STUDY OF FLOW PATTERNS AND VOID FRACTION IN HORIZONTAL TWO-PHASE FLOW

By

NISHANT MATHURE

Bachelor of Engineering
University of Pune
Pune, India
2006

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2010

STUDY OF FLOW PATTERNS AND VOID FRACTION IN HORIZONTAL TWO-PHASE FLOW

Thesis Approved:

Dr. Afshin Ghajar

Thesis Adviser

Dr. David Lilley

Dr. Khaled Sallam

Dr. Mark E. Payton

Dean of the Graduate College

ACKNOWLEDGMENTS

I wish to express my sincere gratitude towards my advisor, Dr. A. J. Ghajar. His untiring patience and encouragement have been vital in my research and studies during my Master's degree. It has been an honor to know him and work under him. I would like to thank my colleagues Pranav Godbole, Clement Tang, Wendell Cook and Swanand Bhagwat for their assistance in my work. The support of my wonderful friends Pranav Godbole, Kaustubh Erande, Siddharth Vaijapurkar, Amit Bhansali, Ford Savage, Jenny Schmig and others has been a big boon.

Very special thanks go to my parents, Deepali and Niranjan Mathure and my brother Varun Mathure. Their love and blessings have been most important during this period.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

NOMENCLATURE

A	Area
a	coefficient in Hughmark's basic model
b	coefficient in Hughmark's basic model
c	coefficient in Hughmark's basic model
D	diameter
D_H	Hydraulic Diameter
D^*_H	Dimensionless hydraulic diameter, $\frac{D_H}{\left(\frac{\sigma}{\rho_L - \rho_G}\right)^{0.5}}$
d	coefficient in Hughmark's basic model
C_o	Distribution parameter
E_L	Liquid holdup for Abdulmajeed's correlation
Fr	Froude number
G	Mass Flux
g	acceleration due to gravity
j_g^*	gas flux in Dimentiev et al. correlation
K	General multiplication factor
K_{GR}	constant in Gardner correlation
K_{MO}	constant in Moussali correlation
$\dot{m}$	mass flow rate
N_{FR}	Froude number in Beggs (1972) correlation
N_{LV}	Liquid velocity number, $U_{SL}\left[\frac{\rho_L}{g\sigma}\right]^{0.25}$
P	pressure
R	Parameter in Abdulmajeed's correlation
R_L	Liquid holdup

Re	Reynolds number
S	Slip ratio
U	Velocity
X	Lockhart and Martenelli parameter
X_{tt}	Lockhart and Martenelli parameter for turbulent-turbulent case
X_A	Parameter in Abdulmajeed's correlation
x	Quality
x	Length along direction of flow
We	Weber number,

<u>Greek letters:</u>

α	Void fraction
β	volumetric quality,α_H
ρ	Density
μ	Viscosity
θ	Angle of inclinaiton
λ	Input liquid content, $\frac{U_{SL}}{U_{SL}+U_{SG}}$
σ	Surface tension

<u>Subscripts:</u>

atm	atmospheric
cs	Cross Section
G	Gas
H	Homogenous
L	Liquid
S	Superficial
M	Mixture
C	critical

Chapter 1. Introduction

Simultaneous flow of two phases inside a closed channel constitutes Two-Phase Flow. It can be of different types; Gas-Liquid, Solid-Liquid or Gas-Solid. Examples of such flows are found in many day-to-day activities as well as in industries. Industries such as chemical, petroleum, power and refrigeration are typical examples. Gas-liquid two phase flow is the most commonly occurring type in these industries. Non boiling gas-liquid flow usually involves two components, while boiling gas-liquid flow involves single component. Flow of natural gas and crude oil in pipelines is of the first type. Flow of refrigerant through the evaporator coil of an air conditioner is an example of the second kind.

Gas-liquid two-phase flow has been studied for a long time. The key aspects that have been the focus of these studies are: flow patterns, void fraction, pressure drop and heat transfer. The present study is dedicated to flow patterns and void fraction in two-component non-boiling gas-liquid flow in horizontal tubes. Specifically air and water are employed as the two phases.

The term ‘Flow Pattern’ refers to the spatial arrangement of the two phases inside the channel. Different flow patterns are observed at different combinations of gas and liquid flow rates. Moreover, they also change with changes in the inclination of the pipe. The physics involved with the flow often changes with the flow patterns, which makes it an important parameter characteristic. Consequently, void fraction and other parameters are also sensitive to flow pattern changes. For industrial applications, certain flow patterns may be beneficial while others may be inefficient or even cause damage to equipment.

‘Void Fraction’ as a general term refers to the ratio of the space occupied by the gas phase to the total space available for flow. Determining the void fraction is a simple task when the two phases are flowing in a homogenous manner with no relative velocity. However, in almost all cases, the velocities are different giving rise to the ‘slip’ phenomenon. This complicates the void fraction calculation. A plethora of correlations have been developed that calculate void fraction based on the knowledge of the other flow parameters. These are often limited in their applicability. The choice of the best correlation is often a vexing one for the designer of any system involving two-phase flow.

The present study was conducted at the Two Phase Flow Laboratory of the Oklahoma State University. The distinguishing feature of the setup is its ability to study pressure drop, void fraction, and non-boiling heat transfer as well as flow visualization at any angle of inclination from positive to negative 90^o. This combination of capabilities is quite unique and not found in open literature. Chapter 3 discusses the setup.

As mentioned, Flow Patterns and Void Fraction were the two focus areas of this study. For flow patterns, the following aims were set:

a) Conduct a detailed analysis of the setup's capability of reproducing the commonly acknowledged flow patterns.
b) Develop a flow pattern map based on the data collected that would be used as a future reference for the setup.
c) Compare the map to other maps found in open literature. This step would act as a validation of the setup and the data.

Chapter 4 discusses the flow pattern part of the present study.

The aims set for the void fraction part of the study were:

a) Collect reliable data in the laboratory. The knowledge of the accuracy of the data collected in the laboratory (covered in Chapter 3) makes it a valuable resource for further study.
b) Using the above data and that found in open literature; create a comprehensive database to evaluate void fraction correlations from open literature. Determine the correlations best suited

for specific cases within two main categories; flow pattern dependant and flow pattern independent. Determine one or more ‘best overall’ correlations.

Chapter 5 discusses the void fraction part of the study.

Appendices 1, 2 and 3 list the correlations that were tested in the study. Appendix 4 gives details of the external datasets used. Appendices 5 and 6 list the performances of all the correlations in all the different categories considered.

For the above mentioned purposes of finding the flow maps, void fraction correlations and data from open literature, a thorough literature review was conducted which has been covered in Chapter 2.

Chapter 2. Literature Review

A comprehensive yet concise overview of the basic concepts in gas-liquid two-phase flow has been given by Ghajar (2005). The paper discusses the key variables involved in the study of Flow Patterns, Void Fraction, Pressure Drop and Heat Transfer of two-phase flow. The Wolverine Engineering Data Book III (Thome (2006)) is also a valuable resource for fundamentals of two phase flow. Individual chapters have been dedicated to Flow Patterns and Void Fractions. Both these works formed the starting points for the literature review undertaken during the course of this study.The literature review is divided into three main sections: Flow Patterns, Flow Maps and Void Fraction Correlations. The last part of the chapter describes the experimental databases used in addition to the data from the present study to evaluate the void fraction correlations.

2.1 Flow Patterns

When a liquid and a gas flow in a channel, they assume various spatial shapes or configurations depending on the flow rates of the two phases. These are referred to as Flow Patterns. Gravity, surface tension, buoyancy are some of the factors affecting flow patterns. Flow patterns are one of the most basic and important aspects of two phase flow studies. Many of the pressure drop, heat transfer and void fraction correlations often depend on knowledge of the flow pattern for their correct use. Flow patterns almost always form a part of any two phase flow study. However, flow pattern recognition is subjective in nature and depends to a certain degree on the interpretation of the researcher. Most researchers agree on the basic flow patterns that exist. The observed flow patterns depend largely on the orientation of the tube/pipe. While some flow patterns are common to all inclinations, others are characteristic of a particular inclination. This literature review considers only horizontal co-current flow in circular tubes.

Alves (1954) identified Bubble flow, Plug flow, Stratified flow, Wavy flow, Slug flow, Annular flow and Spray flow as the main flow patterns. These are the most typical flow patterns identified throughout the available literature. These were also used by Baker (1954) to present one of the first and most widely recognized flow pattern maps. Hence, this was chosen as the starting point for the literature review of this study.

Thome (2006) has presented concise definitions and sketches of flow patterns. These match very closely those of Alves (1954) and are presented here. Bubble flow is said to be characterized by gas bubbles dispersed in liquid with heavy concentration of bubbles in the upper half of tube. It is said to typically occur only at high mass flow rates. Stratified flow is defined as the flow in which complete horizontal separation of the two phases occurs with the liquid phase occupying the bottom of the tube and the gas phase occupying the upper part. The two phases are separated by a smooth undisturbed interface. Stratified-wavy flow occurs when the gas velocity in stratified flow is increased. This causes formation of waves on the interface that travel in the direction of flow. The waves have notable amplitude which is dependent on the relative velocities of the two phases. However, the crests of the waves are not high enough to wet the top of the tube. The waves climb up the sides of the tubes and leave behind thin films of liquid on the walls after they pass. Plug flow, or Elongated Bubble flow, consists of liquid plugs separated by elongated bubbles smaller than the tube diameter. With increasing gas velocities, the diameters of the bubbles increases and becomes comparable to the channel height. This is slug flow. Thome (2006) mentions that Slug and Plug flow are both subcategories of Intermittent flow. The characteristic of this flow regime is large amplitude waves that periodically wash the top of the tube and leave behind thin liquid films. Annular flow occurs at even larger gas flow rates. Here the liquid is swept in an annulus around a central gas core. Due to gravity, the liquid film is much thicker at the bottom. The gas core may have small droplets dispersed in it. At higher gas velocities, all the liquid gets stripped from the wall and appears as droplets entrained in the continuous gas core giving rise to Mist flow.

It is essential to note that the term bubbly flow needs some further clarification. In all the literature encountered during the course of this study, bubbly flow refers to the dispersed bubbly flow mentioned above. However, while observing flow patterns, it was noticed that at low flow rates even plug flow or elongated bubble flow may at times resemble large bubbles. This may cause some confusion. It is inferred that all such large bubbles are part of plug flow and do not constitute bubbly flow.

Lumping of flow patterns together has also been pursued by some researchers for ease of modeling the transition theories. Taitel & Dukler (1976) have combined the slug and plug flow patterns into one and called it as the Intermittent flow pattern, identifying it as all the flow configurations seen between the stratified (and wavy) flow patterns and the annular flow pattern.

On the other hand certain researchers have sub classified the above-mentioned flow patterns into many more categories. Barnea et al. (1980) have identified a flow pattern between the slug and annular flows. They refer to it as Wavy Annular flow. It is said to be observed at the lowest gas rates when transition from slug to annular flow starts. The flow is defined as that which lacks a competent bridge of liquid needed for slug flow and also the stable film over the entire perimeter of the tube as required by annular flow.

Spedding & Nguyen (1980) have identified a total of 13 flow patterns. These include sub-divisions like Stratified + Ripple, Stratified + Roll wave, Stratified + Inertial wave, Slug + Froth, Annular + Droplet, Annular + Slug, Annular + Blow-through Slug, Pulsating Froth, Film + Droplet etc. However, they have divided these into four broad categories; Stratified, Bubble and Slug, Droplet and Mixed flows.

2.2 Flow Pattern Maps

A flow pattern map is a graphical representation of the occurrence of various flow patterns in the course of two phase flow. The axes of the map directly or indirectly represent the flow rates of the two phases. Transition lines or bands on the graph separate the different flow patterns visible at specific combinations of the flow rates or related quantities. The transition of flow from one pattern to another to another is gradual. Thus the lines separating the flow patterns should always be seen as a zone and not a distinct line. It should be noted that most researchers combine certain flow patterns into a hybrid one while representing them on a flow map, even though they acknowledge the presence of the individual flow patterns.

Baker (1954) provided one of the first and more widely used flow pattern maps. Mandhane et al. (1974) developed a map which has been widely mentioned in various horizontal two phase flow studies. Most of the maps developed later often compare their findings with this map. Other maps include Weisman et al. (1979) and Lin & Hanratty (1987).

The flow pattern maps discussed above all differ at least slightly from one another. This is attributed to the difference in the experimental setups used by different researchers and the parameters of the experiments.

The different flow maps use different systems of coordinates for the X and Y axes. These may be dimensional or non-dimensional. Despite being studied by many researchers like Spedding & Nguyen (1980), Troniewski & Ulbrich (1984), Spedding & Spence (1993) who compared and contrasted different coordinate systems and attempted to find a definitive solution, no universal consensus exists on the issue. Part of the reason is that the interactions of the physical phenomena that cause the flow pattern in a tube to change are complicated and not fully understood. This is demonstrated by Taitel & Dukler (1976) wherein they propose different coordinates for different transitions. The use of superficial liquid and gas velocities as the coordinates seems to be more popular than other systems.

Taitel & Dukler (1976) developed a theoretical model for the various flow pattern transitions. From the mathematical analysis of the physics involved in various transitions, five dimensionless parameters were realized.

$$X = \left[\frac{\left|\left({}^{dP}/_{dx}\right)_{SL}\right|}{\left|\left({}^{dP}/_{dx}\right)_{SG}\right|}\right]^{1/2};\ T = \left[\frac{\left|\left({}^{dP}/_{dx}\right)_{SL}\right|}{(\rho_L-\rho_G)g\ cos\alpha}\right]^{1/2};\ Y = \frac{(\rho_L-\rho_G)g\ sin\theta}{\left|\left({}^{dP}/_{dx}\right)_{SG}\right|};\ F = \sqrt{\frac{\rho_G}{\rho_L-\rho_G}}\frac{U_{SG}}{\sqrt{Dg\cos\alpha}};\ K = F[Re_{SL}]^{1/2}$$

where, the subscript S refers to the condition of that phase flowing alone in the tube.

The various transitions are said to be governed by the following groups of parameters:

Stratified to Annular:	X, F, Y	Stratified to Intermittent:	X, F, Y
Intermittent to Dispersed bubbly:	X, T, Y	Stratified Smooth to Wavy:	X, K, Y
Annular to Intermittent:	X, Y	Annular to Bubbly:	X,Y

The map resulting from this theory is unique since no experimental data was used in its development. Figure 2.1 shows this map for horizontal orientation. Note that for horizontal flow, $Y = 0$

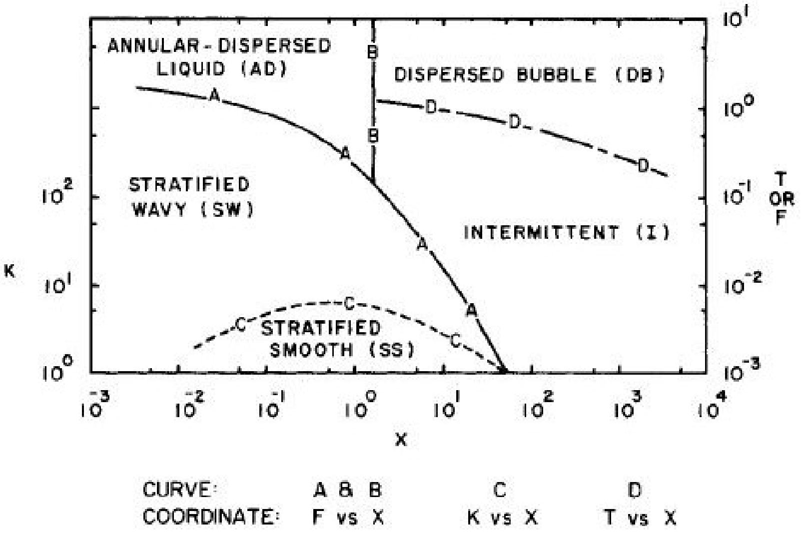

Figure 2.1 Flow map of Taitel & Dukler (1976) [From Taitel & Dukler (1976)]

Thus it is observed that the flow patterns and flow maps are subject to differences in interpretations and experimental setups. While broad agreements exist between the results of researchers, specific differences are always present.

2.3 Void Fraction

Void fraction as a general term refers to the ratio of the space occupied by the gas phase to the total space available for flow. Ghajar (2005) has described four basic types of void fraction measurements;

namely (a) Pipe-average measurements, (b) Cross-sectional average measurements, (c) Chordal-average void fraction measurements and (d) Local void fraction measurements. The techniques used to measure these also vary by type. Pipe-average void fraction is determined by use of ‘quick-closing valves’. Cross-sectional average void fraction can be measured by using transversable single-beam radiation absorption method, multi-beam radiation absorption techniques or neutron-scattering techniques. Chordal void fraction is measured by radiation absorption method while the local void fraction can be measured using optical or electrical void probes.

The Wolverine Engineering Data Book III (Thome (2006)) gives equations for the above four void fraction types . Pipe-average void fraction has been referred to as volumetric void fraction. It is also mentioned that the most commonly used void fraction definition is the cross-sectional average void fraction. The correlations/models for this type of void fraction are said to be of the following types:

a. Homogenous model (assumes that the two phases travel at the same velocity)
b. One-dimensional model (accounts for the differing velocities of the two phases)
c. Models incorporating radial distribution of local void fraction and flow velocity
d. Models based on the physics of specific flow regimes
e. Empirical and semi-empirical models

Detailed discussions of the homogenous model and velocity ratio, selected analytical void fracion models and empirical void fraction equations are also included.

Other researchers have often used different methods of classifying the void fraction correlations. Vijayan et al. (2000) have defined four categories: Slip ratio models, $K\alpha_H$ models, correlations based on the drift flux model and lastly miscellaneous empirical correlations. It is interesting to note that Wojtan et al. (2004) have included the drift flux model in the category of empirical models. However, it is a very widely used generic model with several correlations based on it. Thus, the separate classification by Vijayan et al. (2000) is justified.

From the above, the key equations in studying the void fraction in two-phase flow are briefly summarized below.

The void fraction is defined as the ratio of gas flow cross sectional area to the total cross sectional area.

$$\alpha = \frac{(Area)_G}{(Area)_{cs}} \qquad \dots(1)$$

Liquid holdup is complementary to the void fraction

$$R_L = 1 - \alpha = \frac{(Area)_L}{(Area)_{cs}} \qquad \dots(2)$$

The superficial gas and liquid velocities are important parameters appearing throughout the study of two-phase flow. Superficial velocity of a phase is defined as the velocity that the phase would have had if it was flowing alone in the tube. In other words, if the same mass flow occurred through the entire cross section instead of a part of it.

$$U_{SG} = \frac{\dot{m}_G}{\rho_G (Area)_{cs}}; \qquad U_{SL} = \frac{\dot{m}_L}{\rho_L (Area)_{cs}} \qquad \dots(3)\ \&\ (4)$$

It is related to the actual velocity of the phase by the equation

$$U_{SG} = U_G \alpha\,; \qquad U_{SL} = U_L (1 - \alpha) \qquad \dots(5) \&\ (6)$$

Another important definition is that of the slip ratio. This is the ratio of the velocities of the two phases.

$$S = \frac{u_G}{u_L} \qquad \dots(7)$$

From the above relations between the superficial velocities, actual velocities and void fraction, the homogenous void fraction (α_H) can be determined by assuming no slip between the phases.

$$S = 1 \rightarrow \alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)} = \alpha_H \qquad \dots (8)$$

Zuber & Findlay (1965) developed their 'Drift Flux model' which has the general equation

$$\alpha = \frac{U_{SG}}{C_0 U_M + U_{GM}} \qquad \dots (9)$$

Here C_0 is the distribution parameter and $U_{GM}=U_G-U_M$ is the drift velocity.

Many correlations have been developed on the basis of this theory utilizing different values and expressions for the distribution parameter and the drift velocity.

2.3.1 Review of Previous Comparative Studies

Void Fraction correlations have been appearing in the literature for over 60 years. Due to the large number of correlations available in literature, it is difficult to find and study them individually. Many research studies have focused on the comparison of performances of different void fraction correlations when tested against some experimental data. A review of such studies provides an insight into the different correlations and hence was chosen to be the starting point for finding correlations.

This section presents a review of the comparative studies applicable to horizontal flow. The popular correlations appear in these studies repetitively. The next section discusses the ones relevant to the present study in greater detail.

Dukler et al. (1964) compared the correlations of Hoogendoorn (1959), Hughmark (1962) and Lockhart & Martinelli (1949). The correlations were tested against 706 data points of Hoogendoorn (1959). Taking into account the difficulty of measuring the void fraction accurately at low void fractions, they selected the said data for its higher accuracy. They concluded that the Hughmark (1962) correlation was the best.

Mandhane et al. (1975) presented a comparison of 12 correlations for horizontal flow. They used a two step process for evaluation. First the data was classified into flow pattern based categories and then the correlations applicable to that flow regime were used to predict the data. Thus, different sets of correlations stood out as good performers in the different flow pattern categories. Four different flow pattern maps including one developed by Mandhane et al. (1974) were used to classify the points. It was found that despite substantial differences in the flow pattern predictions by the different maps, similar results were obtained when it came to the top performing correlations.

Spedding (1997) has presented the successful correlations for horizontal, upward and downward flows. Different correlations have been proposed for different flow pattern regimes. They have grouped the horizontal and upward flows into one category and the downward flow into a separate category. The combining of the horizontal and vertical upward flow has also been done by Diener & Friedel (1998). It is mentioned that in upward flow, the effect of buoyancy is to increase the slip.

Diener & Friedel (1998) compared 13 correlations against a data bank of 24000 experimental results from single and two-component mixtures. The HTFS-ALPHA Collier et al. (1974) and Rouhani-I [Rouhani & Axelsson (1970)] were the two correlations recommended. The 13 correlations themselves were selected out of 26 initial correlations after testing them for robustness at limits of single phase liquid and vapor flow.

Coddington & Macian (2002) focussed their evaluation on the correlations based the drift flux model. Thirteen correlations of this type were tested using rod bundle data from nine different sources. The study was aimed at proving the usefullnes of the drift flux techniques for analysing transient conditions in nuclear reactors. No specific recommendations were made.

Woldesemayat & Ghajar (2007) undertook an exhaustive study of 68 void fraction correlations. A database of 2845 data points from 8 different datasets (covering multiple angles, fluids, tube diameters and other physical parametes) appearing in the literature was used to test the correlations. It should be noted that the study disregarded the conditions of applicablity placed by various correlations and tested them all against the entire databank. The correlations were classified according to the system of Vijayan et al. (2000) discussed above. However, this was done purely for the presentation of the correlations and is not included as a parameter in the final results. Six correlations were recommended from the overall comparison: Dix (1971), Filimonov et al. (1957), Hughmark (1962), Morooka et al. (1989), Rouhani-I (Rouhani & Axelsson (1970)).

A sub-study included also analysed only the horizontal data. The correlations that were seen to be the best for the horizontal air-water data were Armand – Massena (Leung (2005)), Rouhani-I (Rouhani & Axelsson (1970)) and Hughmark (1962).

Note: Morooka et al. (1989) correlation has been previously referred to as 'Toshiba correlation'.

2.3.2 Selected Void Fraction Correlations

A large number of correlations were evident from the above literature review. Woldesemayat & Ghajar (2007) was found to be the most comprehensive of all the studies. Thus the database of correlations included in that study was chosen as a base for this study. As mentioned previously, Woldesemayat & Ghajar (2007) included correlations covering all angles of orientation. Table 2.1 classifies these correlations according to their intended orientations. For some correlations, this information could not be found or inferred definitively.

Table 2.1 Void Fraction Correlations from Woldesemayat & Ghajar (2007)

Horizontal	**Multiple Orientations including Horizontal**	**Vertical**	**Unknown**
Abdul-Majeed (1996)	Armand – Massena[3]	Bonnecaze et al. (1971)	Baroczy (1966)
Armand (1946)	Bankoff (1960)	Dix (1971)	Bestion[4]
Kawaji et al. (1987)	Beggs (1972)	El-Boher et al. (1988)	Chisholm & Laird (1958)
Gregory & Scott (1969)	Chen (1986)	Huq & Loth (1992)	Dimentiev et al.[5]
Hamersma & Hart (1987)	Chisholm (1973)	Inoue et al. (1993)	Fauske (1961)

Horizontal	**Multiple Orientations including Horizontal**	**Vertical**	**Unknown**
Hart et al. (1989)	Czop et al. (1994)	Kowalczewski, (1964)[2]	Filimonov et al. (1957)
Hoogendroon (1959)	Flanigan (1958)	Kutucuglu[2]	Graham et al. (2001)
Hughmark (1965)	Fujie (1964)	Moussali[2]	Jowitt[4]
Kokal & Stanislav (1989)	Gomez et al. (2000)	Neal & Bankoff (1965)	Maier (1997)
Minami & Brill (1987)	Homogeneous	Nicklin et al. (1962)	Turner & Wallis (1965)
Petalaz & Aziz (1997)	Guzhov et al. (1967)	Premoli et al. (1970)	Zivi (1964)
Lockhart & Martinelli (1949)	Greskovich & Cooper (1975)	Rouhani & Axelsson (1970) Rouhani I	Loscher & Reinhardt (1973)[1]
Spedding & Chen (1984)	Hughmark (1962)	Rouhani & Axelsson (1970) Rouhani II	Nishino & Yamazaki (1963)
Chisholm(1983), Armand(1946)	Madsen (1975)	Sun et al. (1980)	Gardner (1980) Gardner -1
Spedding & Spence (1989)	Mattar & Gregory (1974)	Thom (1964)	Gardner (1980) Gardner -2
Wallis (1969)	Woldesemayat & Ghajar (2007)	Morooka et al. (1989) (called as Toshiba)	
Zhao et al. (2000)	Mukherjee (1979)		
	Smith (1969)		
	Tandon et al. (1985)		

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

This section presents the correlations that are developed for horizontal flow or applicable to horizontal flow (Also listed in Appendix 1). The correlations for vertical orientation and those classified as unknown are summarized in Appendices 2 and 3. The correlations are presented in chronological order. The equations used may not be in the original format. The formats used by Woldesemayat (2006) have been used below.

