, distribution parameter (C_o) and the drift velocity (U_{GM}) in the drift flux model, it is possible to develop a correlation to predict the void fraction accurately in the downward two phase flow.

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APPENDIX

List of correlations used for performance evaluation in the present study

Correlations not based on the concept of drift flux models	
Correlation	Equation
Homogeneous	$\alpha = \frac{Q_{sg}}{Q_{sg} + Q_{sl}} = \frac{U_{sg}}{U_{sg} + U_{sl}} = \beta$
Armand (1946), Chisholm (1983)	$\alpha = (0.833 + 0.167x) \frac{U_{sg}}{(U_{sg} + U_{sl})}$
Beggs (1972)	Refer to Chapter II, section 2.3.2
Chisholm (1973)	$\alpha = \frac{1}{\beta + (1 - \beta)^{0.5}}$
Huq and Loath (1992)	$\alpha = 1 - \frac{2(1-x)^2}{1 - 2x + \sqrt{1 + 4x(1-x)\left(\frac{\rho_l}{\rho_g} - 1\right)}}$
Mukherjee (1979)	Refer to Chapter II, section 2.3.2
Smith (1986)	$\alpha = \left[1 + \frac{\rho_g}{\rho_l} \left(\frac{1-x}{x} \right) \left[0.4 + 0.6 \left(\frac{\rho_l/\rho_g + 0.4(1/x - 1)}{1 + 0.4(1/x - 1)} \right)^{0.5} \right] \right]^{-1}$
Usui and Sato (1989) ^{FF}	$\alpha = 1 - (2C_w Fr_l^2)^{7/23} \text{ Where } C_w = 0.005$
Yamazaki and Yamaguchi (1979)	$\frac{\alpha}{(1-\alpha)(1-K\alpha)} = \frac{\beta}{1-\beta}$ <p>For $\beta \leq 0.2$, $K = 2 - 0.4/\beta$ For $\beta \geq 0.2$ $K = -0.25 + 1.25\beta$</p>

^{FF}- falling film, indicates the flow pattern dependent correlation developed by Usui and Sato (1989)

List of correlations used for performance evaluation in the present study (continued)

Correlations based on the concept of drift flux model		
Correlation	Distribution Parameter (C_o)	Drift Velocity (U_{GM})
Bonnecaze et al. (1971)	1.2	$0.35 \sqrt{gD \left(1 - \frac{\rho_g}{\rho_l}\right)}$
Cai et al. (1997) ^B	1.185	$1.53 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$
Cai et al. (1997) ^S	1.15	$0.345 \sqrt{gD \left(1 - \frac{\rho_g}{\rho_l}\right)}$
Clark and Flemmer (1985)	1.17	$1.53 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$
Dix (1971)	$\frac{U_{sg}}{U_{sl} + U_{sg}} \left[1 + \left(\frac{U_{sl}}{U_{sg}} \right) \left(\frac{\rho_g}{\rho_l} \right)^{0.1} \right]$	$2.9 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$
For $-20 \leq \langle j^* \rangle < 0$		
Goda et al. (2003)	$C_o = (-a + 0.772) + (a + 0.228) \sqrt{\frac{\rho_g}{\rho_l}}$	$1.41 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$
	where $a = 0.214 \langle j^* \rangle$	
	for $\langle j^* \rangle < -20$	
	$C_o = (b + 1) - (b \sqrt{\frac{\rho_g}{\rho_l}})$	
	Where $b = (0.2 \exp(0.00848 \langle j^* \rangle) + 20)$	
Gomez et al. (2000)	1.15	$1.53 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25} (1 - \alpha)^{0.5} \sin \theta$
Hasan (1995)	1.12	$0.345 \sqrt{gD \left(1 - \frac{\rho_g}{\rho_l}\right)}$
Kawanishi et al. (1990)	for $0 \leq U_m \leq -3.5$ $C_o = 1.2 - 0.2 \sqrt{\rho_g / \rho_l}$	$1.41 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$

	$\text{for } -3.5 \leq U_m \leq -2.5$ $C_o = 0.9 + 0.1 \sqrt{\frac{\rho_g}{\rho_l}} -$ $0.3 \left(1 - \sqrt{\frac{\rho_g}{\rho_l}} \right) (2.5 + U_m)$ $\text{for } -2.5 \leq U_m < 0$ $C_o = 0.9 + 0.1 \sqrt{\frac{\rho_g}{\rho_l}}$	
Kokal and Stainslav (1989)	1.2	$0.345 \sqrt{gD \left(1 - \frac{\rho_g}{\rho_l} \right)}$
Nicklin et al. (1962)	1.2	$0.35 \sqrt{gD}$
Rouhani and Axelsson (1970) ¹	$1 + 0.2(1 - x)$ $1 + 0.2(1 - x) \left(gD \rho_l^2 / G^2 \right)^{0.25}$	$1.18 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$
Sun et al. (1981)	$\left[0.82 + 0.18 \left(\frac{P_{sys}}{P_{cr}} \right) \right]^{-1}$	$1.41 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$
Usui and Sato (1989) ^S	$1.2 - \frac{1}{(2.95 + 350 Eo^{-1.8})}$	$0.345 \left[1 - \exp \left\{ \frac{(3.37 - Eo)}{10} \right\} \right]$ $\times \sqrt{gD \frac{(\rho_l - \rho_g)}{\rho_l}}$
Woldeamayat and Ghajar (2007)	$\frac{U_{sg}}{U_{sl} + U_{sg}} \left[1 + \left(\frac{U_{sl}}{U_{sg}} \right) \left(\frac{\rho_g}{\rho_l} \right)^{0.1} \right]$	$2.9(1.22 + 1.22 \sin \theta)^{\frac{P_{g,m}}{P_{sys}}}$ $\times \left(g \sigma D (1 + \cos \theta) \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$
Zuber and Findlay (1964)	1.2	$1.53 \left(g \sigma \left(\frac{\rho_l - \rho_g}{\rho_l^2} \right) \right)^{0.25}$

^B- Bubbly, ^S- Slug, indicate two or more flow pattern specific correlations given by same author,
¹ reported by Rouhani and Axelsson (1970) for $0 < \alpha \leq 0.25$, also analyzed for $\alpha > 0.25$ as reported by
Woldeamayat and Ghajar (2007).

VITA

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Scope and Method of Study: An experimental investigation on the flow patterns and void fraction in vertical downward two phase flow was carried out accompanied by exhaustive literature review. The flow patterns and the variation of the void fraction with the flow patterns were compared against the experimental data in the present study. Detailed flow visualization was helpful for insightful discussion on the appearance of the flow patterns. Drift flux model was examined and it was shown that the void fraction correlations developed for vertical upward flow can be applied to predict the void fraction in vertical downward flow. Finally this thesis concluded by a rigorous analysis of the void fraction correlations followed by the recommendation of the best flow pattern independent correlation.

Findings and Conclusions: Flow visualization confirmed the existence of the five major flow patterns in the downward two phase flow. The characteristics of the bubbly and slug flow were elucidated on the basis of photographic evidences. The experimental measurement of the void fraction contributed in assembly of a comprehensive void fraction data set. Owing to the flexibility of the drift flux model it was found to be the most successful model to predict the void fraction in downward two phase flow. The performance analysis of the void fraction correlations was useful in identifying the top performing flow pattern independent void fraction correlations. This analysis gave a better understanding of the physical structure of the drift flux models and concluded with the recommendation of the requirements of an ideal downward two phase void fraction model.

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