Armand (1946) gave an equation for the bubble and slug type of flows (ref. Spedding & Chen (1984))

$$\frac{\alpha}{1-\alpha} = \frac{1}{0.2 + \frac{1.2}{\left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)}}$$

Woldesemayat & Ghajar (2007) give the correlation due to Armand-Massena (Leung (2005)) which is a modification of the original correlation by Armand (1946).

$$\alpha = (0.833 + 0.167x)\alpha_H$$

Lockhart & Martinelli (1949) presented one of the first correlations for void fraction measurement. The original study presented a plot of the liquid holdup against the newly introduced parameter X, known as the Lockhart & Martenelli parameter.

$$X = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}$$

Butterworth (1975) showed that the graph can be approximated by:

$$\frac{1-\alpha}{\alpha} = 0.28X^{0.71}$$

This form of the Lockhart and Martinelli correlation has been often used by researchers (Spedding et al. (1990) and Woldesemayat & Ghajar (2007)) due to its ease of use and accuracy.

The equation for the Flanigan (1958) correlation is given by Woldesemayat & Ghajar (2007). It depends only on the superficial gas velocity.

$$\alpha = \left[1 + 3.063{U_{SG}}^{-1.006}\right]^{-1}$$

Hoogendoorn (1959) studied air-water and air-oil mixtures in horizontal smooth pipes with inner diameter ranging from 24 mm to 140 mm and rough pipes of inner diameter 50 mm. The correlation proposed following the study was

$$\frac{\alpha}{1-\alpha} = \left(0.6 * U_{SG}(1 - \frac{\alpha}{1-\alpha}\frac{U_{SL}}{U_{SG}})\right)^{0.85}$$

Bankoff (1960) provided a model for bubbly flow. The rearranged form of the equation presented by Woldesemayat & Ghajar (2007) is

$$\alpha = (0.71 + (1.45 \times 10^{-2})P)\alpha_H$$

where P is pressure in MPa

Hughmark (1962) developed a correlation based on the correlation of Bankoff (1960). It was supposed to be applicable to both horizontal and vertical flows.

$$\alpha = \left[\frac{\mathrm{Re}^{1/6}\mathrm{Fr}^{1/8}}{\lambda^{1/4}}\right]\alpha_H$$

Where,

$$\mathrm{Re} = \frac{GD}{(1-\alpha)\mu_L + \alpha\mu_G} \qquad \mathrm{Fr} = \frac{{U_M}^2}{gD} \qquad \lambda = \frac{1}{1 + \frac{x}{1-x}\frac{\rho_L}{\rho_G}}$$

Fujie (1964) developed a theoretical model for the annular flow region. It covered horizontal and vertical cases with and without heat addition. Woldesemayat & Ghajar (2007) have reduced the horizontal correlation for the case of no heat addition to the Butterworth (1975) type equation.

$$\alpha = [1 + (\sqrt{\left(\frac{68947.57}{P}\right)\alpha + 1})(\frac{1-x}{x})(\frac{\rho_G}{\rho_L})]^{-1}$$

Hughmark (1965) developed a correlation applicable to slug flow regime in horizontal flow. It used the correlation developed by Nicklin et al. (1962) for vertical slug flow and adapted it to horizontal flow using appropriate coefficients. The equation is:

$$\alpha = \frac{U_{SG}}{1.2U_M}$$

Guzhov et al. (1967) correlation is mentioned by Woldesemayat & Ghajar (2007). It is stated to be applicable to plug and stratified flow regimes in pipes with small inclinations to the horizontal (± 9^{o}).

$$\alpha = 0.81\alpha_H\left(1 - \exp\left(-2.2\sqrt{\mathrm{Fr}}\right)\right)$$

Here Fr is the mixture Froude number given by,

$$\mathrm{Fr} = \frac{{U_M}^2}{gD}$$

Gregory & Scott (1969) presented a correlation based on the work of Nicklin et al. (1962).

$$\alpha = \frac{U_{SG}}{1.19U_M}$$

Smith (1969) correlation is supposed to be valid for all conditions of cocurrent two-phase flow.

$$\alpha = \left[1 + \left(\frac{\rho_G}{\rho_L}\right)\left(\frac{1-x}{x}\right)\left(0.4 + 0.6\left\{\frac{\frac{\rho_L}{\rho_G} + 0.4\left(\frac{1-x}{x}\right)}{1 + 0.4\left(\frac{1-x}{x}\right)}\right\}^{0.5}\right)\right]^{-1}$$

The Wallis (1969) correlation is a function of the Lockhart-Martinelli parameter and is a best fit for the data of Lockhart & Martinelli (1949).

$$\alpha = [1 + X^{0.8}]^{-0.38}$$

The correlation by Beggs (1972) involves two steps. First the flow pattern is predicted. Different constants and correlations for different flow regimes in horizontal flow are given in Table 2.2. For other inclinations, a correction factor is utilized and void fraction determined from the equation,

$$\frac{\alpha(\theta)}{\alpha(0)} = 1 + C[\sin(1.8\theta) - \frac{1}{3}\sin^3(1.8\theta)]$$

Where C is the inclination factor given in Table2.2.

Table 2.2 Void Fraction equations and Inclination Factors for different flow patterns for Beggs(1972) correlation

Flow pattern	**Horizontal Void fraction**	**Inclination factor**
Segregated	$\alpha(0) = 1 - \frac{0.98\lambda^{0.4846}}{N_{FR}^{0.0868}}$	$C = (1-\lambda)\ln\left[\frac{0.011{N_{LV}}^{3.539}}{\lambda^{3.768}N_{FR}^{1.614}}\right]$

Flow pattern	**Horizontal Void fraction**	**Inclination factor**
Intermittent	$\alpha(0)=1-\frac{0.845\lambda^{0.5351}}{N_{FR}^{0.0173}}$	$C=(1-\lambda)\ln\left[\frac{2.96\lambda^{0.305}N_{FR}^{\;\;0.0978}}{N_{LV}^{0.4473}}\right]$
Distributed	$\alpha(0)=1-\frac{1.065\lambda^{0.5824}}{N_{FR}^{0.609}}$	$C=0$

Chisholm (1973) provided the correlation

$$\alpha=\left[1+\left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)\left(\frac{\rho_G}{\rho_L}\right)\sqrt{1-\mathrm{x}(1-\frac{\rho_L}{\rho_G})}\right]^{-1}$$

Mattar & Gregory (1974) developed a correlation applicable to 0° (horizontal) to 10° inclined flows.

$$\alpha=\frac{U_{SG}}{1.3U_M+0.7}$$

Butterworth (1975) provided a remarkable insight by showing the similarity between six correlations. He expressed the correlations in the general form:

$$\frac{1-\alpha}{\alpha}=a\left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)^b\left(\frac{\rho_G}{\rho_L}\right)^c\left(\frac{\mu_L}{\mu_G}\right)^d$$

The Homogenous correlation along with the correlations of Zivi (1964), Turner & Wallis (1965), Lockhart & Martinelli (1949), Thom (1964) and Baroczy (1966) were all shown to follow it while having different values for the coefficients a, b, c and d.

Greskovich & Cooper (1975) gave a correlation for slug flows in inclined pipes

$$\alpha=\left[1+0.671\left(\frac{(\sin\theta)^{0.263}}{\mathrm{Fr}^{0.5}}\right)\right]^{-1}\alpha_H$$

Madsen (1975) developed a model for the void fraction in bulk boiling of water applicable to vertical and horizontal flows.

$$\alpha = \left[1 + \left(\frac{1-x}{x}\right)^{b}\left(\frac{\rho_G}{\rho_L}\right)^{-0.5}\right]^{-1}; \quad b = 1 + \log\left(\frac{\rho_L}{\rho_G}\right)(\log\left(\frac{1-x}{x}\right))^{-1}$$

Mukherjee (1979) presented a correlation applicable to all angles of inclination from vertically upwards to vertically downwards.

$$\alpha = 1 - \exp\left(C_1 + C_2\sin\theta + C_3\sin^2\theta + C_4\frac{\mu_L}{(\rho_L\sigma^3)^{0.25}}\right)\left[U_{SG}\left(\frac{\rho_L}{g\sigma}\right)^{0.25}\right]^{C_5}\left[U_{SL}\left(\frac{\rho_L}{g\sigma}\right)^{0.25}\right]^{-C_6}$$

Here C_1, C_2, C3, C_4, C_5 and C_6 are regression coefficients. It is mentioned that horizontal flow is treated as vertical uphill flow and so the values of the coefficients used are:

Table 2.3 Coefficients for horizontal flow for Mukherjee (1979)

C_1	C_2	C_3	C_4	C_5	C_6
-0.38011	0.129875	-0.11979	2.343227	0.475686	0.288657

Naturally, for the horizontal case, C_2 and C_3 are not required.

Chisholm (1983) gave a modification of the Armand (1946) correlation.

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

Spedding & Chen (1984) presented a correlation for the horizontal annular flow.

$$\alpha = \left[1 + 2.22\left(\frac{1-x}{x}\right)^{0.65}\left(\frac{\rho_G}{\rho_L}\right)^{0.65}\right]^{-1}$$

Tandon et al. (1985) gave a correlation for two phase annular flow.

$$\alpha = \left\{1 - 1.928\,\mathrm{Re}_L^{-0.315}[F(X)]^{-1} + 0.9293\,\mathrm{Re}_L^{-0.63}[F(X)]^{-2}\right\} \qquad 50 < \mathrm{Re}_L < 1125$$

$$\alpha = \left\{1 - 0.38\,\mathrm{Re}_L^{-0.088}[F(X)]^{-1} + 0.0361\,\mathrm{Re}_L^{-0.176}[F(X)]^{-2}\right\} \qquad \mathrm{Re}_L > 1125$$

Where, $F(X) = 0.15 * (X^{-1} + 2.85X^{-0.476})$; X is the Lockhart & Martenelli parameter.

Chen (1986) also presented a correlation for annular flow. It included an empirical parameter 'k'. Various values for k were given according to the different flow conditions and diameters.

$$\alpha = \frac{k}{k + \left(\frac{1-x}{x}\right)^{0.6}\left(\frac{\rho_G}{\rho_L}\right)^{0.33}\left(\frac{\mu_L}{\mu_G}\right)^{0.06}}$$

Hamersma & Hart (1987) presented a correlation for void fractions in the range from 0.96 to 1.

$$\frac{1-\alpha}{\alpha} = 0.26\left(\frac{1-x}{x}\right)^{0.67}\left(\frac{\rho_G}{\rho_L}\right)^{0.33}$$

Kawaji et al. (1987) presented a correlation valid for high pressure steam-water flow with mixture velocity U_M< 1.5 m/s

$$\alpha = 1.05\left[U_{SL}\left[\frac{\rho_L}{gD(\rho_L - \rho_G)}\right]^{0.5}\right]^{0.5}$$

Minami & Brill (1987) proposed a correlation for the entire range of void fractions for horizontal two-phase flow.

$$\alpha = \exp\{-[\frac{\ln Z_1 + 9.21}{8.7115}]^{4.3374}\}$$

Where, $$Z_1 = 1.84\frac{{U_{SL}}^{0.575}g^{0.0924}\sigma^{0.0451}{\mu_L}^{0.1}}{{\rho_L}^{0.1451}D^{0.0277}}\left(\frac{P}{P_{atm}}\right)^{0.05}$$

Spedding & Spence (1988) modified the correlation by Spedding & Chen (1984)

$$\frac{\alpha}{1-\alpha} = [0.45 + 0.08\exp(-100(0.25 - {U_{SL}}^2))](\frac{U_{SG}}{U_{SL}})^{0.65}$$

The correlation of Hart et al. (1989) is developed for very high void fraction range (0.94 and above).

$$\alpha = 1 - \frac{U_{SL}}{U_{SG}}\left[1 + \left(108\frac{\rho_L}{\rho_G}{Re_{SL}}^{-0.726}\right)^{0.5}\right]$$

Kokal & Stanislav (1989) presented their correlation based on the drift-flux model

$$\alpha = \frac{U_{SG}}{1.2U_M + 0.345\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}}$$

Czop et al. (1994) presented a correlation from studies on a helical coiled tube.

$$\alpha = -0.285 + 1.097\alpha_H$$

Abdul-Majeed (1996) provided a correlation by simplifying the mechanistic model of Taitel & Dukler (1976). The final form of the equation is:

$$\alpha = 1 - 0.528(U_{SG}U_{SL})^{-0.216121}(E_L)_{theo}$$

For turbulent flow,

$$(E_L)_{theo} = \exp(-0.9304919 + 0.5285852R - 9.219634 * 10^{-2}R^2 + 9.02481 * 10^{-4}R^4)$$

For laminar flow,

$$(E_L)_{theo} = \exp(-1.1 + 0.6788495R - 0.1232191 * 10^{-2}R^2 - 1.778653 * 10^{-3}R^3 + 1.626819 * 10^{-3}R^4)$$

Where,

$$R = \ln X_A\,; \qquad X_A = \left[\frac{U_{SG}\rho_G\mu_L}{U_{SL}\rho_L\mu_G}\right]^L \frac{\rho_L {U_{SL}}^2}{\rho_G {U_{SG}}^2}$$

With L=0.2 for turbulent flow and L=1 for laminar flow.

The correlation by Petalaz & Aziz (1997) is developed for the annular-mist flow

$$\frac{1-\alpha}{\alpha} = 0.735\left(\frac{\mu_L{}^2 U_{SG}{}^2}{\sigma^2}\right)^{0.074}\left(\frac{1-x}{x}\right)^{-0.2}\left(\frac{\rho_G}{\rho_L}\right)^{-0.126}$$

Gomez et al. (2000) presented a correlation for the slug flow regime valid for all angles of inclination from horizontal to vertical upwards.

$$\alpha = 1 - e^{-(0.45\theta + 2.48\times10^{-6}\mathrm{Re}_M)}$$

Where, $\theta < 1.57$ radians and Re_M is the slug Reynolds number given by,

$$\mathrm{Re}_M = \frac{\rho_L U_M D}{\mu_L}$$

The Zhao et al. (2000) correlation is developed for geothermal two-phase flow

$$\alpha = \left[1 + \alpha^{-0.125}\left(\frac{1-x}{x}\right)^{0.875}\left(\frac{\rho_G}{\rho_L}\right)^{0.875}\left(\frac{\mu_L}{\mu_G}\right)^{0.875}\right]^{-1}$$

Woldesemayat & Ghajar (2007) proposed a new correlation which was a modification of the Dix (1971) correlation. This correlation is expected to handle all angles of inclination from horizontal to vertical upwards.

$$\alpha = \frac{U_{SG}}{U_{SG}\left(1 + \left(\frac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}}\right) + 2.9\left[\frac{gD\sigma(1+\cos\theta)(\rho_L-\rho_G)}{\rho_L{}^2}\right]^{0.25}(1.22 + 1.22\sin\theta)^{\frac{P_{atm}}{P_{system}}}}$$

The leading constant value of 2.9 has a unit such that the drift flux velocity carries the units of m/s. The correlation should be used with parameters in conformance to the International System of Units (SI).

2.4 Experimental Databases

For the purpose of void fraction evaluation, 14 datasets from available literature were used. They covered multiple fluid combinations and a wide range of flow conditions.

The data from the following sources was used. Eaton (1966), Beggs (1972), Spedding & Nguyen (1976), Mukherjee (1979), Minami & Brill (1987), França & Lahey (1992), Abdul-Majeed (1996), Chen et al. (1997), Ottens (1998), Badie et al. (2000) and Wojtan et al. (2004).

The data of Chen et al. (1997), Ottens (1998) and Badie et al. (2000) was provided by Prof. Neima Brauner of Dept. of Fluid Mechanics and Heat Transfer, Tel-Aviv University Ramat-Aviv, Israel. The data of Wojtan et al. (2004) was provided by Dr. Andrea Cioncolini and Dr. John Thome of Laboratory of Heat and Mass Transfer (LTCM), Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland. The author is thankful for their co-operation.

Table 2.4 gives all the datasets and the tube diameters used.

Table 2.4 Brief summary of the datasets used in the present study

Dataset	**Diameter**	**Fluid Combination**	**No. of data points**
Abdul-Majeed (1996)	5.08 cm	air-kerosene	88
Beggs (1972)	2.54 cm 3.81 cm	air-water	58
Eaton (1966)	5.25 cm 10.23cm	natural gas-water	238
França & Lahey (1992)	1.9c m	air-water	88
Minami & Brill (1987)	7.79 cm	air-kerosene	57
Minami & Brill (1987)	7.79 cm	air-water	54
Mukherjee (1979)	3.81 cm	air-kerosene	75
Spedding & Nguyen (1976)	4.55 cm	air-water	270
Badie et al. (2000)	0.78 cm	air-water	36
Badie et al. (2000)	0.78 cm	air-oil	30
Ottens (1998)	0.51 cm	air-water	42
Chen et al. (1997)	0.78 cm	air-kerosene	48
Wojtan et al. (2004)	1.59 cm	R22 vapour-liquid	116
Wojtan et al. (2004)	1.59 cm	R410A vapour-liquid	121
TOTAL			*1321*

The details of all datasets are given in Appendix 4.

Chapter 3. Experimental Setup

The data for this study was collected using the experimental setup present at the Two Phase Flow Lab of Oklahoma State University. The distinguishing feature of the setup is its ability to study pressure drop, void fraction, and non-boiling heat transfer measurements as well as flow visualization at any angle of inclination from positive to negative 90^{o}. The setup was built by Wendell Cook, a former Masters' student and team member of the research group. It has been discussed in detail in Cook (2008). In this chapter, a brief summary of the same is given along with the data collection methodology used.

3.1 Details of the Setup

Figure 3.1 shows a schematic diagram of the setup. The Flow Visualization/Void Fraction Branch and the Heated Branch are the test branches of the setup where various aspects of the two-phase flow are studied. Both of these branches are fixed to a test platform. The test platform is mounted on a variable inclination frame, which can orient it at any angle from $+90^{o}$ to -90^{o}. The rest of the setup consists of the air and water circuits and the data acquisition system.

The inside diameter of the tube used in the experimental setup for flow pattern and void fraction studies is 0.0127 m. The tubes are made from polycarbonate. The working fluids used for the present study are air and distilled water.

3.1.1 Air circuit

An industrial air compressor (Ingersoll-Rand T30, 2545) is used in the setup. It sends the air to a regulator/filter-drier assembly. Next, the air passes through a heat exchanger. The heat exchanger consists of a copper coil submerged in running tap water. After this, the air is passed through a second filter-drier assembly and then regulated via a needle valve (Parker 24NS 82(A)-V8LN-SS). The regulated air is sent to either of the two gas flow meters. For high air flows, the Micro Motion Elite Series model

CMF 025 is used while for low air flows model LMF 3M of the same series is used. From here, the air goes to a tee junction where it is mixed with water and then sent to the test branches.

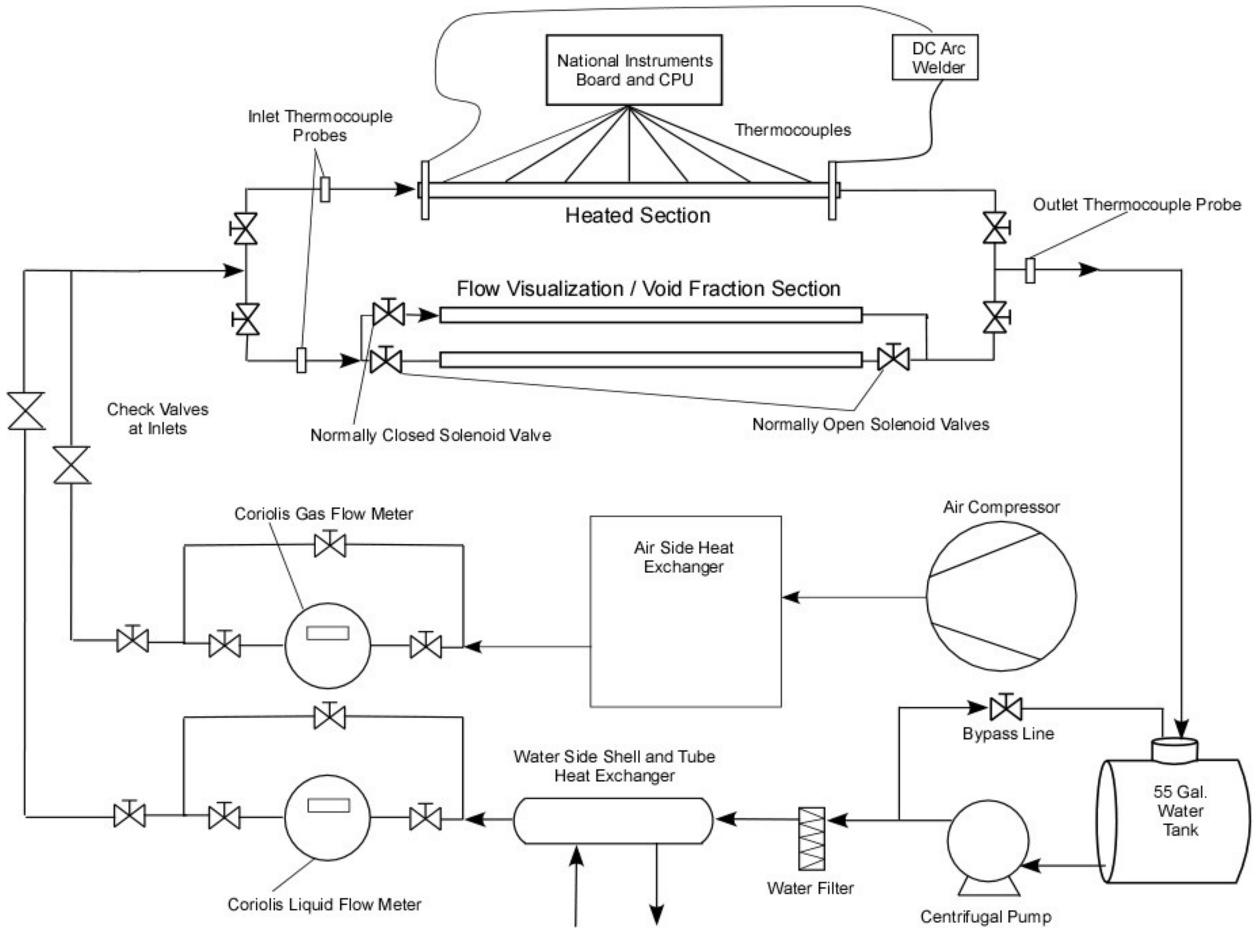

Figure 3.1 Schematic of Experimental Setup (From Cook (2008))

3.1.2 Water circuit

Distilled water used in the setup is stored in a 208.2 L (55 gal) cylindrical tank. It is pumped through the system by a centrifugal pump (Bell and Gosset, series 1535, model 3545 D10). From the pump, the water travels via a water purification system (Aqua-Pure AP12T) to the heat exchanger. The heat exchanger is a one shell and two-tube pass type (ITT Standard, BCF 4063.) The water used in the shell is drawn from the same supply as that used in the air side heat exchanger. This ensures similar temperatures for the air and water used in the system. After the heat exchanger, the water passes through the coriolis flow meter (Micro Motion Elite Series model CMF 100). A gate valve located immediately after the flow meter is used to control the flow rate. The water is next mixed with the air in the tee junction and sent to the test branches.

At the outlet of the test branches, the two lines are combined and two-phase mixture is carried to the water tank. Here the air is vented to the atmosphere while the water gets collected in the tank and reused.

3.1.3 Test Branches

The Flow Visualization / Void Fraction Branch and the Heated Branch are the two test branches in the setup. The two phase mixture can be passed through either of the two. This is achieved by using quarter turn ball valves at the inlet of the two branches. At the end of the testing area, the two branches converge. Both branches have individual static mixers at the inlet and a common outlet mixer. The Heated Branch was not used in the present study and thus is not discussed here. Figure 3.2 shows a photograph of the top view of the test platform and the test branches.

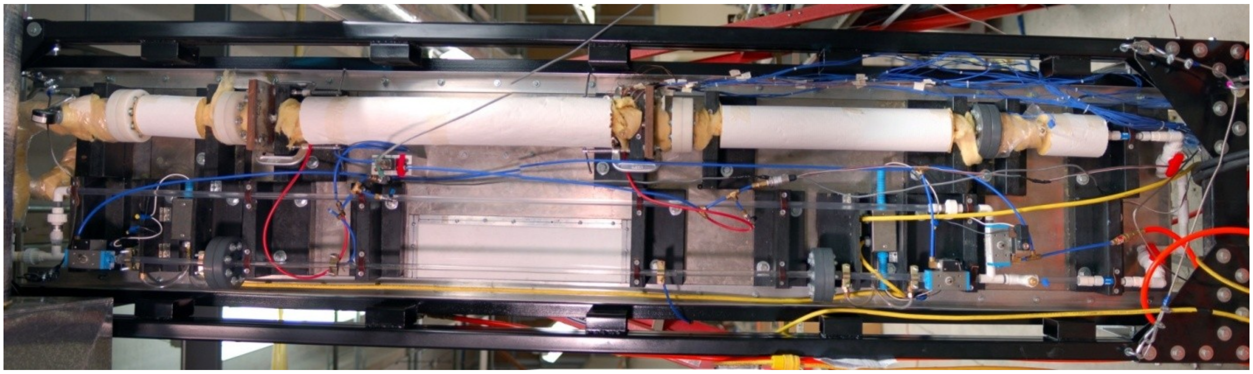

Figure 3.2 Top View of test platform (Adapted From Cook (2008))

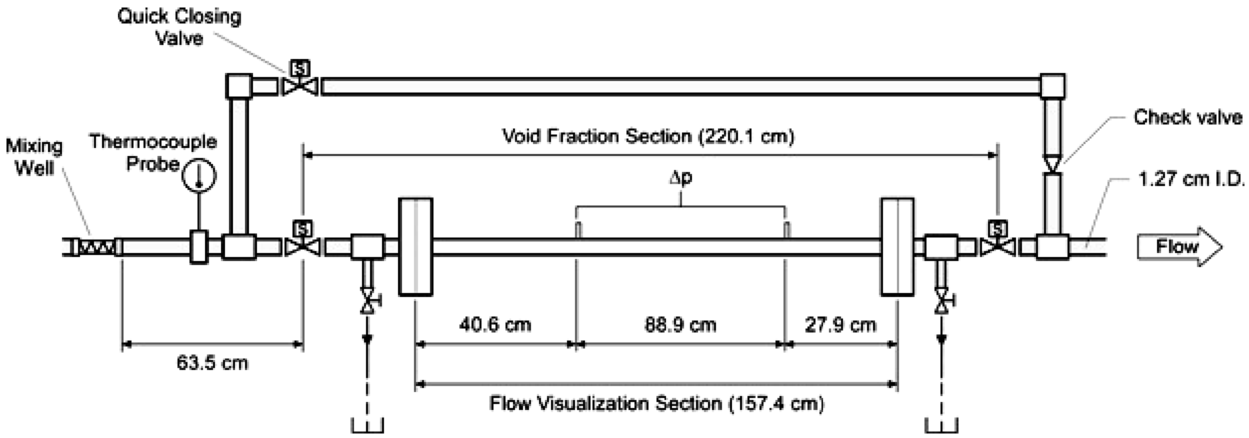

Figure 3.3 Details of the Flow Visualization / Void Fraction Branch (From Cook (2008))

3.1.3.1 Flow Visualization / Void Fraction Branch

Figure 3.3 shows the details of the Flow Visualization / Void Fraction Branch. There are four major sections: mixing section, flow visualization section, void fraction system and the thermocouples array.

3.1.3.2 Mixing Section

The two-phase mixture generated by the tee junction is further mixed by the inlet static mixer. This ensures that the inlet geometry does not affect the flow patterns observed in the flow visualization section and also enables the inlet thermocouple to measure a representative temperature for the two-phase mixture. The mixer used is a Koflo model 3/8-40C-4-3V-2 3/8in. This shared outlet mixer (Koflo 1/2-80-4C-3-2), is placed just before the exit thermocouple probe and also helps to measure the representative temperature of the mixture.

3.1.3.3 Thermocouples Array

For this branch, the thermocouple probes serve the sole purpose of verifying that the process is a constant temperature process. Two probes (Omega TMQSS-06U-6) are used; one at the inlet and one at the outlet. The outlet probe is common for both branches and placed after the outlet mixer mentioned above.

3.1.3.4 Void Fraction System

The setup uses the ‘quick closing valves technique’ for void fraction measurement. Three solenoid controlled pneumatic ball valves (W. E. Anderson ABV1DA101) are used. The solenoid controllers (Dynaquip Controls 145750.01) are operated by air at pressure of 689.5 kPa (100 psi) from the lab air compressor. When the valves are triggered, the two valves on the main line close and trap a portion of the two phase mixture between them. The third valve on the bypass line opens simultaneously and allows the flow through the system to continue unhampered.

The trapped water is then drained into a tank via a series of four valves and clear PVC tubes. In cases when fluid remains in the section after initial draining, one of the PVC tubes is disconnected from the tank and instead used to force compressed air through the section for thorough water removal. The water is then weighed and the mass is converted to volume.

Using the length of the pipe between the two valves and the diameter of the tube, the volume of the void fraction section is determined. The void fraction can be easily determined using the formula:

$$\alpha = 1 - \frac{volume\ of\ water\ trapped}{volume\ of\ void\ fraction\ section}$$

3.1.3.5 Flow Visualization Section

This section is used to make visual observations of the flow patterns and record them on photographs and videos. The central portion of the void fraction system serves as the flow visualization section. It is made from clear polycarbonate tubing of 1.27 cm (0.5 in) ID and is 157.4 cm (62 in) in length. The choice of material was made due to its optical clarity. This section also includes the pressure taps needed to record pressure drop across the section.

3.1.4 Data Acquisition System

A National Instruments Data Acquisition System is used to collect the data from the setup. The chassis, modules and the terminal blocks make up the system. The chassis model used in the setup is SCXI 1000.

It is AC powered and four slots for modules and accompanying terminal blocks. Two 32 channel analog modules (SCXI 1102) and one 8 channel analog module (SCXI 1125) are employed for signal conditioning. The terminal blocks serve as the direct connection to the various devices being monitored. Model numbers for the terminal blocks connected to the 32 and 8 channel modules were SCXI 1303 and SCXI 1313, respectively.

The data is recorded and stored on a computer using the software LabVIEW. The original program was developed by Jae-yong Kim, a former PhD candidate. The modifications needed to adapt the program to this setup were performed by Clement Tang, current PhD candidate and member of the research team.

3.2 Data Collection Methodology

Data Collection on the setup is preceded by Pre-Operation Checks and System Warm Up, and followed by System Shut Down. Cook (2008) has details of all of these. The actual data collection may be for either of the two purposes, flow visualization or void fraction. In both cases, the observations were made in a methodical way to cover the entire available range of liquid and gas flow rates. The liquid flow rate was held constant and the gas flow rate was varied in incremental steps from the lowest to the highest obtainable value. Then the liquid flow rate was changed to the next incremental value and the process repeated. Care was taken to ensure that temperature does not fluctuate beyond acceptable limits.

3.2.1 Flow Visualization

The final aim of the data collected for this part is development of a flow map for the setup. Visual observations were made to this effect. Photographs and videos were taken to document the various flow patterns for future reference.

It was initially thought to use photographs and videos as supplements to visual observations for flow pattern recognition. However, it was found that at high velocities the two were ineffective in determining the flow pattern boundaries. This was due to the narrow field of view available via the cameras. On the other hand, observations through the naked eye offered a wide field of view and lead to better understanding of the flow. Thus it was decided to rely only on visual observations for flow pattern recognition and use photos and videos to record representative samples.

The steps followed for visual observations were as follows:

1. The desired flow rates (air and water) were set.
2. After the flow had stabilized, the system pressure and temperature were noted.
3. The flow pattern was observed and recorded. Along with classification of the flow into the known patterns, brief descriptions of the observed flow were also made. This was done to facilitate the proper understanding of the flow transition zones and also serve as a memory-aid for later reference. Since the observations were made over a period of several weeks, this technique was used to make the reporting less prone to the variations in interpretation on different days.

A digital video camera (Sony Handycam DCR-VX2100) was used to record the videos of the flow patterns. It has shutter speeds up to 1/10,000th of a second, frame rate of 1/60th of a second and video resolution of 3.8 megapixels. Photographs were taken with a digital SLR (Nikon D50) having a maximum shutter speed of 1/4,000th of a second and resolution of 6.0 megapixels.

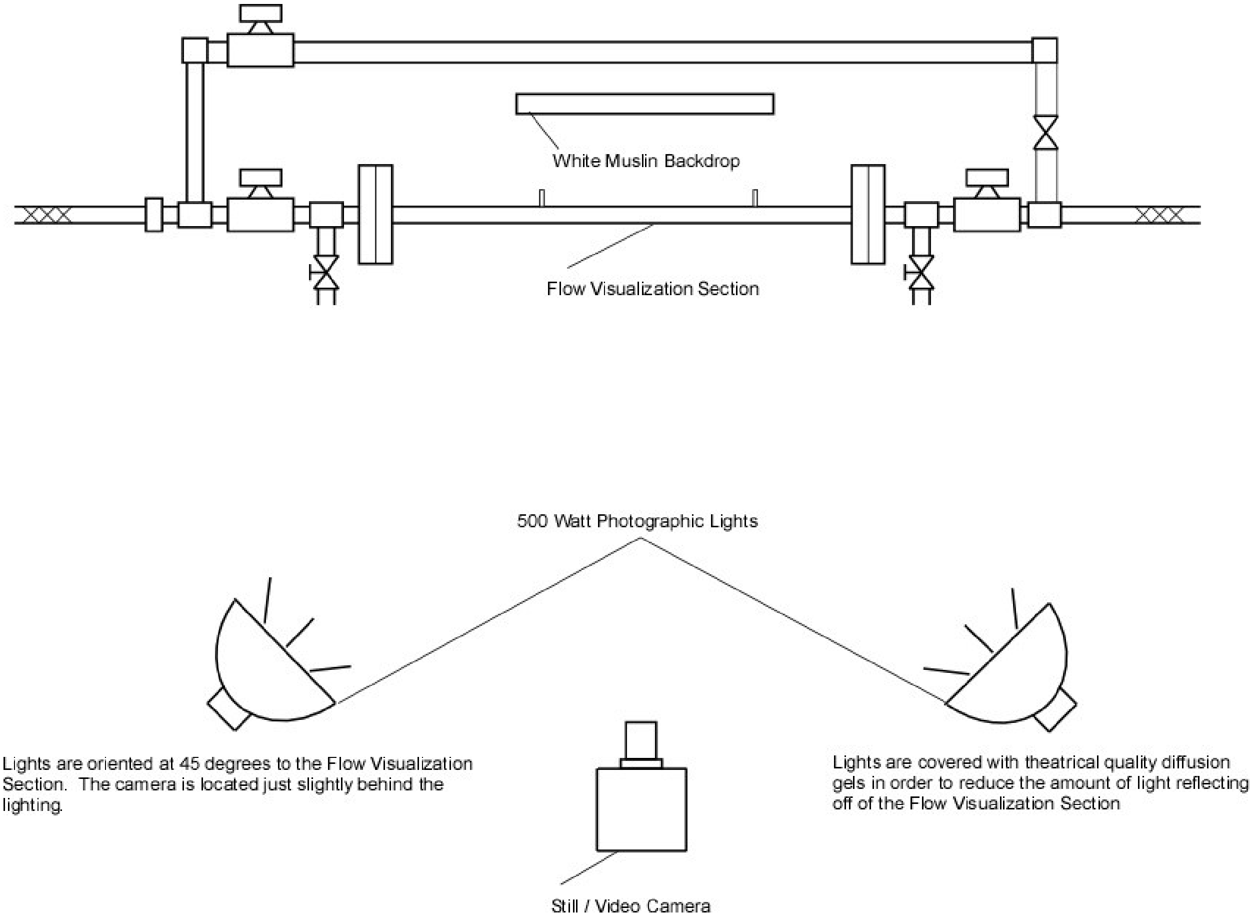

Figure 3.4 Setup for Photos and Videos (From Cook (2008)

The methodology for taking photographs and videos as set by Cook (2008) was closely followed. Figure 3.4 shows the setup used. Two sets of lights were placed at approximately 45^{0} to the flow visualization section. Diffusers were used on the lights to minimize glare on the tube. The camera was placed on a tripod slightly behind the lights. A white muslin cloth was used as the background.

3.2.2 Void Fraction

The steps followed for void fraction data collection are as follows:

1. The desired flow rates (air and water) were set.
2. After the flow had stabilized, the Data Acquisition System was used to record the system data.
3. Next, water was trapped in the void fraction system and the actual void fraction determined:

$$\alpha = 1 - \frac{volume\ of\ water\ trapped}{volume\ of\ void\ fraction\ section}$$

4. The procedure was repeated to obtain more readings for the same flow rates based on the criteria below.

The criteria used to determine the number of readings needed for a certain flow rate combination were as follows:

1. Two initial readings were taken. If the two were within the acceptable tolerance, then the average of the two was used, and no further readings were deemed necessary.

   The acceptable tolerance for difference between two void fraction readings was set as 2 grams difference in the weight of the water collected in the tank. This translates to an approximate error of 6% at the higher void fractions and 1% at the lower void fractions. The high accuracy obtained at lower void fractions is beneficial while comparing results with the predictions of correlations, since that process introduces higher errors at lower void fractions. This is further discussed in section 3.3.

2. If the two initial readings did not conform to each other within the acceptable tolerance, more readings were taken until any two readings were within the acceptable tolerance.
3. In the rare cases where despite multiple readings a satisfactory result was not obtained, the readings were re-taken at a different time and the previous readings of that flow rate combination were disregarded. This variability is attributed to the dynamic nature of two-phase flow.

While the data was being collected, a close watch was kept on the trend of the void fraction variation with the liquid and gas flow rates. This served as a secondary check to ensure proper data collection methodology and validity of the data. This is shown in Figure 3.5.

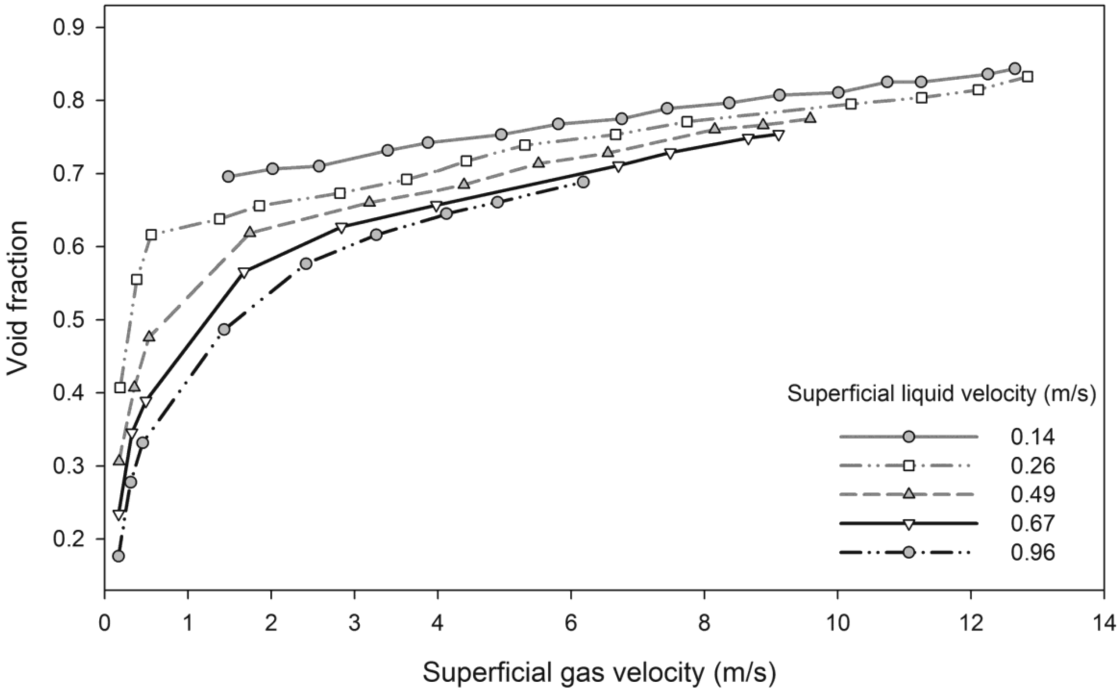

Figure 3.5 Variation of void fraction with superficial gas and liquid velocities for data from present study

3.3 Validation of the Collected Data

It is necessary to establish the validity the data collected via the above process before continuing the study to establish a flow map and evaluate various void fraction correlations. The two factors that have to be checked are the accuracy and capability of the setup and the verification of the data collected as a part of the present study.

Cook (2008) has verified the data collection ability of the setup through uncertainty analysis and also comparisons of the void fractions obtained on the setup with the data of other researchers. Three main parameters were selected for the uncertainty analysis: friction factor, void fraction and heat transfer coefficient.

For void fraction, the uncertainty associated with the mass of the liquid drained from the test section and the resolution (least count) of the scale involved were analyzed. Noting that the uncertainty would be different at different void fractions (VF), the best and worst case scenarios were calculated. Table 3.1 shows these runs.

Table 3.1 Uncertainty analysis at best and worst conditions (from Cook (2008))

Condition	α	Uncertainty	
High VF	0.864	± 0.0108	± 1.25%
Low VF	0.284	± 0.0117	±4.16%

Cook (2008) also compared the void fraction values with the horizontal flow data of França & Lahey (1992), Spedding & Nguyen (1976) and Minami & Brill (1987). It was reported that 82% of the data points were found to be comparable within ± 15%.

For the present study, the data obtained was also subjected to similar tests. The value of void fraction measured was lower than that used in the uncertainty analysis above. Thus it is recalculated. The results for the present study obtained from the same method as followed by Cook (2008) are given in Table 3.2.

Table 3.2 Uncertainty analysis at best and worst conditions for the present study

Condition	α	Uncertainty	
High VF	0.8432	± 0.0108	± 1.28%
Low VF	0.1405	± 0.0122	±8.6%

For a head-on comparison with external data, a total of 43 points were selected from the available datasets. While an exact match of the flow parameters cannot be expected, the points were selected such that the superficial velocities (gas and liquid) matched within ±10%. Figure 3.6 shows this comparison. As it can be seen, most of the points are inside the 15% error bands. França & Lahey (1992) have reported the accuracy of their data to be within ±5%. The accuracy for the other datasets used for this comparison is either not mentioned or not available to the author. When the head-on comparison is done with only the datapoints from this dataset, excellent results are obtained. Figure 3.7 shows this comparison. Incidentally, the tube diameter in the study of França & Lahey (1992) (19 mm) is closest to that used in the present study (12.7 mm) among all datasets. As it can be seen, all points are within ±5% of the compared values.

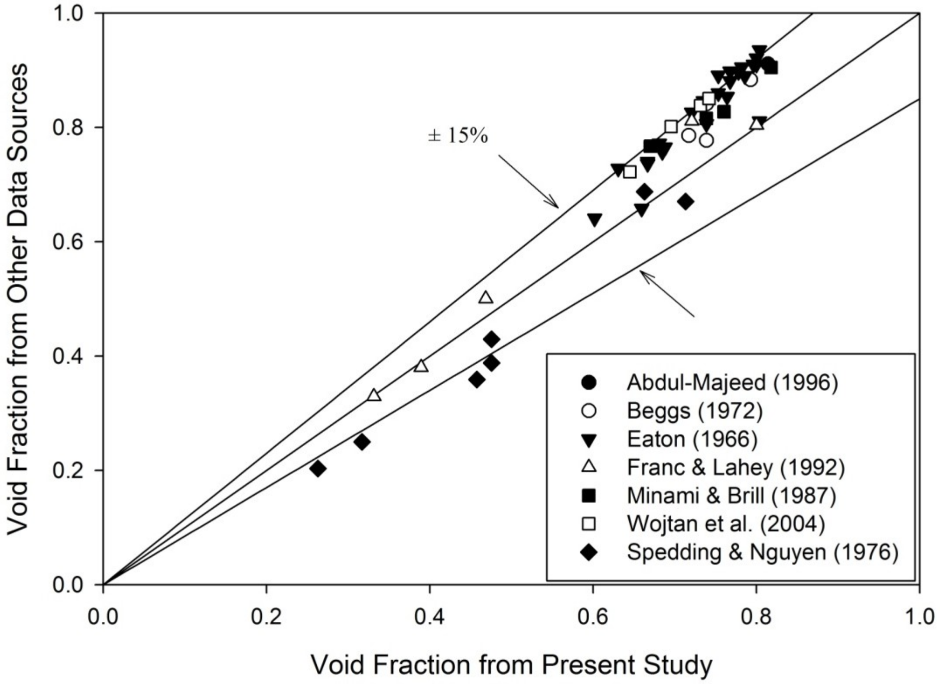

Figure 3.6 Comparison of void fractions from present study with external datapoints

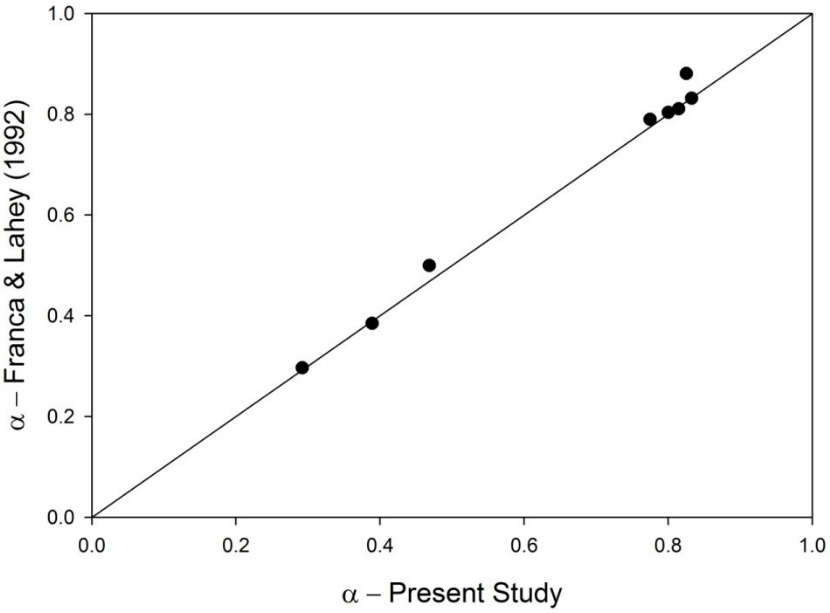

Figure 3.7 Head-on comparison of present data with data of Franca & Lahey (1992)

Another verification mentioned employed by Cook (2008) is the comparison of the data with some popular correlations. However, since evaluation of correlations is one of the aims of this study, it is deemed that such a validation would be unjust and consequently has not been followed.

As such, no objective criteria exist for determining the setup's accuracy with regards to the flow patterns. However, it was demonstrated by Cook (2008) that the setup could recreate some of the flow patterns found in the existing literature. Comparison of the flow patterns and the final flow pattern map with other researchers' flow maps is the only method that can be employed. The flow map for the present study is compared with other flow maps in the next chapter.

Chapter 4. Flow Patterns

530 data points were used to make flow pattern observations covering the entire available flow range to determine a flow pattern map. A variety of flow patterns were observed. As mentioned in the literature review, the definitions of the flow patterns are very subjective and there is no universal agreement among the researchers. Thus to avoid confusion, it was decided that the flow patterns would be classified only into broad categories. These categories have been recognized by most researchers to be observed in horizontal two phase flow. These can be classified into four main categories; Bubbly Flow, Plug Flow, Slug Flow and Annular Flow.

4.1 Data Collection Procedure

The observations were made in a methodical way to cover the entire available range of liquid and gas flow rates. The liquid flow rate was held constant and the gas flow rate was varied in incremental steps from the lowest to the highest obtainable value. Then the liquid flow rate was changed and the process repeated. Care was taken to ensure that temperature does not fluctuate beyond acceptable limits. For every reading, first the desired combination of flow rates was set. The flow was allowed to settle for about a minute. Visual observations were then made at the flow visualization section of the tube. (The location of the flow visualization section is shown in Fig. 3.1 in the previous chapter. Figure 3.3 shows the details of the same.) The system pressure and temperature were also recorded. Along with classification of flow into the known patterns, brief descriptions of the observed flow were also written. This was done to facilitate the proper understanding of the flow transition zones and also serve as a memory-aid for later reference. Since the observations were made over a period of several weeks, this technique was used to make the reporting less prone to the variations in interpretation on different days.

It was noticed that the range of gas flow rates available was not uniform across the range of the liquid flow rate. At higher liquid flow rates, the range of gas flow rates available reduced greatly. Higher flow rates could not be attained as the higher back pressure associated with the increased gas flow rate would act upon the liquid flow rate and reduce it.

A mention about the use of two gas flow meters is also in order. Since the range of coverage of the two meters does not overlap, data could not be obtained in the range from 0.0075 kg/min to 0.016 kg/min gas flow rate. Incidentally, the flow pattern observed on either side of this gap was found to be the same for all liquid flow rates. Thus it is safe to assume that the gap will not affect the integrity of the flow map.

4.2 Flow Pattern Descriptions

This section describes the flow patterns identified in the current study. An effort has been made to keep the terminology and descriptions similar to those found most commonly in open literature.

4.2.1 Bubbly Flow (or Dispersed Bubbly Flow)

This flow pattern was observed at high liquid flow rates. As seen in Fig. 4.1, small bubbles are seen distributed in the liquid core. Higher concentration of bubbles in the upper half of the tube is observed due to buoyancy. The interface between the bubbly upper half and the relatively clear lower half appeared to have waves on it.

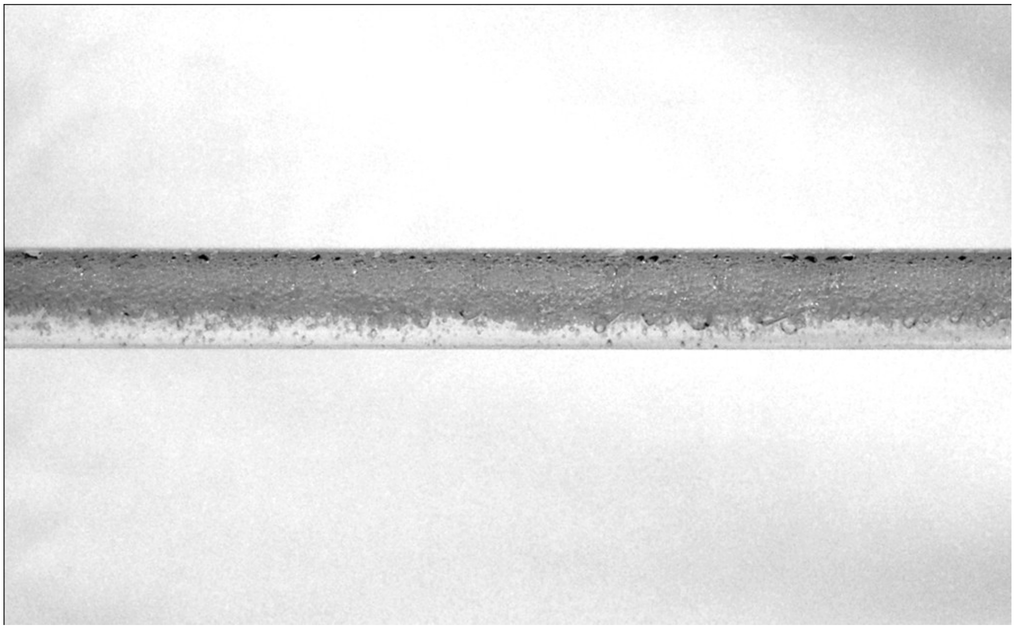

Figure 4.1 Dispersed Bubbly Flow observed in the present study

4.2.2 Plug Flow

In this flow pattern, water can be seen to occupy most of the tube. The air is transported across the tube length as pockets (called plugs) that move along the top of the tube. These plugs may be small and resemble large bubbles or may be long as shown in Fig. 4.2. The long plugs are also referred to as elongated bubbles (Mandhane et al. (1974)).

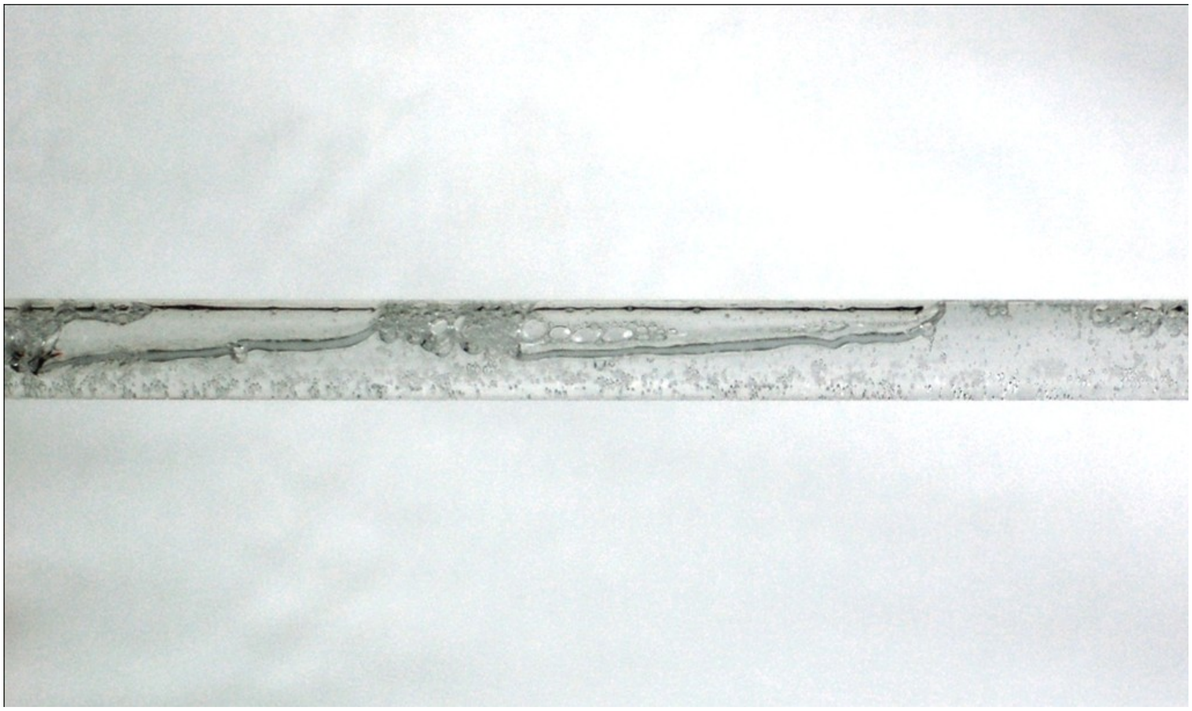

Figure 4.2 Plug Flow observed in the present study

4.2.3 Slug Flow

This flow pattern is found to occur in the central parts of the flow ranges. Lower flow rates, make it easy to observe the flow. As can be seen in Fig. 4.3 the liquid occupies the bottom of the tube. Frequent slugs of liquid that occupy the whole cross section of the tube and are 4-6 inches in length are the main characteristic of this flow pattern. At lower flow rates, it can be observed that majority of the slugs are aerated and become highly aerated at higher flow rates. Similar observation has been made by Lin & Hanratty (1987).

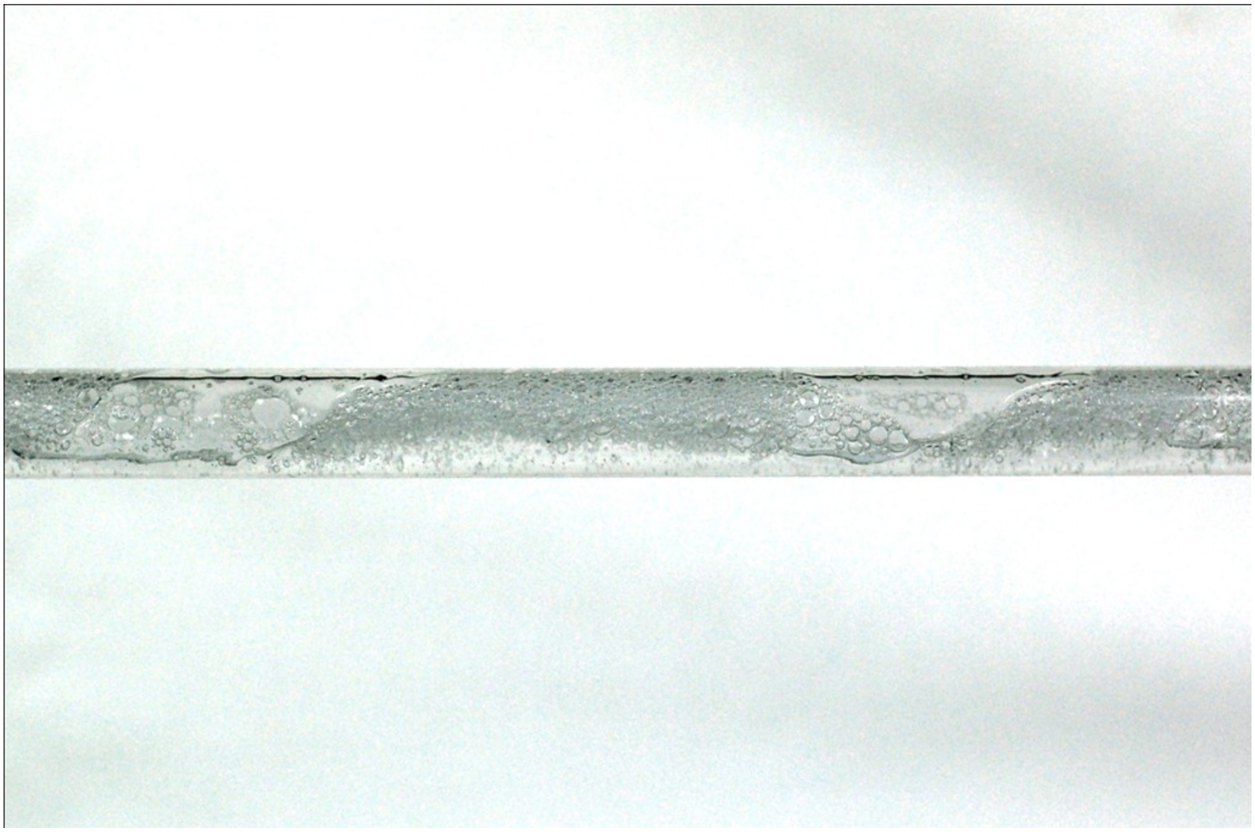

Figure 4.3 Slug flow observed in present study

4.2.4 Wavy Annular Flow

At higher gas flow rates, the flow becomes more and more agitated and chaotic. The flow resembles the Wavy-Annular Flow defined by Barnea et al. (1980). As aptly described in that work, most of the liquid flows at the bottom of the tube, and the upper walls are intermittently wet by large aerated waves sweeping through the tube.

For flow combinations of high liquid flow rate and moderate to high gas flow rate, the Wavy-Annular flow is too fast to be accurately observed and described. It is likely to have changed to Bubbly/Slug or Annular/Bubbly/Slug flow of Kim & Ghajar (2006) who have photo-documented the flow patterns. Figure 4.4 shows this flow as observed during the present study.

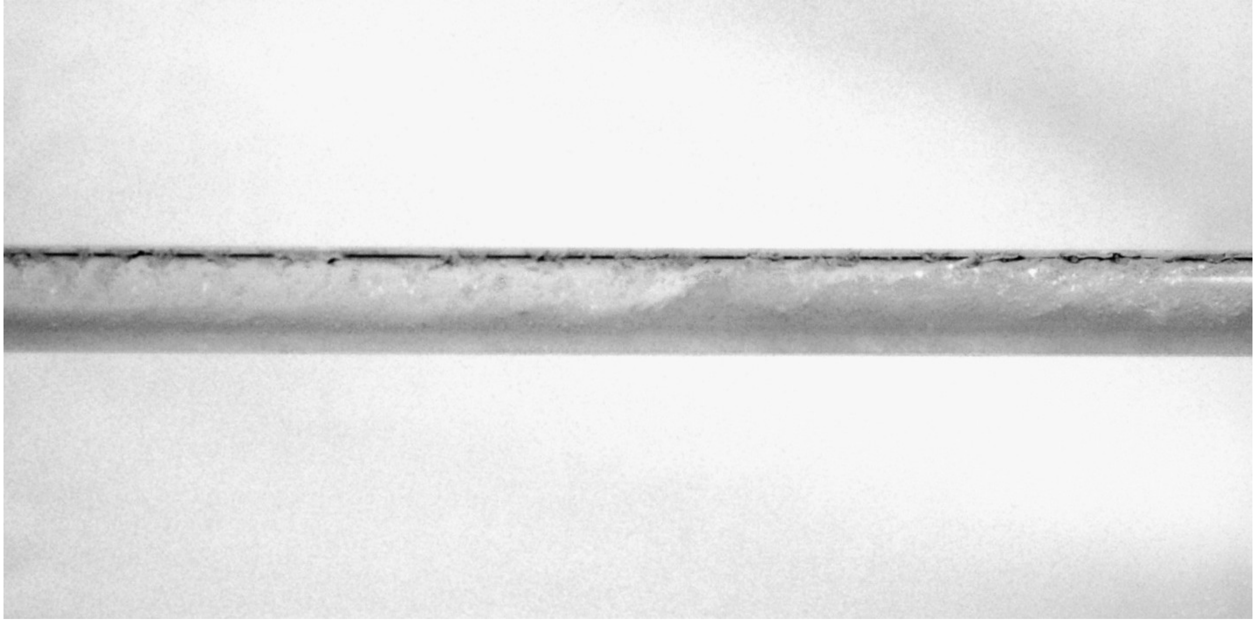

Figure 4.4 Wavy Annular flow observed in the present study

4.2.5 Annular Flow

This flow is not very evidently recognized when glanced at for the first time. This is because, the tube wall are completely covered with water in the annular film and gas flows in the central core. Thus one cannot observe distinguishable features like bubbles, or plugs etc. The presence of the film all around can be recognized due to the ripples seen on the surface of the film in contact with the gas core. Also it can be perceived that the tube is not full of water, despite the walls being wet, due to a 'hollowness' that can be seen when comparing to the appearance of bubbly flow. Figure 4.5 shows this flow pattern.

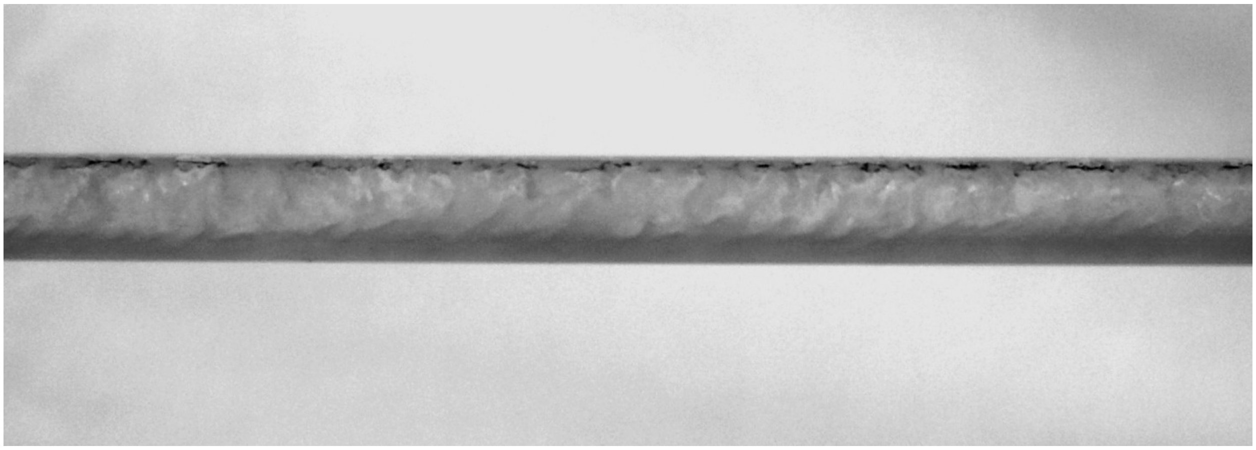

Figure 4.5 Annular flow observed in the present study

4.2.6 Flow Pattern at Lowest Mass Flow Rate

The observations made for the lowest liquid flow rate are also to be noted here. The flow pattern seen in this case appears to be very close to transition to stratified flow especially for low gas flow rates. In the plug flow region, there is an almost continuous train of gas plugs separated only by a very thin (around 1mm) film of water. Rarely is the entire cross section of the tube covered by water. However, since actual transition to stratified flow is not complete, no transition line can be drawn. Instead this row of data (lowest liquid rate) is not considered at all for the purpose of determining transition lines. It is labeled as unclassified flow in the map in Figure 4.7. Figure 4.6 shows a photograph of this flow.

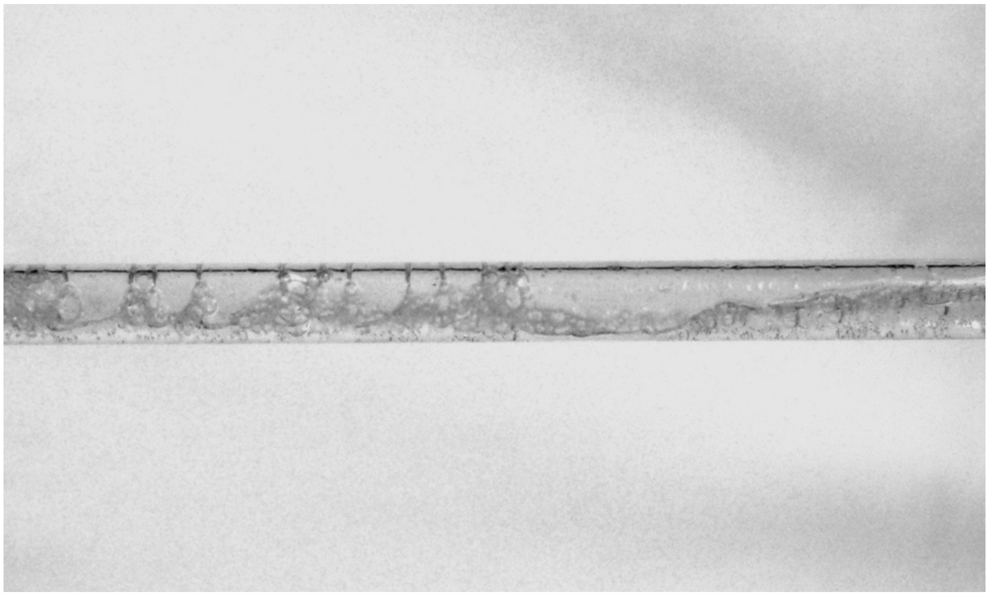

Figure 4.6 Flow observed in the present study at lowest liquid and gas flow rates

4.3 Flow Pattern Map

The observed flow patterns were plotted on a flow pattern map that had the gas and liquid superficial velocities on the x and y axes respectively. Figure 4.6 shows this map.

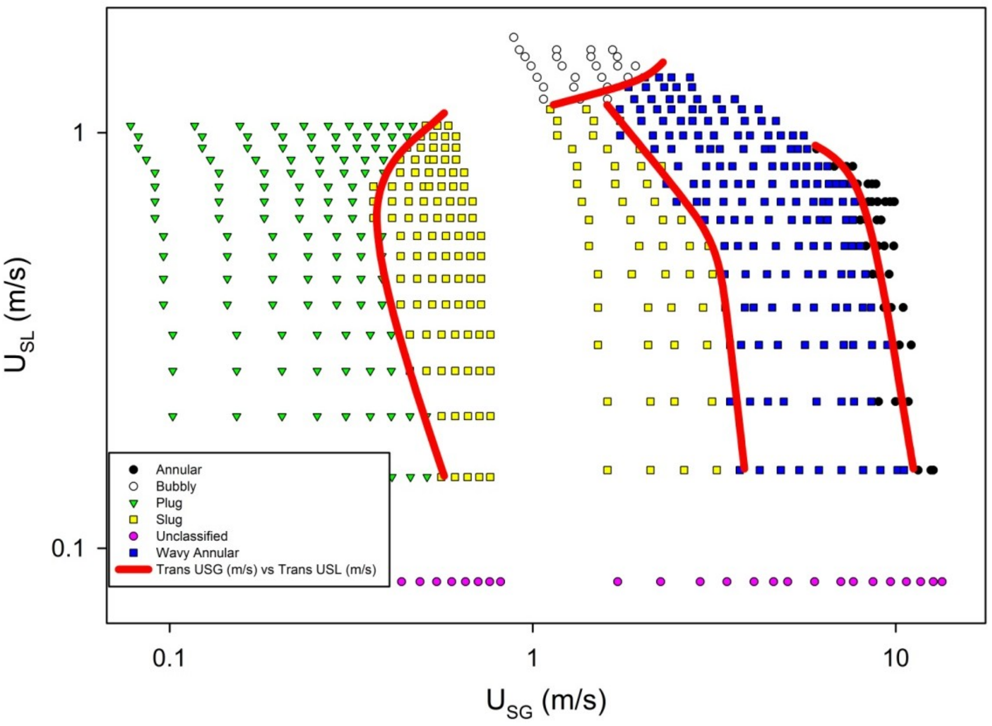

Figure 4.7 Flow map for present study with superficial velocities as coordinates

The map represents all the flow patterns described in the previous section. It must be remembered that the transition of one flow pattern into another is not instantaneous. It is rather gradual and as such must be interpreted as a wide band or zone with the transition line shown to be in the center of the band. The transition lines can be approximated as smooth curves. The map developed is from data collected on a tube with diameter 12.7 mm with air and water as the working fluids and must be used accordingly.

As previously mentioned, there is a gap in the map due to the use of two gas mass-flow meters with non-overlapping ranges. The flow pattern observed on either side of the gap at all liquid flow rates was slug flow. This makes the gap insignificant for purpose of flow map generation. Note that the gap appears to be much larger than it is due to the use of logarithmic scales for this and subsequent maps. The said gap is from 0.0075 kg/min to 0.016 kg/min gas flow rate. Due to the base of the log scale being 10, it stretches a large portion of the gap. If it is assumed that the range of the high flow meter had extended to include the gap, it would only add two data points to the plot. Since this is small compared to the number of points on either side of the gap, it is safe to assume that there is no loss in accuracy due to the gap.

The choice of the coordinate system for the map was made due to a number of reasons. Simplicity of use combined with the observation of Mandhane et al. (1974) that more complicated coordinate systems do not seem to provide a significant advantage make a strong case for the use of superficial liquid and gas velocities as the coordinates for the map. Researcher often used this system as a base for comparing their map with other maps.

4.4 Comparison with other Maps

In this section, we compare our map with the other maps available in open literature. The maps selected in this comparison are those that are most commonly quoted by researchers.

4.4.1 Comparison with Mandhane et al. (1974) Map

This map was developed from air-water data taken in tubes of diameters in the range 0.5-6.5 in (1.27 cm to 16.51 cm). The map identifies only one flow pattern between plug flow and annular flow, namely, slug flow. As noted by Barnea et al. (1980) the annular-wavy pattern is included in the slug flow regime. This is observed in some other maps as well. Figure 4.8 shows the flow map of the present study superimposed on the map of Mandhane et al. (1974). It should be noted that the map of Mandhane et al. (1974) does not account for different diameters having an effect the flow patterns. However, the work of Weisman et al. (1979) shows a very definite diameter effect on flow pattern transitions.

The following observations can be made regarding flow pattern predictions. The plug to slug transition for the data from the present study matches reasonably to that predicted by the map. The deviation may be attributed to the said diameter effect. The transition between the annular and slug flow regimes appears to be considerably mismatched. Weisman et al. (1979) also observed a similar disparity. They point out that Mandhane et al. (1974) had very scattered data in this region of transition. The transition to the dispersed bubbly regime appears to occur at lower rates for the experimental data of the present study. However, the map failed to accurately predict this transition even for the data that was used in the original study by Mandhane et al. (1974). The map also has the transitions of the plug and slug flows to the stratified and wavy flows respectively. These lines almost correspond to the lowest values of the liquid flow rates for the present data.

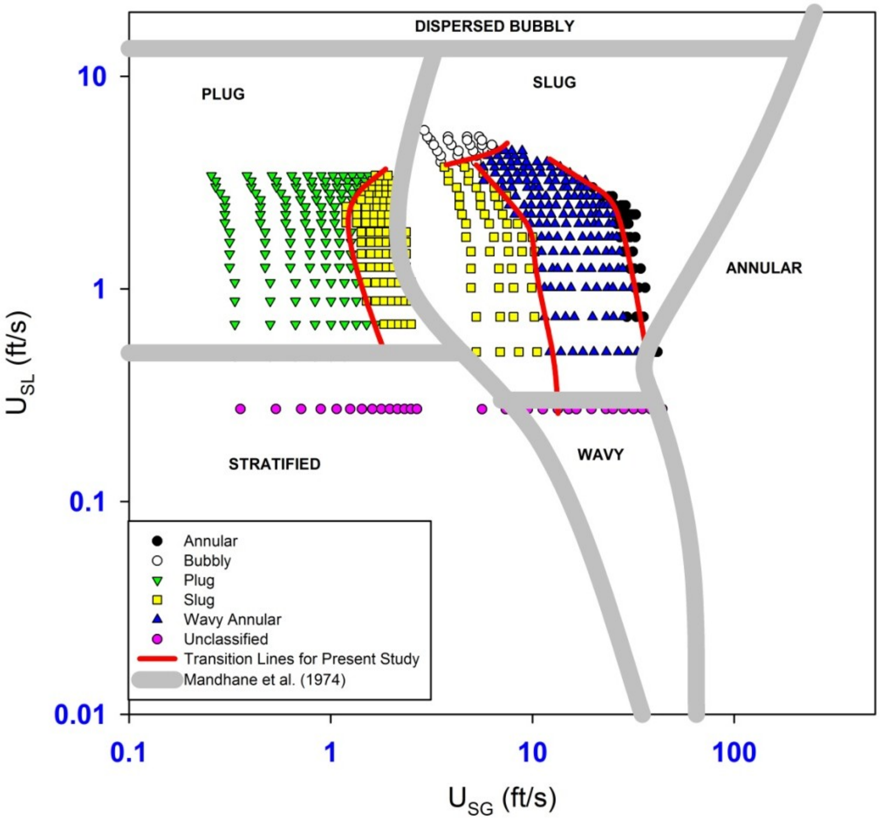

Figure 4.8 Data from present study compared with Mandhane et al. (1974) map

4.4.2 Comparison with Baker (1954) map

This map uses two parameter groups for its axes. $G_l.\lambda\psi/G_g$ for x-axis and G_g/λ for y-axis.

Where $$G_l = \frac{\dot{m}_l}{(A\rho_l)}, \qquad G_g = \frac{\dot{m}_g}{A\rho_g},$$

and $$\lambda = \left(\frac{\rho_l}{\rho_{go}}\frac{\rho_l}{\rho_{lo}}\right)^{0.5}, \psi = \left(\frac{\sigma_o}{\sigma}\right)\left[\frac{\mu_l}{\mu_{lo}}\left(\frac{\rho_{lo}}{\rho_l}\right)^2\right]^{\frac{1}{3}}$$

Where ρ_{go}, ρ_{lo}, σ_o are the air density, water density and the surface tension of water, respectively, at one atmosphere pressure and room temperature. The map is developed from data taken on 1, 2 and 4 inch pipes. Figure 4.9 shows the flow map of the present study superimposed on the map of Baker (1954).

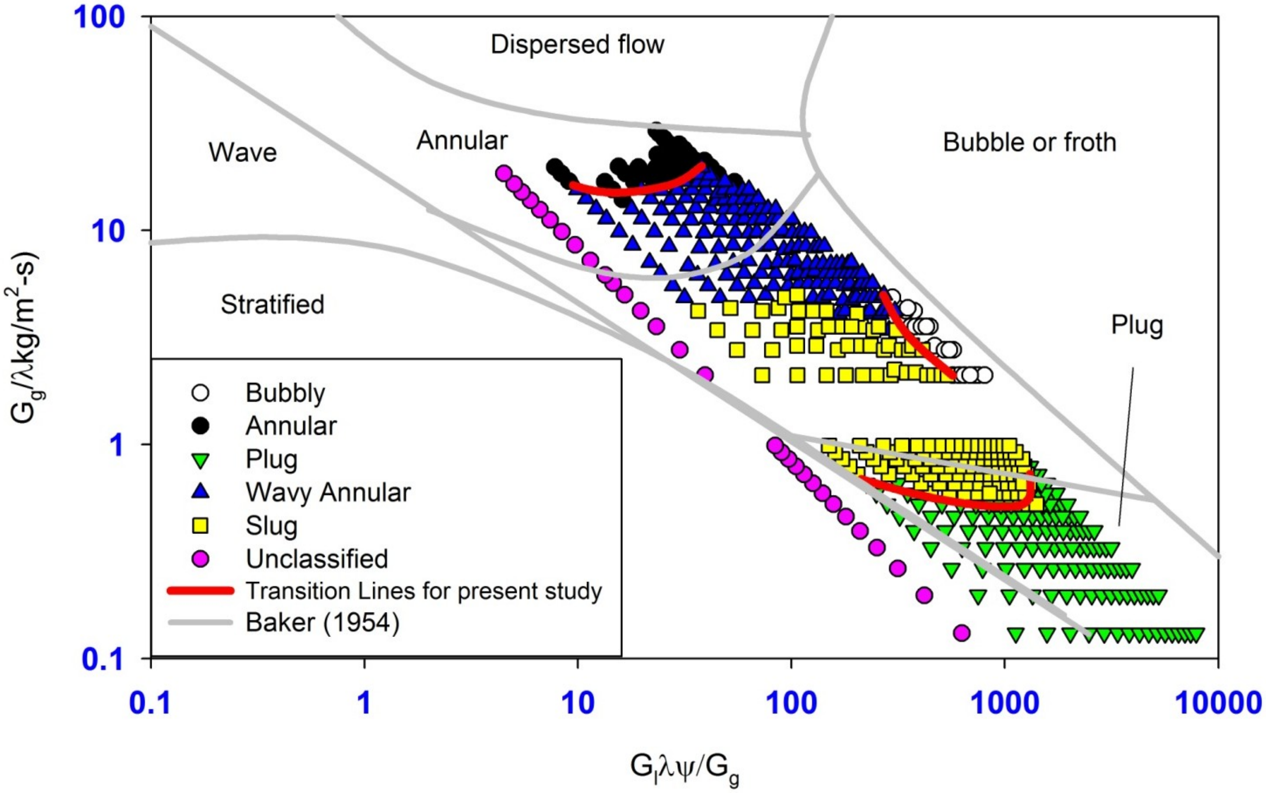

Figure 4.9 Data from the present study compared with Baker (1954) map

It can be clearly observed that the intermittent to annular transition line passes through the wavy slug regime of the data. The plug to slug transition is in reasonable agreement. The transition line between stratified flow and slug flow and stratified flow and plug flow appears near the lowest liquid flow level for the data. It appears that the transition to dispersed bubbly flow occurs at lower liquid flow rates for the experimental data as compared to the prediction of the map.

4.4.3 Comparison with Weisman et al. (1979)

The map uses superficial velocities adjusted to account for different densities, surface tension values and diameters according to the specific setup. $U_{SL}/\ \Phi_2$ is plotted on x-axis and $U_{SG}/\ \Phi_1$ is plotted on y-axis. Φ_1 and Φ_2 assume different parametric forms depending on the specific transition under consideration (See Table 4.10 below). Due to this reason, only the relevant transition lines (and not the data) from the present study have been shown in Figure 4.10 to compare with the map of Weisman et al. (1979).

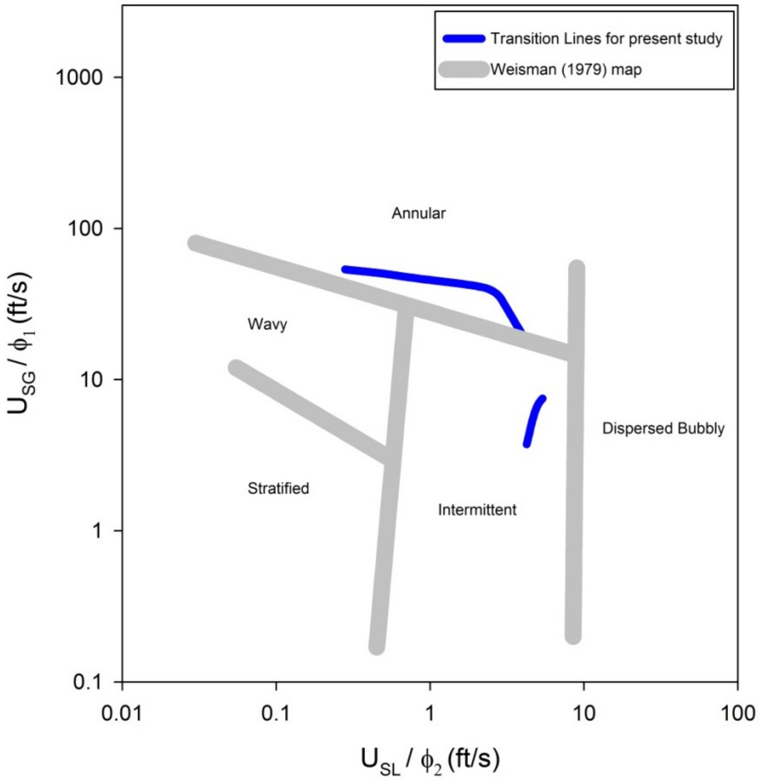

Figure 4.10 Data from the present study compared with Weisman et al. (1979) map

Table 4.1 Property and pipe diameter corrections for flow map of Weisman et al. (1979)

	ϕ_1	ϕ_2
Transition to dispersed flow	1	$\left(\frac{\rho_L}{\rho_{sl}}\right)^{-0.33}\left(\frac{D}{D_S}\right)^{0.16}\left(\frac{\mu_{sl}}{\mu_L}\right)^{0.09}\left(\frac{\sigma}{\sigma_S}\right)^{0.24}$
Transition to annular flow	$\left(\frac{\rho_{sg}}{\rho_G}\right)^{0.23}\left(\frac{\Delta\rho}{\Delta\rho_S}\right)^{0.11}\left(\frac{\sigma}{\sigma_S}\right)^{0.11}\left(\frac{D}{D_S}\right)^{0.415}$	1
Intermittent-seperated transition	1	$\left(\frac{D}{D_S}\right)^{0.45}$
Wavy-stratified transition	$\left(\frac{D_S}{D}\right)^{0.17}\left(\frac{\mu_G}{\mu_{sg}}\right)^{1.55}\left(\frac{\rho_{sg}}{\rho_G}\right)^{1.55}\left(\frac{\Delta\rho}{\Delta\rho_S}\right)^{0.69}\left(\frac{\sigma_S}{\sigma}\right)^{0.69}$	1
	“s” denotes standard conditions $D_S = 2.54\ cm; \rho_{sg} = 0.0013\ kg/l; \rho_{sl} = 1.0\ kg/l;$ $\mu_{sl} = 1\ centipoise; \sigma_s = 70\ dynes/cm$	

Weisman et al. (1979) have also included the map for 1.2 cm diameter tube for the air-water combination. Since the tube diameter and fluid combination matches those in the present study, this map can be compared directly with the experimental data. It should be noted that the map uses different coordinate system, i.e. mass flow rates. Figure 4.11 shows this map and the data from present study.

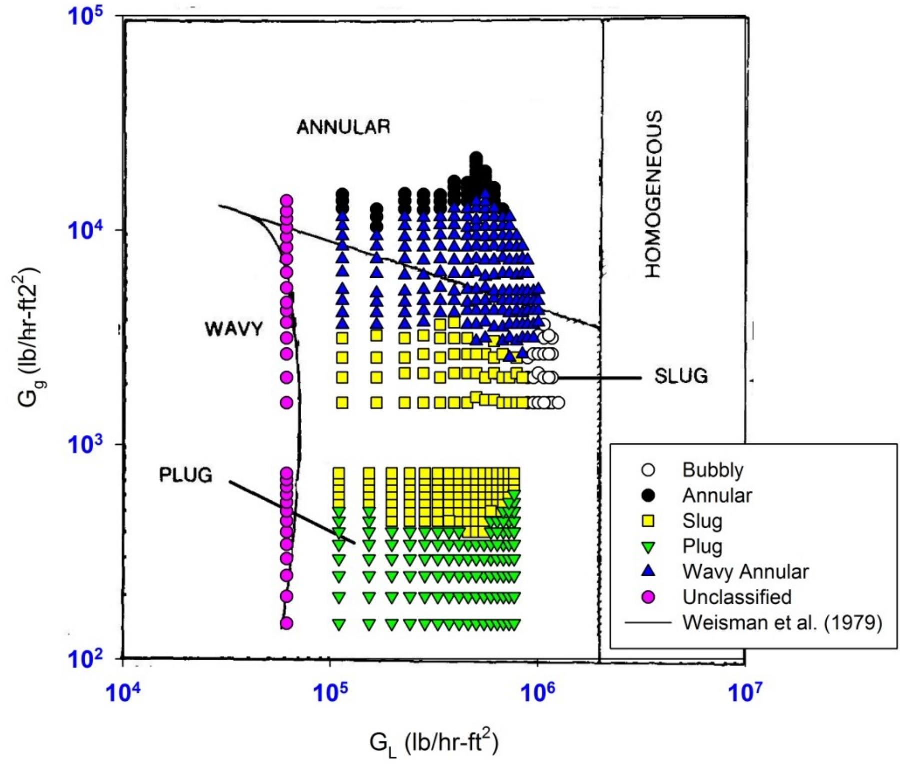

Figure 4.11 Data from present study compared with Weisman et al. (1979) map for 1.2 cm diameter tube

Once again, observations similar to those made for the Baker (1954) map in regards to certain transitions can be made. The annular-intermittent flow transition line passes through the wavy slug regime. Transition to wavy and stratified flow from intermittent flow occurs near the lowest liquid flow rates. Transition to the dispersed bubbly flow regime occurs at lower liquid flow rates than predicted by the map. However, the data compared in the map in the original study of Weisman et al. (1979) also shows a similar trend. Since the map combines the plug and slug flow patterns into a single intermittent flow regime, this transition cannot be compared.

4.4.4 Comparison with Taitel & Dukler (1976)

The map of Taitel & Dukler (1976) is derived from their transition theory. The original map is plotted with the parameter X on the x-axis and the parameters K, T or F on the y-axis depending on the specific transition in focus. The details of these have been provided in the Literature Review section of this study (see Chapter 2). However, they also provide maps with the superficial velocities as axes. Their map for the case of horizontal flow in a 2.5 cm diameter tube for air-water system at temperature 25°C and pressure 1 atm is used here for comparison. Figure 4.12 shows this map compared with the data from the present study.

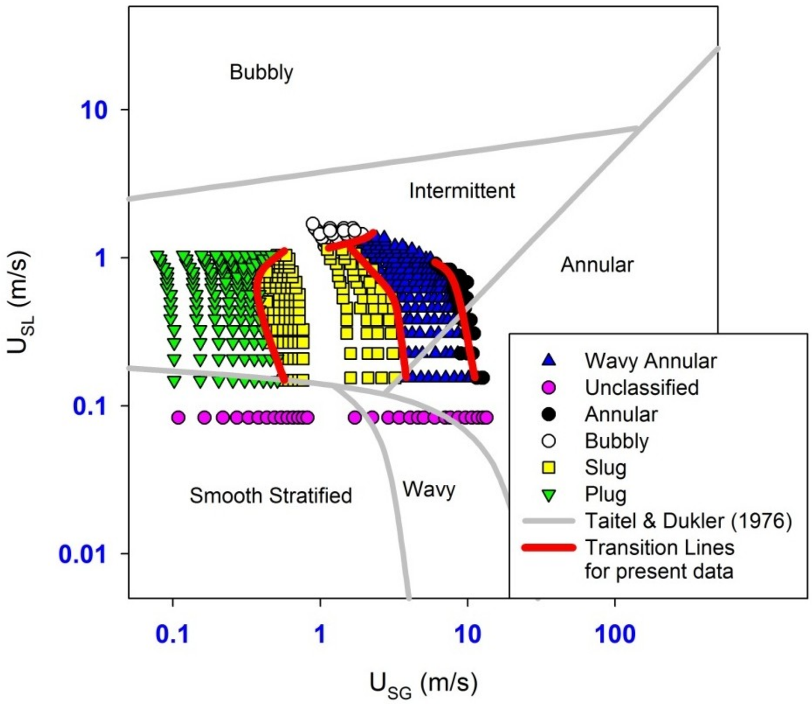

Figure 4.12 Data from the present study compared with Taitel & Dukler (1976) map

Once again, the dispersed bubbly flow is seen at lower liquid flow rates than predicted, and the transition to stratified and wavy flow regimes are near the lowest liquid flow rates for the present study.

The annular to intermittent flow transition cuts across the wavy annular flow regime of the data from the present study. The study of Taitel & Dukler (1976) acknowledges the presence of the wavy annular regime, but does not define it on the map. Instead, it is included in the annular flow regime.

From the above comparisons, the following observations are made:

All the maps considered have very similar predictions for the transition from wavy or stratified flow to the intermittent flow. The data collected at the lowest liquid flow rate possible in the present setup is predicted to be very close to this transition. As previously mentioned, at this flow rate, transition to the stratified flow seemed imminent while observing the flow patterns. This flow has been shown in Fig. 4.7.

The transition from plug flow to slug is reasonably matched to the predictions in the two maps that define such a transition. However, both maps disregard any effect of differing diameters on transition lines. Weisman et al. (1979) has reported a shift in transition lines to lower flow rates when diameter was reduced. Again considering that the maps of Mandhane et al. (1974) and Baker (1954) were developed using data from tubes with varying diameters all greater than that used in the present study, the observed shift is justified.

All the maps considered above ignore the wavy annular flow regime as a separate flow pattern between the annular and slug regimes. The transition lines for all maps (except Mandhane et al. (1974)) pass through this regime. Comparing the slope of this transition line in the maps of Taitel & Dukler (1976) and Weisman et al. (1979) it can be observed that they are widely differing, yet within the wavy annular regime of the data from the present study. All this is indicative of the subjective nature of flow pattern recognition.

The final transition line to be discussed is the transition to dispersed bubbly flow. Considering the specific reasons mentioned above for certain maps and the discussed diameter effect, it is safe to say that the agreement is within acceptable limits.

This concludes the discussion on flow patterns and flow pattern maps. Out of the maps tested, those of Taitel & Dukler (1976) and Weisman et al. (1979) seem to be best suited for the setup used in the present study. The map of Taitel & Dukler (1976) is among the most popular ones used today as it uses theoretical models as a base instead of experimental data.

Chapter 5. Evaluation of Void Fraction Correlations

As discussed in the Literature Review (see Chapter 2), a vast variety of correlations is available in open literature. For the present study, it was decided that all the correlations included in the study of Woldesemayat & Ghajar (2007) would be tested. While it was noted that it would be unfair to compare the performances of the correlations intended for vertical flow, they were still included in order to provide a wider perspective. The evaluation was done in two different modes: Flow Pattern dependant and Flow Pattern independent. For the Flow Pattern independent evaluation the data was divided into sub categories based on void fraction ranges. The categorization of data in multiple ways caters to the dynamic nature of two phase flow. A suite of correlations applicable to specific cases is achieved. The last section of the chapter attempts to find the best overall performing correlation with the widest possible applicability.

5.1 Flow Pattern Specific Comparison

591 points from 8 datasets were used in this analysis. Out of these, 184 are from the data collected in the present study. The following flow patterns were found to be covered in the total database: Stratified, Plug, Slug and Annular. No distinction was made between smooth stratified and wavy stratified flows. Table 5.1 summarizes the total numbers of points for each flow. Table 5.2 shows the number of points in each regime for different data sets.

Table 5.1 Total data points in different flow patterns

Flow Pattern	**No. of points**
Stratified	231
Plug	66
Slug	207
Annular	87

Table 5.2 Number of data points for different flow patterns for different data sets.

Dataset	Flow Pattern	No. of Points
Present Study (184 points)	Plug	35
	Slug	118
	Annular	31
Abdul-Majeed (1996) (88 points)	Stratified Smooth	20
	Stratified Wavy	13
	Slug	33
	Annular	22
França & Lahey (1992) (88 points)	Stratified	30
	Plug	16
	Slug	26
	Annular	16
Mukherjee (1979) (75 points)	Stratified	12
	Slug	30
	Annular	18
	Plug (referred to as Bubbly)	15
Badie et al. (2000) (Oil) (30 points)	Stratified	30
Badie et al. (2000) (Water) (36 points)	Stratified	36
Chen et al. (1997) (48 points)	Stratified	48
Ottens (1998) (42 points)	Stratified	42
TOTAL		***591***

5.1.1 Stratified Flow

This flow pattern occurs at moderate to high void fractions. This flow pattern was not encountered in the present study. However, the other datasets typically exhibited this flow pattern at void fraction 0.5 and above. Table 5.3 shows the correlations that predict over 90% of the 231 data points in the 15% error band. Appendix 4 lists the performance of all correlations for this stratified flow. Figure 5.1 shows the performance of the Dix (1971) correlation.

Table 5.3 Best performing correlations for Stratified Flow

Correlation	Percentage of data predicted within		
	± 5%	± 10%	± 15%
Dix (1971)	78.35%	92.64%	96.54%
Hart et al. (1989)	87.88%	92.64%	95.24%
Graham et al. (2001)	83.12%	92.64%	95.24%
Morooka et al. (1989)	20.78%	83.98%	95.24%
Tandon et al. (1985)	75.32%	88.74%	94.81%
Hughmark (1962)	22.94%	86.15%	93.51%
El-Boher et al. (1988)	36.36%	75.32%	93.51%
Woldesemayat & Ghajar (2007)	80.09%	90.04%	93.07%
Rouhani & Axelsson (1970) Rouhani I	36.36%	89.61%	93.07%
Filimonov et al. (1957)	69.70%	87.88%	93.07%
Minami & Brill (1987)	74.46%	87.88%	92.21%
Kowalczewski (1964)[1]	79.22%	87.88%	91.77%

[1] Isbin & Biddle (1979)

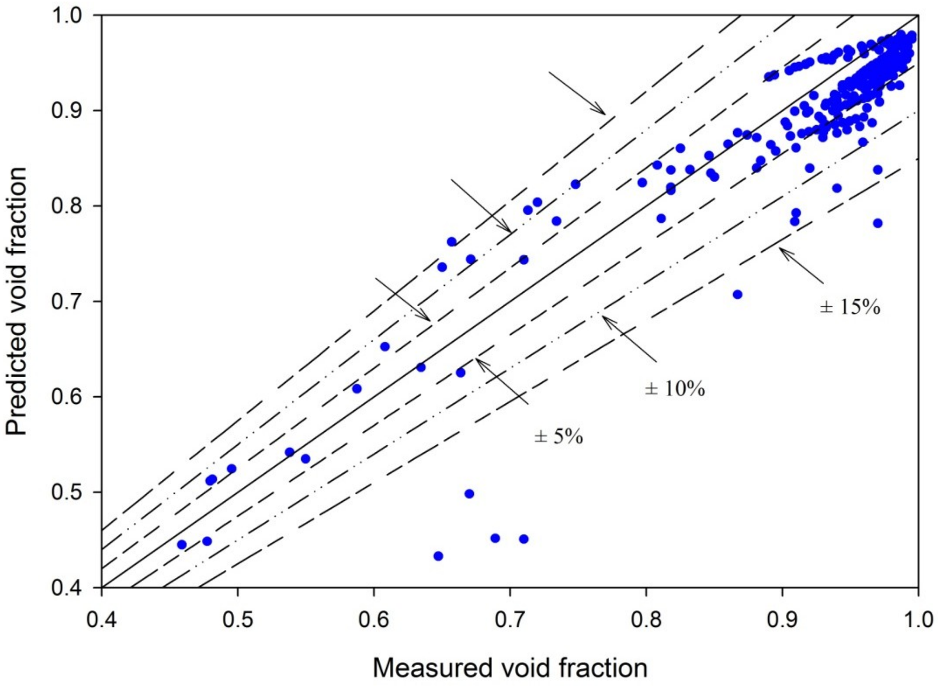

Figure 5.1 Performance of Dix (1971) correlation for Stratified Flow

5.1.2 Plug Flow

This flow pattern typically appears at low to moderate void fractions. For the present study, the range of void fraction was from 0.14 (lowest measured value) to 0.59. Table 5.4 shows the top performing correlations for this flow pattern (166 data points) that have over 80% prediction in the 20% error band. Appendix 4 lists the performance of all correlations for plug flow. It should be noted that there is a big difference in the performance of the top two correlations and the next best correlation of Chen (1986) that predicts 77% of the points in the 20% error band. Figure 5.2 and Figure 5.3 show the predictions of the correlations in Table 5.4.

Table 5.4 Best performing correlations for Plug Flow

Correlation	**Percentage of data predicted within**			
	± 5%	**± 10%**	**± 15%**	**± 20%**
Greskovich & Cooper (1975)	27.27%	48.48%	75.76%	87.88%
Homogeneous	30.30%	48.48%	74.24%	87.88%

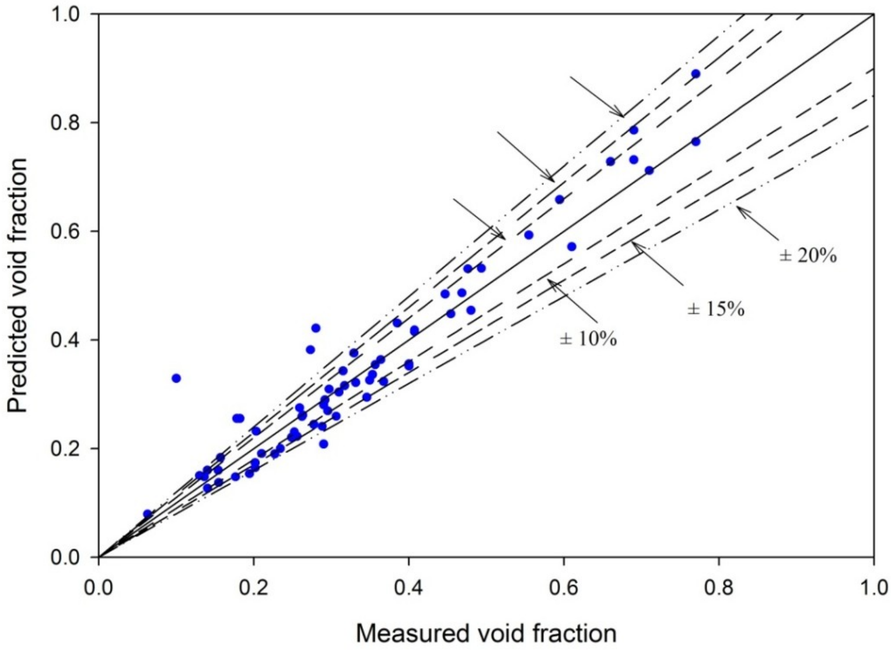

Figure 5.2 Performance of Greskovich & Cooper(1975) correlation for Plug Flow

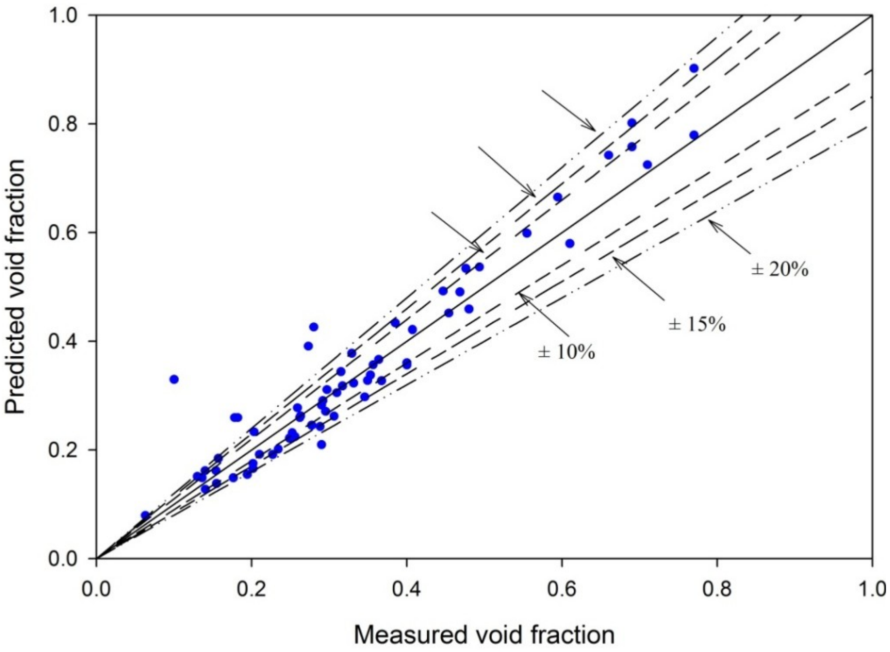

Figure 5.3 Performance of Homogenous correlation for Plug Flow

5.1.3 Slug flow

For this flow pattern the void fractions are typically moderate to high. For the present study, it was found to be 0.33 to 0.82. Table 5.5 shows the top performers for this flow pattern (207 data points) with over 85% prediction in the 15% error band. Appendix 4 lists the performance of all correlations for slug flow. Figure 5.4 shows the predictions of the top performing correlation of Woldesemayat & Ghajar (2007) for slug flow.

Table 5.5 Best performing correlations for Slug Flow

Correlation	Percentage of data predicted within		
	± 5%	± 10%	± 15%
Woldesemayat & Ghajar (2007)	34.78%	80.68%	93.72%
Chen (1986)	30.43%	63.29%	90.82%
Gregory & Scott (1969)	28.02%	68.60%	90.82%
Chisholm (1983), Armand (1946)	30.43%	67.63%	90.34%
Armand – Massena[1]	30.43%	71.01%	89.86%
Armand (1946)	29.95%	69.08%	89.86%
Chisholm (1973)	32.37%	66.18%	89.86%
El-Boher et al. (1988)	14.98%	66.18%	87.92%
Minami & Brill (1987)	28.02%	53.14%	87.92%
Hughmark (1965)	37.20%	67.15%	87.44%
Guzhov et al. (1967)	42.51%	65.22%	85.99%
Smith (1969)	31.40%	59.90%	85.51%

[1] Leung (2005)

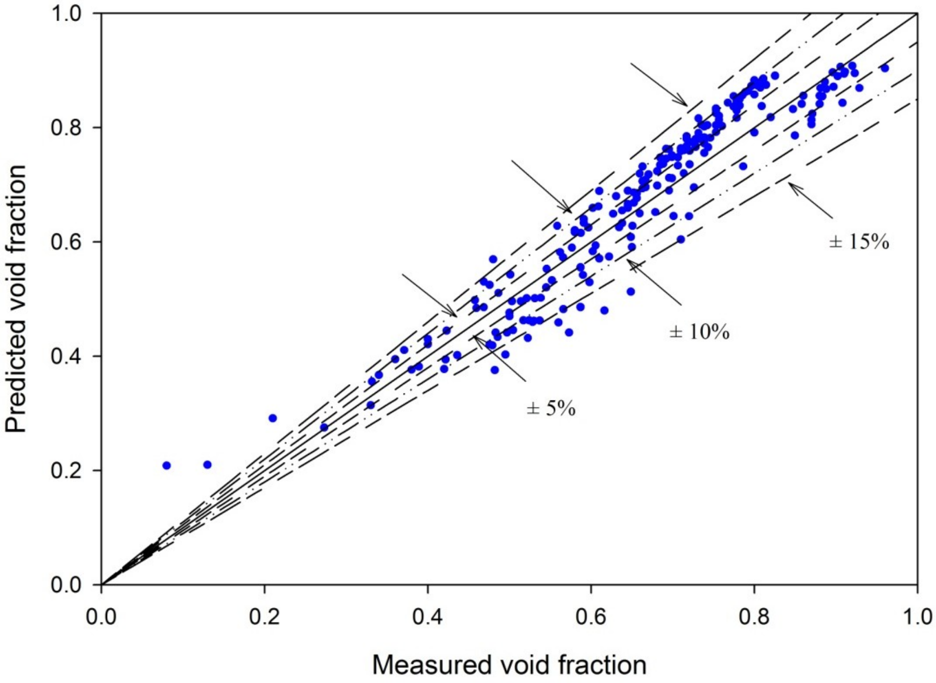

Figure 5.4 Performance of Woldesemayat & Ghajar (2007) correlation for Slug Flow

5.1.4 Annular Flow

This is a high void fraction flow pattern. It occurred in the present study above 0.7. Many correlations give very good predictions for Annular flow. Table 5.6 shows the top performing correlations that predict over 95% of the 87 data points in the 10% error band. Appendix 4 lists the performance of all correlations for annular flow. Figure 5.5 shows the performance of the top performing correlation of Dix (1971).

Table 5.6 Best performing correlations for Annular Flow

Correlation	**Percentage of data predicted within**		
	± 5%	**± 10%**	**± 15%**
Dix (1971)	86.21%	100.00%	100.00%
Woldesemayat & Ghajar (2007)	66.67%	98.85%	100.00%
Hughmark (1962)	59.77%	98.85%	100.00%
Chisholm (1973)	67.82%	97.70%	100.00%
Chisholm (1983), Armand (1946)	62.07%	97.70%	100.00%
Chen (1986)	58.62%	97.70%	100.00%
Armand – Massena[1]	56.32%	97.70%	100.00%
El-Boher et al. (1988)	34.48%	97.70%	100.00%
Lockhart & Martinelli (1949)	80.46%	96.55%	98.85%
Huq & Loth (1992)	73.56%	96.55%	98.85%
Smith (1969)	65.52%	96.55%	100.00%
Graham et al. (2001)	82.76%	95.40%	98.85%
Wallis (1969)	73.56%	95.40%	100.00%
Nishino & Yamazaki (1963)	73.56%	95.40%	97.70%
Kowalczewski (1964)[2]	66.67%	95.40%	97.70%

[1] Leung (2005); [2] Isbin & Biddle (1979)

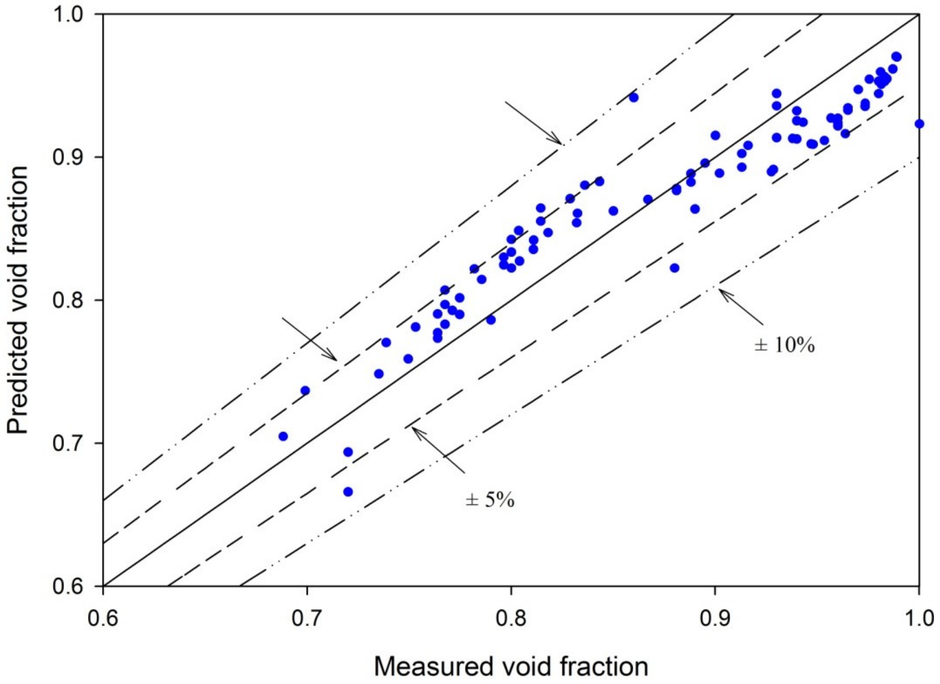

Figure 5.5 Performance of Dix (1971) correlation for Annular Flow

5.2 Flow Pattern Independent Comparison

Another way of evaluating the performance of the correlations is by classifying the data into void fraction ranges. Unlike the flow pattern based classification, this classification is not subjective. A total of 1505 data points from 15 datasets were analyzed. 184 of these were collected in the present study. The data is divided into four void fraction ranges. Table 5.7 shows the spread of the data points across these categories.

Table 5.7 No. of data points in different void fraction ranges

Void Fraction Range	No. of points
0 < α ≤ 0.25	54
0.25 < α ≤ 0.50	171
0.50 < α ≤ 0.75	348
0.75 < α < 1.0	932
TOTAL	***1505***

As it can be observed, the number of points in each category is very different. This skewed distribution of data would mean that a general comparison of correlations that looks at the entire data at once would be heavily biased towards the high void fraction values. Thus, we look at the categories individually.

For each category, the percentage of data points accurately predicted in appropriate error bands was calculated. In order to arrive at a list of recommended correlations for every category, two parameters were checked: (a) Percentage of points correctly predicted within selected error bands and (b) Root Mean Square (RMS) error of the predictions. The RMS error is calculated by the following formula:

$$\%\ error_{RMS} = \sqrt{\frac{\sum\left(\left(\frac{\alpha_{predicted} - \alpha_{experimental}}{\alpha_{experimental}}\right) * 100\right)^2}{N-1}}\ , where\ N\ is\ the\ number\ of\ points$$

The correlations were arranged in descending order of their prediction percentages. The cutoff point was decided where a considerable gap was encountered. This system of deciding cutoffs on the basis of data rather than absolute values ensures that the correlations are not discriminated against.

The criteria for every category were different. For low void fractions, the percentage error becomes high. A quick calculation yields that a 10% error at void fraction of 0.85 translates to a 56% error at void fraction of 0.15. The RMS error is also subject to similar mathematical constraints and gives higher errors at low void fractions. Thus a relaxation of the criteria at lower void fractions is necessary.

The selected criteria for all the void fraction ranges are given in Table 5.8. Only correlations that satisfy both the conditions simultaneously were deemed to be satisfactory.

Table 5.8 Criteria for selection of satisfactory performance of correlations

Void Fraction Range	Minimum Prediction	Maximum RMS Error %
$0 < \alpha \leq 0.25$	70% points within ± 30% error band	65
$0.25 < \alpha \leq 0.50$	75% points within ± 20% error band	20
$0.50 < \alpha \leq 0.75$	80% points within ± 15% error band	15
$0.75 < \alpha < 1.0$	85% points within ± 10% error band	10

5.2.1 Void Fraction Range 0-0.25

In the void fraction range 0 to 0.25, the performance of the correlations is quite poor. The rapid increase in void fraction in this region makes it difficult for the void fraction to be measured accurately. The criteria set for this category were 70% prediction in the 30% error band with RMS error less than 65%. Seven correlations satisfy these conditions. Their performance is given in Table 5.9. Appendix 5 lists the performance of all correlations for this void fraction range. The top performing correlation in this category is the correlation by Guzhov et al. (1967). Fig 5.6 shows the performance of this correlation.

Table 5.9 Best performing correlations for void fraction range 0 to 0.25

Correlation	Percentage of data predicted within			RMS Error %
	± 15%	± 20%	± 30%	
Guzhov et al. (1967)	44.44%	54.72%	73.58%	38.58
Huq & Loth (1992)	35.19%	50.94%	73.58%	57.32
Smith (1969)	29.63%	43.40%	73.58%	59.80
Armand – Massena[1]	31.48%	45.28%	71.70%	61.96
Armand (1946)	31.48%	45.28%	71.70%	61.48
Chisholm (1973)	29.63%	41.51%	71.70%	63.17
Chisholm (1983) , Armand (1946)	29.63%	39.62%	71.70%	62.51

[1] Leung (2005)

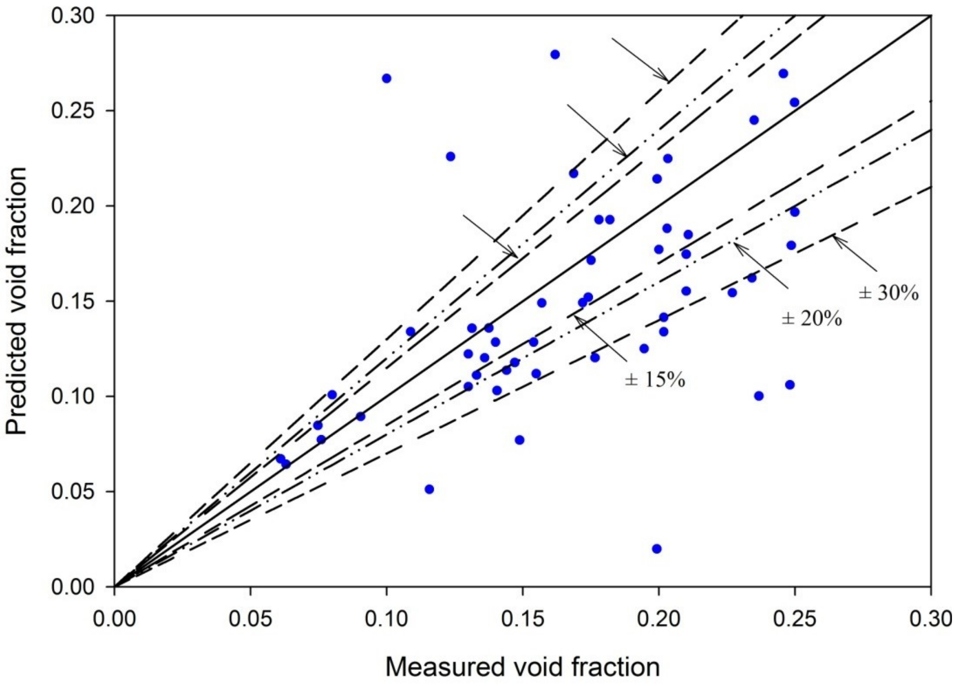

Figure 5.6 Performance of Guzhov et al. (1967) correlation for void fraction range 0-0.25

5.2.2 Void Fraction Range 0.25-0.50

For the void fraction range of 0.25 to 0.5, an improvement in the performance can be noticed. The criteria set for this category were 75% prediction in the 20% error band with RMS error less than 20%. Three correlations satisfy this condition. Table 5.10 shows the performance of these correlations. Appendix 5 lists the performance of all correlations for this void fraction range. Figure 5.7 shows the top performing correlation by Mukherjee (1979).

Table 5.10 Best performing correlations for void fraction range 0.25 to 0.50

Correlation	**Percentage of data predicted within**			**RMS Error %**
	± 10%	**± 15%**	**± 20%**	
Mukherjee (1979)	50.88%	64.33%	81.29%	15.31
Woldesemayat & Ghajar (2007)	46.78%	64.33%	76.02%	17.67
Minami & Brill (1987)	40.94%	60.23%	75.44%	18.59

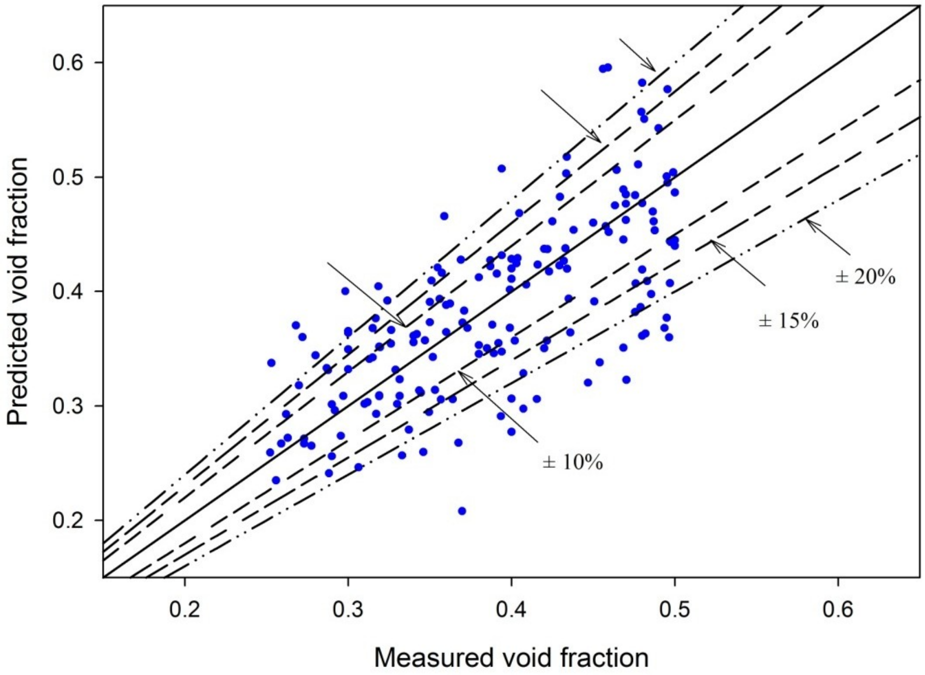

Figure 5.7 Performance of Mukherjee (1979) correlation for void fraction range 0.25-0.50

5.2.3 Void Fraction Range 0.50-0.75

For the void fraction range 0.50 to 0.75, the criteria set were 80% prediction in the 15% error band with RMS error less than 15%. The 12 correlations that satisfy this condition are given in Table 5.11. Appendix 5 lists the performance of all correlations for this void fraction range. The performance of the best correlation in this range is by Woldesemayat & Ghajar (2007). Its performance is shown in Fig. 5.8.

Table 5.11 Best performing correlations for void fraction range 0.50 to 0.75

Correlation	**Percentage of data predicted within**			**RMS Error %**
	± 5%	**± 10%**	**± 15%**	
Woldesemayat & Ghajar (2007)	41.38%	75.29%	87.93%	11.51
Rouhani & Axelsson (1970) - Rouhani I	44.54%	71.26%	85.63%	11.32
Hughmark (1962)	36.49%	69.54%	85.34%	11.11
Guzhov et al. (1967)	43.97%	72.70%	85.06%	11.93
Hughmark (1965)	36.21%	69.83%	84.77%	11.39
Armand (1946)	30.75%	65.52%	83.91%	12.25
Sun et al. (1980)	40.52%	66.95%	82.47%	12.50
Gregory & Scott (1969)	29.60%	61.21%	82.18%	12.80
Bonnecaze et al. (1971)	28.16%	65.52%	81.90%	12.98
Kokal & Stanislav (1989)	28.45%	65.23%	81.90%	12.92
Minami & Brill (1987)	33.05%	57.47%	81.32%	12.72
Nicklin et al. (1962)	26.44%	64.66%	81.32%	13.08

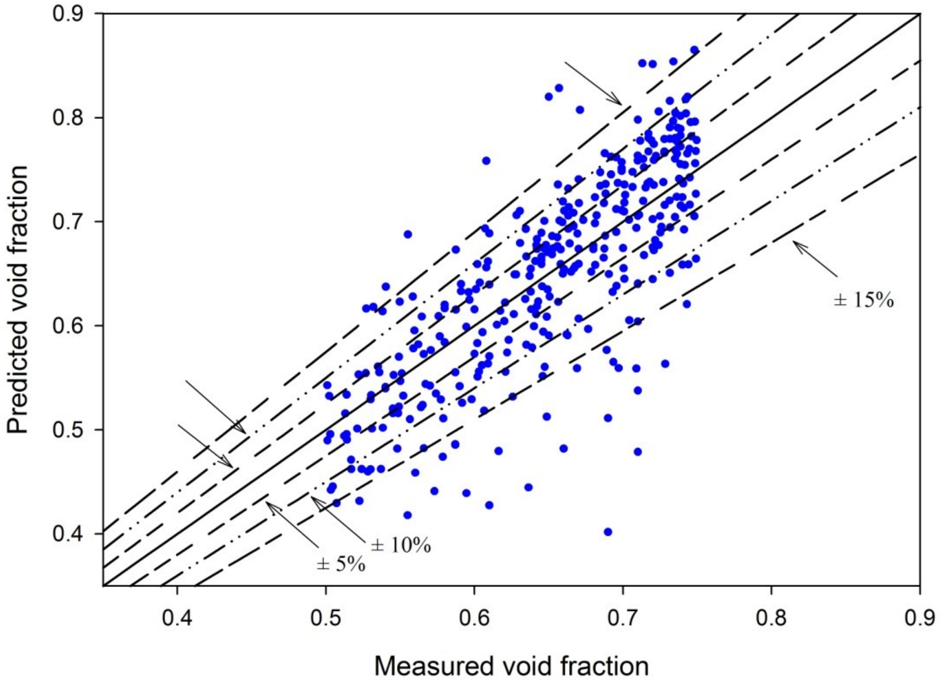

Figure 5.8 Performance of Woldesemayat & Ghajar (2007) correlation for void fraction range 0.5-0.75

5.2.4 Void Fraction Range 0.75-1.0

A large number of correlations are found to give very good predictions in this range. The selected correlations in this category had to predict above 85% of the points in 10% error band and have RMS error less than 10%. Even for this condition, 21 correlations were found to be satisfactory. Table 5.12 shows these. Appendix 5 lists the performance of all correlations for this void fraction range. The top performing correlation is that of Armand-Messena (Leung (2005)) and this is shown in Fig. 5.9.

Table 5.12 Best performing correlations for void fraction range 0.75 to 1.0

Correlation	**Percentage of data predicted within**			**RMS Error %**
	± 5%	**± 10%**	**± 15%**	
Armand – Massena[1]	71.35%	97.32%	99.89%	4.69
Woldesemayat & Ghajar (2007)	78.54%	96.03%	97.85%	7.70
Wallis (1969)	79.08%	95.06%	98.82%	4.60
Lockhart & Martinelli (1949)	80.04%	94.64%	98.61%	4.58
Graham et al. (2001)	82.51%	93.88%	97.53%	7.30
Chisholm (1973)	75.21%	92.60%	98.93%	5.01
Rouhani & Axelsson (1970) – Rouhani I	44.53%	92.60%	98.07%	8.21
Huq & Loth (1992)	73.82%	92.27%	98.39%	5.27
Tandon et al. (1985)	72.96%	91.85%	97.42%	7.08
Smith (1969)	73.82%	91.63%	98.39%	5.28
Chisholm (1983), Armand (1946)	68.56%	90.88%	98.61%	5.43
Hart et al. (1989)	79.72%	90.88%	95.28%	7.89
Minami & Brill (1987)	69.10%	90.77%	98.39%	6.05
Hughmark (1962)	39.38%	89.59%	99.03%	7.24
Dix (1971)	65.13%	89.38%	95.92%	9.70
Chen (1986)	72.10%	89.16%	97.00%	5.73
Kowalczewski (1964)[2]	65.24%	88.63%	96.78%	6.53
Zivi (1964)	70.92%	88.09%	94.74%	7.16
Mukherjee (1979)	65.56%	87.77%	96.35%	6.82
Baroczy (1966)	70.49%	86.59%	93.67%	7.05
Nishino & Yamazaki (1963)	62.55%	86.27%	94.42%	7.00

[1] Leung (2005); [2] Isbin & Biddle (1979)

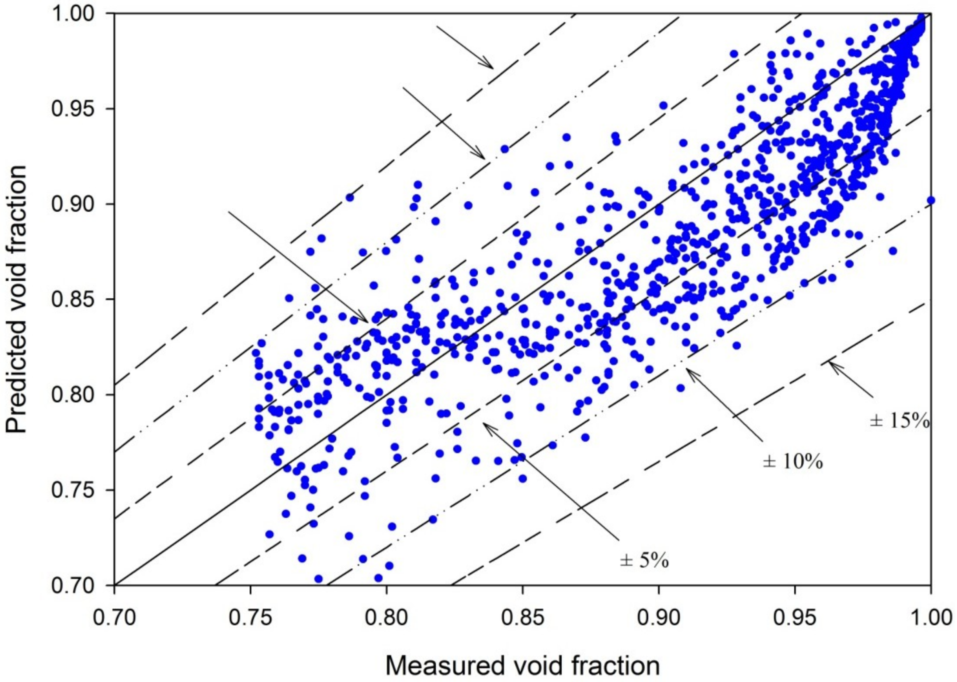

Figure 5.9 Performance of Armand-Messena (Leung (2005)) correlation for void fraction range 0.75-1.0

The above analysis highlights the differences in the prediction capabilities of the correlations in different areas. Thus for situations where only a specific flow pattern, or a narrow range of void fractions are expected, appropriate correlations can be used. However for situations where a broad spectrum of flow patterns or void fractions is expected, a general overall correlation is needed. It must be noted that the prediction of this correlation may not be the best for a certain situation, but its applicability lies in the being suitable across a wider range.

5.3 Best Overall Performing Correlations

In order to recommend one or more correlations as the best overall correlation/correlations, the flow pattern independent analysis is used as the basis. This is done to avoid the subjectivity involved with the flow pattern dependant analysis.

For the four void fraction categories considered, none of the correlations performed satisfactorily in all the categories. Two correlations were satisfactory in 3 out of the 4 categories, while 9 correlations appeared in the 2 categories. This is summarized in Table 5.13.

Table 5.13 Objective comparison of performance of selected correlations in all void fraction ranges

Correlation	**Void Fraction Range**			
	0 - 0.25	**0.25 - 0.50**	**0.50 - 0.75**	**0.75 - 1**
Woldesemayat & Ghajar (2007)	NS	S	S	S
Minami & Brill (1987)	NS	S	S	S
Armand – Massena[1]	S	NS	NS	S
Armand (1946)	S	NS	S	NS
Chisholm (1973)	S	NS	NS	S
Chisholm(1983), Armand(1946)	S	NS	NS	S
Guzhov et al. (1967)	S	NS	S	NS
Huq & Loth (1992)	S	NS	NS	S
Mukherjee (1979)	NS	S	NS	NS
Rouhani & Axelsson (1970) – Rouhani I	NS	NS	S	S
Smith (1969)	S	NS	NS	S
S = Satisfactory; NS = Not Satisfactory				

[1] Leung (2005),

The correlations by Woldesemayat & Ghajar (2007) and Minami & Brill (1987) both perform unsatisfactorily only in the lowest void fraction range (0 – 0.25). The correlation of Minami & Brill (1987) predicts 64% of the points in the 30% error band as against the set criterion of 70%. Noting the scarcity of data points in this range, this difference of around 6% translates to only 3 points. The RMS error for the Minami & Brill (1987) correlation is 58% and this satisfies the set criterion of 65% RMS error. Woldesemayat & Ghajar (2007) on the other hand only predicts 43% points and has an RMS error of 68%.

As a further check, the performance of these two correlations in the flow pattern specific analysis is also checked. It is observed that both correlations fail in the Plug flow regime. While both correlations are good performers in the Slug and Stratified flows, the performance of the Woldesemayat & Ghajar (2007) correlation is much better than that of Minami & Brill (1987). For the Annular flow region, Woldesemayat & Ghajar (2007) is the second best performer, while Minami & Brill (1987) does not satisfy the strict criterion. A closer examination reveals that while it is able to predict 100% of the data within the 15% error band, it only predicts 77.7% of the data within the 10% error band. This indicates a large number of data points between the two bands. Thus, the correlation should not be completely disregarded.

Based on this discussion, both the correlations of Woldesemayat & Ghajar (2007) and Minami & Brill (1987) are deemed worth a general recommendation while noting their poor performance in the lower void fraction range. Figures 5.10 and 5.11 show the performances of the correlations of Woldesemayat & Ghajar (2007) and Minami & Brill (1987).

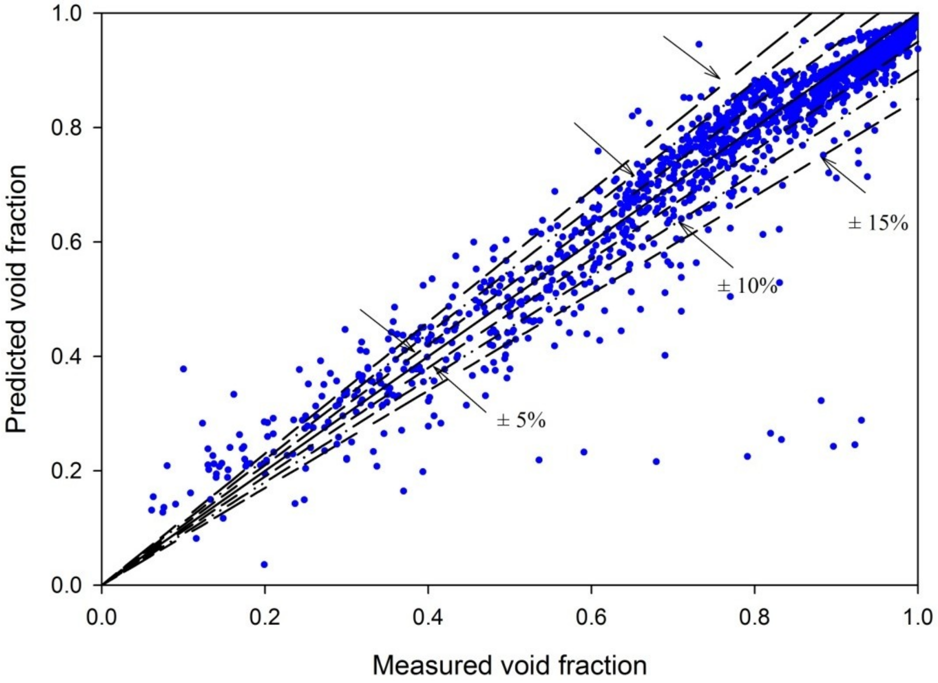

Figure 5.10 Performance of Woldesemayat & Ghajar (2007) correlation for entire void fraction range

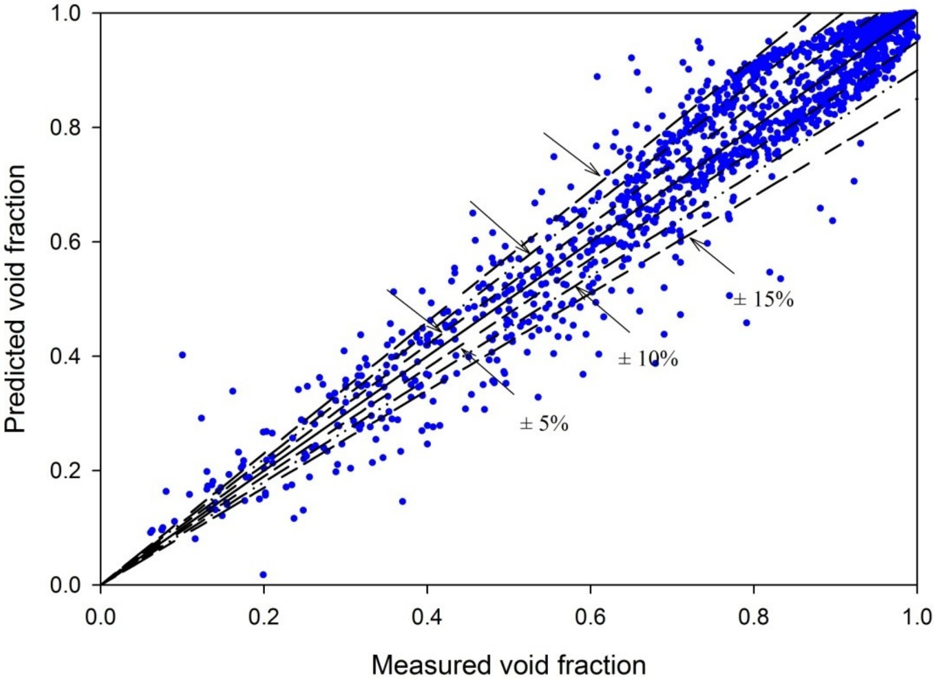

Figure 5.11 Performance of Minami & Brill (1987) correlation for entire void fraction range

The correlation of Woldesemayat & Ghajar (2007) was also found to be the best overall performer for the data collected in the present study (184 points). It was able to predict 80.98% of the points in the 10% error bands and 90.76% points in the 15% error bands. Figure 5.12 shows the performance of this correlation for the data from the present study.

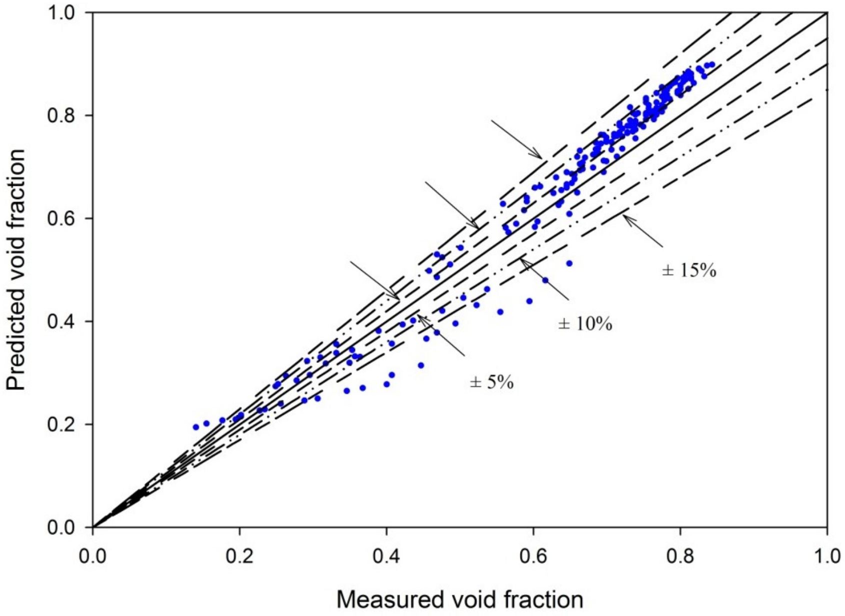

Figure 5.12 Performance of Woldesemayat & Ghajar (2007) correlation for the data collected in present study

This concludes the discussion on void fraction correlations. Out of all the correlations tested, two correlations were found to the overall best performers. For the lowest void fraction range (0-0.25), known difficulties in getting accurate data combined with the lack of sufficient data make it difficult to confidently recommend a correlation. A recommendation based on the present study has been however made.

Chapter 6. Summary, Conclusions and Recommendations

A detailed study of flow patterns and void fraction in non-boiling two phase flow in a horizontal air-water system was conducted. Tube of diameter 12.7 mm was used. (For more details about the test conditions, refer to Appendix 4.)

6.1 Summary and Conclusions

Four most commonly acknowledged flow patterns; plug, slug, annular and dispersed bubbly were observed in the course of the study. A total of 530 data points collected during the study conclusively proves the setup's capability of reproducing flow patterns. Though stratified flow was not directly observed, the onset of transition to this flow was detected. The flow pattern itself could not be observed due to system limitations. Wavy Annular flow appeared to be a separate flow pattern. Most other researchers combine this with other flow patterns and it was not found on the maps tested. A flow pattern map for the setup was developed from the data points collected. The map was compared with other maps and a good agreement was observed with the maps of Taitel & Dukler (1976) and Weisman et al. (1979). The minor differences are acceptable given the setup dependence of flow patterns. The map developed in this study is recommended for future work on the setup.

A detailed comparison of a 69 void fraction correlations against a comprehensive database of over 1500 data points was conducted. Data collected in the course of the present study (184 points) and 14 other sources (1321 points) was used. The evaluation was done by categorizing the data into flow patterns and void fraction ranges. Correlations with the best predictions for four distinct flow patterns and four void fraction ranges were found. Finally the overall best performing correlations were found through a systematic method including multiple criteria. Correlations by Woldesemayat & Ghajar (2007) and Minami & Brill (1987) are both recommended as 'best overall' correlations. These findings are in tune with those of Woldesemayat & Ghajar (2007).

6.2 Recommendations

A few recommendations for future work can be made.

- The Wavy Annular flow must be recognized as a separate flow pattern on the flow maps.
- More data in the bubble flow region must be obtained. Compared to the other flow patterns, this regime has the least data available.
- More data in the void fraction range below 0.5 must be collected, especially below 0.25.
- Data collected in the course of this study was for the fluid combination of air and water. Collecting data of different combinations on the same setup will enable a comparative study leading to better understanding of the effects of different fluids on flow patterns and void fractions.
- The present data is for a tube of 12.7 mm diameter. Collecting data from a different diameter tube on the same setup will enable a comparative study leading to better understanding of the effects of different diameters on flow patterns and void fractions.

It is acknowledged that significant changes to the present system will be needed in order to accommodate different fluids and/or tubes.

References

Abdul-Majeed, G. H. (1996). Liquid Holdup in Horizontal Two-Phase Gas--Liquid Flow. Journal of Petroleum Science and Engineering 15(2-4): 271-280

Alves, G. E. (1954). Cocurrent Liquid-Gas Flow in a Pipeline Contractor. Chem Engng Prog 50: 449-456

Armand, A. A. (1946). The Resistance During the Movement of a Two-Phase System in Horizontal Pipes. Izv Vse Tepl Inst. 1: 16–23.[As cited by Woldesemayat & Ghajar (2007)]

Badie, S., C. P. Hale, C. J. Lawrence and G. F. Hewitt (2000). Pressure Gradient and Holdup in Horizontal Two-Phase Gas–Liquid Flows with Low Liquid Loadings. Int. J. Multiphase Flow 26: 1525–1543

Baker, O. (1954). Simultaneous Flow of Oil and Gas. Oil and Gas J 53: 183-195

Bankoff, S. G. (1960). A Variable Density Single Fluid Model for Two Phase Flow with Particular Reference to Steam Water Flow. Trans. ASME, J. Heat Transfer 82: 265–272

Barnea, D., O. Shoham, Y. Taitel and A. E. Dukler (1980). Flow Pattern Transition for Gas-Liquid Flow in Horizontal and Inclined Pipes. Comparison of Experimental Data with Theory. International Journal of Multiphase Flow 6(3): 217-225.doi: DOI: 10.1016/0301-9322(80)90012-9

Baroczy, C. J. (1966). A Systemic Correlation for Two Phase Pressure Drop. Chem. Eng. Progr. Symp. Ser. 62: 232–249.[As cited by Woldesemayat & Ghajar (2007)]

Beggs, H. D. (1972). An Experimental Study of Two Phase Flow in Inclined Pipes, Tulsa, The University of Tulsa, PhD

Bonnecaze, R. H., W. Erskine and E. J. Greskovich (1971). Holdup and Pressure Drop for Two Phase Slug Flow in Inclined Pipes. AIChE J. 17: 1109–1113.[As cited by Woldesemayat & Ghajar, (2007)]

Butterworth, D. (1975). A Comparison of Some Void-Fraction Relationships for Co-Current Gas-Liquid Flow. International Journal of Multiphase Flow 1(6): 845-850

Chen, J. J. J. (1986). A Further Examination of Void Fraction in Annular Two-Phase Flow. International Journal of Heat and Mass Transfer 29(11): 1760-1763

Chen, X. T., X. D. Cai and J. P. Brill (1997). Gas–Liquid Stratified-Wavy Flow in Horizontal Pipelines. J. Energy Resour. Technol. 119: 209–216.[As cited by Ullmann & Brauner (2006)]

Chisholm, D. (1973). Pressure Gradients Due to Friction During the Flow of Evaporating Two-Phase Mixtures in Smooth Tubes and Channels. Int. J. Heat Mass Transfer 16: 347–358

Chisholm, D. (1983). Two Phase Flow in Pipelines and Heat Exchangers. London, George Godwin in association with The Institution of Chemical Engineers.[As cited by Woldesemayat & Ghajar, (2007)]

Chisholm, D. and A. D. K. Laird (1958). Two Phase Flow in Rough Tubes. Trans. ASME 80: 276–286.[As cited by Woldesemayat & Ghajar, (2007)]

Coddington, P. and R. Macian (2002). A Study of the Performance of Void Fraction Correlations Used in the Context of Drift-Flux Two-Phase Flow Models. Nuclear Engineering and Design 215(3): 199-216.doi: DOI: 10.1016/S0029-5493(01)00503-9

Collier, I. G., K. T. Claxton and I. A. Ward (1974). Htfs Correlations for Two-Phase Pressure Drop and Void Fraction in Tubes, Design Report 28 Part 4 HTFS, commercial in confidence.[As cited by Diener & Friedel (1998)]

Cook, W. (2008). An Experimental Apparatus for Measurement of Pressure Drop, Void Fraction and Non-Boiling Two-Phase Heat Transfer and Flow Visualization in Pipes for All Inclinations, Mechanical and Aerospace Engineering, Stillwater, OklahomaState University, MS

Czop, V., D. Barbier and S. Dong (1994). Pressure Drop, Void Fraction and Shear Stress Measurements in Adiabatic Two-Phase Flow in Coiled Tube. Nucl. Eng. Design 149: 323–333

Diener, R. and L. Friedel (1998). Reproductive Accuracy of Selected Void Fraction Correlations for Horizontal and Vertical Upflow. Forschung im Ingenieurwesen/Engineering Research 64(4-5): 87-97

Dix, G. E. (1971). Vapor Void Fractions for Forced Convection with Subcooled Boiling at Low Flow Rates, Berkeley, California, University of California, PhD

Dukler, A. E., M. Wicks and R. G. Cleveland (1964). Frictional Pressure Drop in Two-Phase Flow: A. A Comparison of Existing Correlations for Pressure Loss and Holdup. AIChE Journal 10(1): 38-43.10.1002/aic.690100117

Eaton, B. A. (1966). The Prediction of Flow Patterns, Liquid Holdup and Pressure Losses Occurring During Continuous Two-Phase Flow in Horizontal Pipelines., Department of Petroleum Engineering, Austin, Texas, The University of Texas, Austin, PhD

El-Boher, A., S. Lesin, Y. Unger and H. Branover (1988). Experimental Studies of Two Phase Liquid Metal Gas Flows in Vertical Pipes. Proceedings of the 1st World conference on Experimental Heat Transfer, Dubrovnik, Yugoslavia.[As cited by Woldesemayat & Ghajar (2007)]

Fauske, H. (1961). Critical Two-Phase, Steam–Water Flows. 1961 Heat Transfer and Fluid Mechanics Institute, Stanford, CA, Stanford University Press.[As cited by Woldesemayat & Ghajar, (2007)]

Filimonov, A. I., M. M. Przhizhalovski, E. P. Dik and J. N. Petrova (1957). The Driving Head in Pipes with a Free Interface in the Pressure Range from 17 to 180 Atm. Teploenergetika 4: 22-26.[As cited by Woldesemayat & Ghajar(2007)]

Flanigan, O. (1958). Effect of Uphill Flow on Pressure Drop in Design of Two-Phase Gathering Systems. Oil and Gas J. 56: 132–141.[As cited by Woldesemayat &Ghajar, (2007)]

França, F. and R. T. Lahey (1992). The Use of Drift-Flux Techniques for the Analysis of Horizontal Two-Phase Flows. International Journal of Multiphase Flow 18(6): 787-801

Friedel, L. (1977). Momentum Exchange and Pressure Drop. Oxford, Oxford University Press.[As cited by Woldesemayat & Ghajar (2007)]

Fujie, H. (1964). A Relation between Steam Quality and Void Fraction in Two Phase Flow. AIChE J. 10: 227–232.[As cited by Woldesemayat & Ghajar, (2007)]

Gardner, C. G. (1980). Fractional Vapor Content of a Liquid Pool through Which Vapor Is Bubbled. Int. J. Multiphase Flow 6: 399–410.[As cited by Woldesemayat & Ghajar, (2007)]

Ghajar, A. J. (2005). Non-Boiling Heat Transfer in Gas-Liquid Flow in Pipes: A Tutorial. Journal of the Brazilian Society of Mechanical Sciences and Engineering 27: 46-73

Gomez, L. E., O. Shoham and Y. Taitel (2000). Prediction of Slug Liquid Holdup: Horizontal to Upward Vertical Flow. Int. J. Multiphase Flow 26: 517–521.[As cited by Woldesemayat & Ghajar, (2007)]

Graham, D. M., D. A. Yashar, M. J. Wilson, H. R. Kopke, J. C. Chato and T. A. Newell (2001). An Investigation of Refrigerant Void Fraction in Horizontal, Micro Fin Tubes. HVAC&R Res. 7: 67–82.[As cited by Woldesemayat & Ghajar (2007)]

Gregory, G. A. and D. S. Scott (1969). Correlation of Liquid Slug Velocity and Frequency in Horizontal Cocurrent Gas-Liquid Slug Flow. AIChE Journal 15(6): 933-935

Greskovich, E. J. and W. T. Cooper (1975). Correlation and Prediction of Gas Liquid Holdups in Inclined Upflows. AIChE J. 21: 1189–1119

Guzhov, A. L., V. A. Mamayev and G. E. Odishariya (1967). A Study of Transportation in Gas Liquid Systems. 10th International Gas Union Conference, Hamburg, Germany.[As cited by Woldesemayat & Ghajar (2007)]

Hamersma, P. J. and J. Hart (1987). A Pressure Drop Correlation for Gas/Liquid Pipe Flow with a Small Liquid Holdup. Chem. Eng. Sci. 42: 1187-1196

Hart, J., P. J. Hamersma and J. M. H. Fortuin (1989). Correlations Predicting Frictional Pressure Drop and Liquid Holdup During Horizontal Gas-Liquid Pipe Flow with a Small Liquid Holdup. International Journal of Multiphase Flow 15(6): 947-964

Hoogendoorn, C. J. (1959). Gas-Liquid Flow in Horizontal Pipes. Chemical Engineering Science 9(4): 205-217

Hughmark, G. A. (1962). Holdup in Gas Liquid Flow. Chem. Eng. Prog. 58: 62-64

Hughmark, G. A. (1965). Holdup and Heat Transfer in Horizontal Slug Gas-Liquid Flow. Chemical Engineering Science 20(12): 1007-1010

Huq, R. H. and J. L. Loth (1992). Analytical Two-Phase Flow Void Fraction Prediction Method. J. Thermo Phys. 6: 139–144.[As cited by Woldesemayat & Ghajar (2007)]

Inoue, A., T. Kurosu, M. Yagi, S. Morooka, A. Hoshide, T. Ishizuka and K. Yoshimura (1993). In-Bundle Void Measurement of a Bwr Fuel Assembly by an X-Ray Ct Scanner: Assessment of Bwr Design Void Correlation and Development of New Void Correlation. Proceedings of the 2nd ASME/JSME Nuclear Engineering Conference, Part 1, San Francisco, California.[As cited by Woldesemayat & Ghajar, (2007)]

Isbin, H. S. and D. Biddle (1979). Void Fraction Relationships for Upward Flow of Saturated, Steam–Water Mixtures. Int. J. Multiphase Flow 5: 293–299.[As cited by Woldesemayat & Ghajar (2007)]

Kataoka, I. and M. Ishii (1987). Drift Flux Model for Large Diameter Pipe and New Correlation for Pool Void Fraction. Int. J. Heat Mass Transfer 30: 1927–1939.[As cited by Woldesemayat & Ghajar (2007)]

Kawaji, M., Y. Anoda, H. Nakamura and T. Tasaka (1987). Phase and Velocity Distributions and Holdup in High Pressure Steam/Water Stratified Flow in a Large Diameter Horizontal Pipe. Int. J. Multiphase Flow 13: 145-159

Kim, J.-y. and A. J. Ghajar (2006). A General Heat Transfer Correlation for Non-Boiling Gas-Liquid Flow with Different Flow Patterns in Horizontal Pipes. International Journal of Multiphase Flow 32(4): 447-465.doi: DOI: 10.1016/j.ijmultiphaseflow.2006.01.002

Kokal, S. L. and J. F. Stanislav (1989). An Experimental Study of Two Phase Flow in Slightly Inclined Pipes – Ii. Liquid Holdup and Pressure Drop. Chem. Eng. Sci. 44: 681-693

Leung (2005). Two Phase Flow. Thermal hydraulics branch, Chalk River Laboratories, AECL, UNENE Thermal hydraulics course <http://epic.mcmaster.ca> (accessed 15.09.2005.).[As cited by Woldesemayat & Ghajar (2007)]

Lin, P. Y. and T. J. Hanratty (1987). Effect of Pipe Diameter on Flow Patterns for Air-Water Flow in Horizontal Pipes. International Journal of Multiphase Flow 13(4): 549-563.doi: DOI: 10.1016/0301-9322(87)90021-8

Lockhart, R. W. and R. C. Martinelli (1949). Proposed Correlation of Data for Isothermal Two-Phase, Two Component Flow in Pipes. Chem. Eng. Progr. 45: 39-48

Madsen, N. (1975). A Void Fraction Correlation for Vertical and Horizontal Bulk-Boiling of Water. AIChE J. 21: 607–608.[As cited by Woldesemayat and Ghajar, (2007)]

Maier, D., Coddington, P. (1997). Review of Wide Range of Void Fraction Correlations against Extensive Database of Rod Bundle Void Measurements. ICONE-5, Nice, France.[As cited by Woldesemayat & Ghajar, (2007)]

Mandhane, J. M., G. A. Gregory and K. Aziz (1974). A Flow Pattern Map for Gas--Liquid Flow in Horizontal Pipes. International Journal of Multiphase Flow 1(4): 537-553.doi: DOI: 10.1016/0301-9322(74)90006-8

Mandhane, J. M., G. A. Gregory and K. Aziz (1975). Critical Evaluation of Holdup Prediction Methods for Gas–Liquid Flow in Horizontal Pipes. J. Petroleum Technol. 27: 1017-1026

Mattar, L. and G. A. Gregory (1974). Air Oil Slug Flow in an Upward-Inclined Pipe – I: Slug Velocity, Holdup and Pressure Gradient. J. Can. Petroleum Technol 13: 69–76.[As cited by Woldesemayat & Ghajar, (2007)]

Minami, K. and J. P. Brill (1987). Liquid Holdup in Wet Gas Pipelines. SPE Prod. Eng. 5: 36-44

Morooka, S., T. Ishizuka, M. Iizuka and K. Yoshimura (1989). Experimental Study on Void Fraction in a Simulated Bwr Fuel Assembly (Evaluation of Cross-Sectional Averaged Void Fraction). Nuclear Engineering and Design 114(1): 91-98

Mukherjee, H. (1979). An Experimental Study of Inclined Two-Phase Flow, Department of Petroleum Engineering, Tulsa, OK, The University of Tulsa, PhD

Neal, L. G. and S. G. Bankoff (1965). Local Parameters in Co-Current Mercury–Nitrogen Flow: Parts I and Ii. AIChE J. 11: 624–635.[As cited by Woldesemayat & Ghajar, (2007)]

Nicklin, D. J., J. O. Wilkes and J. F. Davidson (1962). Two-Phase Flow in Vertical Tubes. Trans. Instn. Chem. Engrs. 40: 61-68

Nishino, H. and Y. Yamazaki (1963). A New Method of Evaluating Steam Volume Fractions in Boiling Systems. J. Soc. Atomic Energy Japan 5: 39–59.[As cited by Woldesemayat & Ghajar (2007)]

Ottens, M. (1998). Gas–Liquid Flow through Pipes and T-Junctions, University of Amsterdam, PhD

Petalaz, N. and K. Aziz (1997). A Mechanistic Model for Stabilized Multiphase Flow in Pipes. Palo Alto, CA, Technical Report for Members of the Reservoir Simulation Industrial Affiliates Program (SUPRI-B) and Horizontal Well Industrial Affiliates Program (SUPRI-HW).[As cited by Woldesemayat & Ghajar (2007)]

Premoli, A., D. Francesco and A. Prima (1970). An Empirical Correlation for Evaluating Two-Phase Mixture Density under Adiabatic Conditions. European Two-Phase Flow Group Meeting, Milan, Italy.[As cited by Woldesemayat & Ghajar, (2007)]

Rouhani, S. Z. and E. Axelsson (1970). Calculation of Void Volume Fraction in the Subcooled and Quality Boiling Regions. International Journal of Heat and Mass Transfer 13(2): 383-393

Smith, S. L. (1969). Void Fractions in Two-Phase Flow: A Correlation Based Upon an Equal Velocity Head Model. ARCHIVE: Proceedings of the Institution of Mechanical Engineers 1847-1982 (vols 1-196) 184(1969): 647-664

Spedding, P. L. (1997). Holdup Prediction in Vertical Upwards to Downwards Flow. Dev. Chem. Eng. Mineral Process 5: 43-60

Spedding, P. L. and J. J. J. Chen (1984). Holdup in Two Phase Flow. International Journal of Multiphase Flow 10(3): 307-339

Spedding, P. L. and V. T. Nguyen (1976). Data on Holdup, Pressure Loss, and Flow Patterns for Two-Phase Air-Water Flow N and Inclined Pipe. Report Eng. Aukland, New Zealand, University of Aukland. **122**

Spedding, P. L. and V. T. Nguyen (1980). Regime Maps for Air Water Two Phase Flow. Chemical Engineering Science 35(4): 779-793.doi: DOI: 10.1016/0009-2509(80)85062-7

Spedding, P. L. and D. R. Spence (1988). Prediction of Holdup in Two-Phase Flow. Int J Eng Fluid Mech 1(1): 67-82

Spedding, P. L. and D. R. Spence (1989). Prediction of Holdup in Two Phase Flow. Int. J. Engg. Fluid Mechs 2: 109–118

Spedding, P. L. and D. R. Spence (1993). Flow Regimes in Two-Phase Gas-Liquid Flow. International Journal of Multiphase Flow 19(2): 245-280.doi: DOI: 10.1016/0301-9322(93)90002-C

Spedding, P. L., D. R. Spence and N. P. Hands (1990). Prediction of Holdup in Two-Phase Gas-Liquid Inclined Flow. The Chemical Engineering Journal 45(1): 55-74.doi: DOI: 10.1016/0300-9467(90)80026-9

Sterman, L. S. (1956). The Generalization of Experimental Data Concerning the Bubbling of Vapor through Liquid. Tech. Phys. USSR 1: 1479–1485.[As cited by Woldesemayat & Ghajar (2007)]

Sun, K. H., R. B. Duffey and C. M. Peng (1980). A Thermal-Hydraulic Analysis of Core Uncovery. 19th National Heat Transfer Conference, Experimental and Analytical Modeling of LWR Safety Experiments, Orlando, Florida

Taitel, Y. and A. E. Dukler (1976). Model for Predicting Flow Regime Transitions in Horizontal and near Horizontal Gas-Liquid Flow. AIChE Journal 22(1): 47-55.Compilation and indexing terms, Copyright 2008 Elsevier Inc.

1976040005518

Tandon, T. N., H. K. Varma and C. P. Gupta (1985). A Void Fraction Model for Annular Two-Phase Flow. Int. J. Heat Mass Transfer 28: 191–198.[As cited by Woldesemayat & Ghajar (2007)]

Thom, J. R. S. (1964). Prediction of Pressure Drop During Forced Circulation Boiling of Water.[As cited by Woldesemayat & Ghajar (2007)]

Thome, J. R. (2006). Wolverine Engineering Data Book Iii, Wolverine Tube, Inc.http://www.wlv.com/products/databook/db3/DataBookIII.pdf

Troniewski, L. and R. Ulbrich (1984). The Analysis of Flow Regime Maps of Two-Phase Gas-Liquid Flow in Pipes. Chemical Engineering Science 39(7-8): 1213-1224.doi: DOI: 10.1016/0009-2509(84)85082-4

Turner, J. M. and G. B. Wallis (1965). The Separate-Cylinders Model of Two-Phase Flow. Paper No. NYO-3114-6, Thayer's School Eng., Dartmouth College, Hanover, NH, USA.[As cited by Woldesemayat & Ghajar, 2007}

Vijayan, P. K., A. P. Patil, D. S. Pilkhawal, D. Saha and V. V. Raj (2000). An Assessment of Pressure Drop and Void Fraction Correlations with Data from Two-Phase Natural Circulation Loops. Heat and Mass Transfer 36: 541-548

Wallis, G. B. (1969). One Dimensional Two-Phase Flow. New York, McGraw-Hill Inc.[As cited by Woldesemayat & Ghajar (2007)]

Weisman, J., D. Duncan, J. Gibson and T. Crawford (1979). Effects of Fluid Properties and Pipe Diameter on Two-Phase Flow Patterns in Horizontal Lines. International Journal of Multiphase Flow 5(6): 437-462.doi: DOI: 10.1016/0301-9322(79)90031-4

Wilson, J. F., R. J. Grenda and J. F. Patterson (1961). Steam Volume Fraction in Bubbling Two-Phase Mixture. Trans. Am. Nucl. Soc. 4: 356–357.[As cited by Woldesemayat & Ghajar, (2007)]

Wojtan, L., T. Ursenbacher and J. R. Thome (2004). Interfacial Measurements in Stratified Types of Flow. Part Ii: Measurements for R-22 and R-410a. International Journal of Multiphase Flow 30(2): 125-137

Woldesemayat, M. A. (2006). Comparison of Void Fraction Correlations for Two-Phase Flow in Horizontal and Upward Inclined Pipes, Mechanical and Aerospace Engineering, Stillwater, Oklahoma State University, M.S.

Woldesemayat, M. A. and A. J. Ghajar (2007). Comparison of Void Fraction Correlations for Different Flow Patterns in Horizontal and Upward Inclined Pipes. International Journal of Multiphase Flow 33(4): 347-370

Zhao, H. D., K. C. Lee and D. H. Freeston (2000). Geothermal Two-Phase Flow in Horizontal Pipes. World Geothermal Congress 2000, Kyushu-Tokyo, Japan

Zivi, S. M. (1964). Estimation of Steady State Steam Void Fraction by Means of the Principle of Minimum Entropy Production. Trans. ASME, J. Heat Transfer 86: 247–252.[As cited by Woldesemayat & Ghajar, (2007)]

Zuber, N. and J. A. Findlay (1965). Average Volumetric Concentration in Two-Phase Flow Systems. Journal Name: Journal of Heat Transfer (U.S.); Journal Volume: Vol: 87; Other Information: Orig. Receipt Date: 31-DEC-66: Medium: X; Size: Pages: 453-468

APPENDIX 1

List of all correlations applicable to horizontal orientation used in present study.

Armand (1946)	$\frac{\alpha}{1-\alpha}=\frac{1}{0.2+\frac{1.2}{\left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)}}$
Armand-Massena[1]	$\alpha=(0.833+0.167x)\alpha_H$
Lockhart & Martinelli (1949)	$\frac{1-\alpha}{\alpha}=0.28X^{0.71}$
Flanigan (1958)	$\alpha=\left[1+3.063U_{SG}{}^{-1.006}\right]^{-1}$
Hoogendoorn (1959)	$\frac{\alpha}{1-\alpha}=\left(0.6*U_{SG}(1-\frac{\alpha}{1-\alpha}\frac{U_{SL}}{U_{SG}})\right)^{0.85}$
Bankoff (1960)	$\alpha=(0.71+(1.45\times 10^{-2})P)\alpha_H$
Hughmark (1962)	$\alpha=\left[\frac{Re^{\frac{1}{6}}Fr^{\frac{1}{8}}}{\lambda^{\frac{1}{4}}}\right]\alpha_H$
Fujie (1964)	$\alpha=\left[1+\left(\sqrt{\left(\frac{68947.57}{P}\right)}\alpha+1\right)\left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)\right]^{-1}$
Hughmark (1965)	$\alpha=\frac{U_{SG}}{1.2U_M}$
Guzhov et al. (1967)	$\alpha=0.81\alpha_H\left(1-\exp\left(-2.2\sqrt{Fr}\right)\right);\ Fr=\frac{U_M{}^2}{gD}$
Gregory & Scott (1969)	$\alpha=\frac{U_{SG}}{1.19U_M}$
Smith (1969)	$\alpha=\left[1+\left(\frac{\rho_G}{\rho_L}\right)\left(\frac{1-x}{x}\right)\left(0.4+0.6\left\{\frac{\frac{\rho_L}{\rho_G}+0.4\left(\frac{1-x}{x}\right)}{1+0.4\left(\frac{1-x}{x}\right)}\right\}^{0.5}\right)\right]^{-1}$
Wallis (1969)	$\alpha=[1+X^{0.8}]^{-0.38}$
Beggs (1972)	$\frac{\alpha(\theta)}{\alpha(0)}=1+C[\sin(1.8\theta)-\frac{1}{3}\sin^3(1.8\theta)]$
Chisholm (1973)	$\alpha=\left[1+\left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)\sqrt{1-x\left(1-\frac{\rho_L}{\rho_G}\right)}\right]^{-1}$
Mattar & Gregory (1974)	$\alpha=\frac{U_{SG}}{1.3U_M+0.7}$
Greskovich & Cooper (1975)	$\alpha=\left[1+0.671\left(\frac{(\sin\theta)^{0.263}}{Fr^{0.5}}\right)\right]^{-1}\alpha_H$

Madsen (1975)	$\alpha = \left[1 + \left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)^{\mathrm{b}} \left(\frac{\rho_G}{\rho_L}\right)^{-0.5}\right]^{-1} \quad ; \quad \mathrm{b} = 1 + \log\left(\frac{\rho_L}{\rho_G}\right)\left(\log\left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)\right)^{-1}$
Mukherjee (1979)	$\alpha = 1 - \exp\left(\mathrm{C}_1 + \mathrm{C}_2 \sin\theta + \mathrm{C}_3 \sin^2\theta + \mathrm{C}_4 \frac{\mu_L}{(\rho_L \sigma^3)^{0.25}}\right)\left[\mathrm{U}_{SG}\left(\frac{\rho_L}{g\sigma}\right)^{0.25}\right]^{\mathrm{C}_5}\left[\mathrm{U}_{SL}\left(\frac{\rho_L}{g\sigma}\right)^{0.25}\right]^{-\mathrm{C}_6}$
Chisholm(1983), Armand(1946)	$\alpha = \frac{1}{\alpha_H + (1-\alpha_H)^{0.5}} \alpha_H$
Spedding & Chen (1984)	$\alpha = \left[1 + 2.22\left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)^{0.65}\left(\frac{\rho_G}{\rho_L}\right)^{0.65}\right]^{-1}$
Tandon et al. (1985)	$\alpha = \left\{1 - 1.928\,\mathrm{Re}_L^{-0.315}[F(X)]^{-1} + 0.9293\,\mathrm{Re}_L^{-0.63}[F(X)]^{-2}\right\}$ $50 < \mathrm{Re}_L < 1125$ $\alpha = \left\{1 - 0.38\,\mathrm{Re}_L^{-0.088}[F(X)]^{-1} + 0.0361\,\mathrm{Re}_L^{-0.176}[F(X)]^{-2}\right\}$ $\mathrm{Re}_L > 1125$
Chen (1986)	$\alpha = \frac{\mathrm{k}}{\mathrm{k} + \left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)^{0.6}\left(\frac{\rho_G}{\rho_L}\right)^{0.33}\left(\frac{\mu_L}{\mu_G}\right)^{0.06}}$
Hamersma & Hart (1987)	$\frac{1-\alpha}{\alpha} = 0.26\left(\frac{1-\mathrm{x}}{\mathrm{x}}\right)^{0.67}\left(\frac{\rho_G}{\rho_L}\right)^{0.33}$
Kawaji et al. (1987)	$\alpha = 1.05\left[\mathrm{U}_{SL}\left[\frac{\rho_L}{gD(\rho_L - \rho_G)}\right]^{0.5}\right]^{0.5}$
Minami & Brill (1987)	$\alpha = \exp\left\{-\left[\frac{\ln Z_1 + 9.21}{8.7115}\right]^{4.3374}\right\}$
Spedding & Spence (1988)	$\frac{\alpha}{1-\alpha} = \left[0.45 + 0.08\exp\left(-100(0.25 - \mathrm{U}_{SL}{}^2)\right)\right]\left(\frac{\mathrm{U}_{SG}}{\mathrm{U}_{SL}}\right)^{0.65}$
Hart et al. (1989)	$\alpha = 1 - \frac{\mathrm{U}_{SL}}{\mathrm{U}_{SG}}\left[1 + \left(108\frac{\rho_L}{\rho_G}\mathrm{Re}_{SL}{}^{-0.726}\right)^{0.5}\right]$

Kokal & Stanislav (1989)	$\alpha = \frac{U_{SG}}{1.2U_M + 0.345\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{\frac{1}{2}}}$
Czop et al. (1994)	$\alpha = -0.285 + 1.097\alpha_H$
Abdul-Majeed (1996)	$\alpha = 1 - 0.528(U_{SG}U_{SL})^{-0.216121}(E_L)_{theo}$
Petalaz & Aziz (1997)	$\frac{1-\alpha}{\alpha} = 0.735\left(\frac{{\mu_L}^2{U_{SG}}^2}{\sigma^2}\right)^{0.074}\left(\frac{1-x}{x}\right)^{-0.2}\left(\frac{\rho_G}{\rho_L}\right)^{-0.126}$
Gomez et al.(2000)	$\alpha = 1 - e^{-(0.45\theta + 2.48\times10^{-6}Re_M)}$
Zhao et al. (2000)	$\alpha = \left[1 + \alpha^{-0.125}\left(\frac{1-x}{x}\right)^{0.875}\left(\frac{\rho_G}{\rho_L}\right)^{0.875}\left(\frac{\mu_L}{\mu_G}\right)^{0.875}\right]^{-1}$
Woldesemayat & Ghajar (2007)	$\alpha = \frac{U_{SG}}{U_{SG}\left(1 + \left(\frac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}}\right) + 2.9\left[\frac{gD\sigma(1+\cos\theta)(\rho_L - \rho_G)}{{\rho_L}^2}\right]^{0.25}(1.22 + 1.22\sin\theta)^{\frac{P_{atm}}{P_{system}}}}$ The leading constant value of 2.9 has a unit such that the drift flux velocity carries the units of m/s. The correlation should be used with parameters in conformance to the International System of Units (SI).

[1] Leung (2005);

APPENDIX 2

Summary of vertical flow correlations included in Woldesemayat & Ghajar (2007)

Name of correlation	Equation
Nicklin et al. (1962)	$\alpha = \dfrac{U_{SG}}{1.2U_M + 0.35\sqrt{gD}}$
Kowalczewski (1964)[1]	$\alpha = \alpha_H - 0.71(1-\alpha_H)^{0.5} Fr^{-0.045}\left(1 - \dfrac{P}{P_c}\right)$
Thom (1964)	$\alpha = \dfrac{1}{1 + \left(\dfrac{1-x}{x}\right)\left(\dfrac{\rho_G}{\rho_L}\right)^{0.89}\left(\dfrac{\mu_L}{\mu_G}\right)^{0.18}}$
Neal & Bankoff (1965)	$\alpha = 1.25\left(\dfrac{U_{SG}}{U_M}\right)^{1.88}\left(\dfrac{U_{SL}^2}{gD}\right)^{0.2}$
Premoli et al. (1970)	$\left(\dfrac{1-\alpha}{\alpha}\right)\left(\dfrac{x}{1-x}\right)\left(\dfrac{\rho_L}{\rho_G}\right) = 1 + F_1\left\{\dfrac{y}{1+yF_2} - yF_2\right\}^{1/2}$ Where, $F_1 = 1.578\,\mathrm{Re}_L^{-0.19}\left(\dfrac{\rho_L}{\rho_G}\right)^{0.22}$ $F_2 = 0.0273 We_L\,\mathrm{Re}_L^{-0.51}\left(\dfrac{\rho_L}{\rho_G}\right)^{-0.08}$ $y = \dfrac{\beta}{1-\beta},\ \beta = \dfrac{1}{1 + \left(\dfrac{1-x}{x}\right)\left(\dfrac{\rho_G}{\rho_L}\right)}$
Rouhani & Axelsson (1970)	$\alpha = \dfrac{x/\rho_G}{\left[C_0\left(\dfrac{x}{\rho_G} + \dfrac{1-x}{\rho_L}\right) + \dfrac{U_{GM}}{G}\right]}$ Where, $U_{GM} = \left(\dfrac{1.18}{\sqrt{\rho_L}}\right)\left(g\sigma(\rho_L - \rho_G)\right)^{0.25}$ Rouhani I: $C_0 = 1 + 0.2(1-x)$ Rouhani II: $C_0 = 1 + 0.2(1-x)(gD)^{0.25}\left(\dfrac{\rho_L}{G}\right)^{0.5}$

Bonnecaze et al. (1971)	$\alpha = \dfrac{U_{SG}}{1.2U_M + 0.35\sqrt{gD}\left(1 - \dfrac{\rho_G}{\rho_L}\right)}$
Dix (1971)	$\alpha = \dfrac{U_{SG}}{C_0 U_M + U_{GM}}$ Where, $C_0 = \dfrac{U_{SG}}{U_M}\left(1 + \left(\dfrac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}}\right)$, $U_{GM} = 2.9\left(\dfrac{g\sigma(\rho_L - \rho_G)}{\rho_L^2}\right)^{0.25}$
Sun et al. (1980)	$\alpha = \dfrac{U_{SG}}{C_0 U_M + U_{GM}}$ Where, $C_0 = \dfrac{1}{0.82 + 0.18\dfrac{P}{P_C}}$, $U_{GM} = 1.41\left(\dfrac{g\sigma(\rho_L - \rho_G)}{\rho_L^2}\right)^{0.25}$
El-Boher et al. (1988)	$\alpha = \dfrac{1}{\left[1 + 0.27\beta^{-0.69}(Fr)^{-0.177}\left(\dfrac{\mu_L}{\mu_G}\right)^{0.378}\left(\dfrac{Re}{We_L}\right)^{0.067}\right]}$
Morooka et al. (1989) Referred to as Toshiba (1989) in Woldesemayat & Ghajar (2007)	$\alpha = \dfrac{U_{SG}}{C_0 U_M + U_{GM}}$ where, $C_0 = 1.08$, $U_{GM} = 0.45$
Huq & Loth (1992)	$\alpha = 1 - \dfrac{2(1-x)^2}{1 - 2x + (1 + 4x(1-x)(\dfrac{\rho_L}{\rho_G} - 1))^{0.5}}$
Inoue et al. (1993)	$\alpha = \dfrac{U_{SG}}{C_0 U_M + U_{GM}}$ Where, $C_0 = 6.76\times10^{-3}P + 1.026$, $U_{GM} = \left(5.10\times10^{-3}\,m + 6.91\times10^{-2}\right)\times\left(9.42\times10^{-2}P^2 - 1.99P + 12.6\right)$
Kutucuglu[1]	$\alpha = \alpha_{\boldsymbol{H}} - (1-\alpha_{\boldsymbol{H}})^{0.5}Fr^{0.2}\left(1 - \dfrac{P}{P_c}\right)^2$

Moussali[1]	$\alpha = K_{MO}\alpha_H$ Where, $K_{MO} = 1 - \frac{(30.4/d_1) + 11}{60(1+1.6/d_1)(1+3.2/d_1)}$, $d_1 = \frac{1-x}{x}\frac{\rho_G}{\rho_L}$

[1] Isbin & Biddle (1979);

APPENDIX 3

Summary of correlations of unknown orientation from Woldesemayat & Ghajar (2007)

Name of correlation	Equation
Filimonov et al. (1957)	$\alpha = \frac{U_{SG}}{C_0 U_M + U_{GM}}$, $U_{GM} = (0.65 - 0.0385P)\left(\frac{D_H}{0.063}\right)^{0.25}$,$P < 12.7$ MPa $U_{GM} = (0.33 - 0.00133P)\left(\frac{D_H}{0.063}\right)^{0.25}$ $P > 12.7$MPa
Chisholm & Laird (1958)	$\alpha = 1 - \left[\frac{0.8}{1 + \frac{21}{X_{tt}} + \frac{1}{X_{tt}^{2}}}\right]^{1.75}$
Dimentiev et al.[5]	$\alpha = 1.07 j_g^{*0.8} D_H^{*-0.25}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{-0.23}$ For $j_g^{*}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{-0.5} \le 3.7$ $\alpha = 1.9 j_g^{*0.34} D_H^{*-0.25}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{0.09}$ For $j_g^{*}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{-0.5} > 3.7$
Fauske (1961)	$\alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.5}}$
Nishino & Yamazaki (1963)	$\alpha = 1 - \left[\frac{1-x}{x}\frac{\rho_G}{\rho_L}\right]^{0.5}(\alpha_H)^{0.5}$
Zivi (1964)	$\alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.67}}$
Turner & Wallis (1965)	$\alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)^{0.72}\left(\frac{\rho_G}{\rho_L}\right)^{0.4}\left(\frac{\mu_L}{\mu_G}\right)^{0.08}}$
Wilson et al. (1961)	$\alpha = 0.56157 F^{0.62086} D_v^{0.0917}\left(\frac{L}{D}\right)^{0.11033}$ for F < 2

<table>
<tr><td></td><td>$\alpha = 0.68728 F^{0.41541} D_v^{0.10737} \left(\frac{L}{D}\right)^{0.11033}$ for F ≥ 2</td></tr>
<tr><td>Baroczy (1966)</td><td>$\alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)^{0.74} \left(\frac{\rho_G}{\rho_L}\right)^{0.65} \left(\frac{\mu_L}{\mu_G}\right)^{0.13}}$</td></tr>
<tr><td>Loscher & Reinhardt
(1973)[2]</td><td>$\alpha = \alpha_H - \left(\frac{P}{P_c}\right)^{-0.22} \alpha_H^{1.39} (1-\alpha_H)^{0.8} Fr^{-0.25} \left(1 - \frac{P}{P_c}\right)^{3.4}$</td></tr>
<tr><td>Gardner (1980)</td><td>$\frac{\alpha}{(1-\alpha)^{1/2}} = K_{GR} [F_D P^m]^{2/3}$
Gardner I: K_{GR} = 1.7, m = 0.16
Gardner II: K_{GR} = 1.7, m = 0.3</td></tr>
<tr><td>Jowitt[3]</td><td>$\alpha = \frac{U_{SG}}{C_0 U_M + U_{GM}}$
$C_0 = 1 + 0.796 \exp\left(-0.061 \sqrt{\frac{\rho_L}{\rho_G}}\right)$, $U_{GM} = 0.034 \left(\sqrt{\frac{\rho_L}{\rho_G}} - 1\right)$</td></tr>
<tr><td>Bestion[3]</td><td>$\alpha = \frac{U_{SG}}{C_0 U_M + U_{GM}}$
$C_0 = 1$, $U_{GM} = 0.188 \left(\frac{gD(\rho_L - \rho_G)}{\rho_G}\right)^{0.5}$</td></tr>
<tr><td>Maier (1997)</td><td>$\alpha = \frac{U_{SG}}{C_0 U_M + U_{GM}}$
$C_0 = C_{MC1} P + C_{MC2}$, $U_{GM} = \left(v_1 P^2 + v_2 P + v_3\right) G + \left(v_4 P^2 + v_5 P + v_6\right)$
<table>
<tr><th>Constant</th><th>Value</th></tr>
<tr><td>C_{MC1}</td><td>2.57×10^{-3}</td></tr>
<tr><td>C_{MC2}</td><td>1.0062</td></tr>
<tr><td>v_1</td><td>6.73×10^{-7}</td></tr>
<tr><td>v_2</td><td>-8.81×10^{-5}</td></tr>
<tr><td>v_3</td><td>1.05×10^{-3}</td></tr>
<tr><td>v_4</td><td>5.63×10^{-3}</td></tr>
<tr><td>v_5</td><td>-1.23×10^{-1}</td></tr>
<tr><td>v_6</td><td>8.00×10^{-1}</td></tr>
</table></td></tr>
<tr><td>Graham et al. (2001)</td><td>$\alpha = \left(1 + \frac{1}{Ft} + \frac{1}{X_{tt}}\right)^{-0.321}$ where, $Ft = \left(\frac{G^2 x^3}{(1-x)\rho_G^2 g D}\right)^{0.5}$</td></tr>
</table>

[1]Kataoka & Ishii (1987); [2]Friedel (1977); [3]Coddington & Macian (2002);

APPENDIX 4

Experimental Datasets used in the present study

Present Study

184 Points

Diameter: 12.7 mm

Fluids used: air-water

Pressure range: 15.9 – 35.0 Psia

Temperature range: 53.5 – 80.2 ^{o}F

Range of liquid mass flow rate: 27.7 – 222.4 lbm/s-ft2

Range of gas mass flow rate: 0.05 – 5.3 lbm/s-ft2

Range of void fraction covered: 0.14 – 0.84

Eaton (1966)

237 Points

Diameters: 2.067 in and 4.026 in

Fluids used: natural gas – water

Pressure range: 305.30 – 868.70 Psia

Temperature range: 57.0 – 112.0 ^{o}F

Range of liquid volume flow rate: 46.00– 5620.00 bbl/d

Range of gas volume flow rate: 36609.00 – 9126789.00 scf/d

Range of void fraction covered: 0.27 – 0.99

Beggs (1972)

56 Points

Diameter of pipe: 1 in and 1.5 in

Fluids used: air – water

Pressure range: 51.92 – 98.6 Psia

Temperature range: 38 – 85 ^oF

Range of liquid phase flow rate: 4.63 - 535.6 lbm/s. ft^2

Range of gas phase flow rate: 0.48 – 25.41 lbm/s. ft^2

Range of void fraction covered: 0.14 – 0.98

Spedding & Nguyen (1976)

270 Points

Diameter of pipe: 4.55 cm

Fluids used: air – water

Pressure range: 747.84 – 860.52 mm Hg (absolute pressure)

Temperature range: 15.9 – 27.6 ^oC

Range of liquid mass flow rate: 6.01– 6093.40 kg/h

Range of gas mass flow rate: 0.64 – 474.03 kg/h

Range of void fraction covered: 0.06 – 1.00

Mukherjee (1979)

62 Points

Diameter of pipe: 1.5 in

Fluids used: air – kerosene

Pressure range: 28.20 – 91.90 Psia

Temperature range: 62 - 132 ^oF

Range of liquid superficial velocity: 0.05 – 13.07 ft/s

Range of gas superficial velocity: 0.75 – 78.93 ft/s

Range of void fraction covered: 0.08 – 1.00

Minami & Brill (1987)

54 Points

Diameter of pipe: 3.068 in

Fluids used: air – water

Pressure range: 46.40 – 85.40 Psia

Temperature range: 76 - 117 ^{o}F

Range of liquid superficial velocity: 0.02 – 2.96 ft/s

Range of gas superficial velocity: 1.56 – 49.13 ft/s

Range of void fraction covered: 0.55 – 0.99

Minami & Brill (1987)

57 Points

Diameter of pipe: 3.068 in

Fluids used: air – kerosene

Pressure range: 43.70 – 96.70 Psia

Temperature range: 82 - 118 ^{o}F

Range of liquid superficial velocity: 0.02 – 3.12 ft/s

Range of gas superficial velocity: 1.78 – 54.43 ft/s

Range of void fraction covered: 0.56 – 0.99

Franca & Lahey (1992)

81 Points

Diameter of pipe: 0.019 m

Fluids used: air – water

Pressure range: 0.0 – 1.47 m H_2O (Gauge Pressure)

Temperature range: 22 ^{o}C

Range of liquid superficial velocity: 0.01 – 1.49 m/s

Range of gas superficial velocity: 0.13 – 23.76 m/s

Range of void fraction covered: 0.06 – 0.94

Abdul-Majeed (1996)

83 Points

Diameter of pipe: 2 in

Fluids used: air – kerosene

Pressure range: 197.20 – 919.10 KPa

Temperature range: 27.8 – 48.9 ^{o}C

Range of liquid superficial velocity: 0.002 – 1.83 m/s

Range of gas superficial velocity: 0.20 – 48.91 m/s

Range of void fraction covered: 0.39 – 0.99

Chen et al. (1997)

48 Points

Diameter of pipe: 77.9 mm

Fluids used: air – kerosene

Pressure range: 1.9 – 2.4 bar

Temperature range: 16^{o} C

Range of liquid superficial velocity: 0.004 – 0.046 m/s

Range of gas superficial velocity: 3.63 – 12.66 m/s

Range of void fraction covered: 0.85 – 0.99

Ottens (1998)

112 Points

Diameter of pipe: 51 mm

Fluids used: air – water

Pressure range: 1 bar

Temperature range: 20^{o}C

Range of liquid superficial velocity: 0.005 – 0.015 m/s

Range of gas superficial velocity: 4.449 – 15.819 m/s

Range of void fraction covered: 0.914 – 0.989

Badie et al. (2000)

39 Points

Diameter of pipe: 78 mm

Fluids used: air – water

Pressure range: 1 bar

Temperature range: 20^{o}C

Range of liquid superficial velocity: 0.001 – 0.005 m/s

Range of gas superficial velocity: 14.77 – 7.82 m/s

Range of void fraction covered: 0.944 – 0.995 m/s

Badie et al. (2000)

30 Points

Diameter of pipe: 78 mm

Fluids used: air – oil

Pressure range: 1 bar

Temperature range: 20^{o}C

Range of liquid superficial velocity: 0.001 – 0.035 m/s

Range of gas superficial velocity: 14.87 – 25.28 m/s

Range of void fraction covered: 0.890 – 0.987

Wojtan et al. (2004)

116 Points

Diameter of pipe: 5/8 in

Fluids used: R22 vapour liquid (saturated)

Pressure range: 933.9 kPa

Temperature range: 5^{o}C

Range of liquid superficial velocity: 0.007 – 0.157 m/s

Range of gas superficial velocity: 0.04 – 7.37 m/s

Range of void fraction covered: 0 – 0.99

Wojtan et al. (2004)

121 Points

Diameter of pipe: 5/8 in

Fluids used: R410A vapour liquid (saturated)

Pressure range: 584.11 kPa

Temperature range: 5^{o}C

Range of liquid superficial velocity: 0.007 – 0.26 m/s

Range of gas superficial velocity: 0.006 – 4.26 m/s

Range of void fraction covered: 0.07 – 0.96

APPENDIX 5

Performance of all correlations for stratified flow

Correlation	Percentage of data predicted within		
	± 5%	± 10%	± 15%
Abdul-Majeed (1996)	54.55%	80.52%	86.58%
Armand – Massena[3]	69.70%	88.74%	90.04%
Armand (1946)	6.93%	16.88%	74.03%
Bankoff (1960)	3.90%	5.63%	10.82%
Baroczy (1966)	76.19%	86.58%	90.48%
Beggs (1972)	67.97%	82.68%	87.01%
Bestion[4]	0.00%	4.33%	20.78%
Bonnecaze et al. (1971)	5.19%	13.85%	45.89%
Chen (1986)	77.49%	85.28%	88.74%
Chisholm & Laird (1958)	51.95%	76.62%	83.12%
Chisholm (1973)	77.49%	86.15%	89.18%
Chisholm(1983), Armand(1946)	78.79%	86.15%	89.18%
Czop et al. (1994)	3.90%	10.39%	39.83%
Dimentiev et al.[5]	4.33%	6.93%	10.39%
Dix (1971)	78.35%	92.64%	96.54%
El-Boher et al. (1988)	36.36%	75.32%	93.51%
Fauske (1961)	79.65%	89.18%	90.91%
Filimonov et al. (1957)	69.70%	87.88%	93.07%
Flanigan (1958)	1.73%	16.02%	32.47%
Fujie (1964)	54.55%	79.22%	85.28%
Gardner (1980) - Gardner -1	11.26%	17.75%	33.77%
Gardner (1980) - Gardner -2	12.99%	42.42%	58.44%
Gomez et al. (2000)	15.58%	15.58%	18.18%
Graham et al. (2001)	83.12%	92.64%	95.24%
Gregory & Scott (1969)	7.36%	22.08%	83.55%
Greskovich & Cooper (1975)	54.98%	78.79%	84.42%
Guzhov et al. (1967)	3.90%	10.82%	40.26%
Hamersma & Hart (1987)	52.81%	78.35%	83.55%
Hart et al. (1989)	87.88%	92.64%	95.24%
Homogeneous	53.25%	78.79%	84.42%
Hoogendroon (1959)	4.76%	22.08%	45.45%
Hughmark (1962)	22.94%	86.15%	93.51%
Hughmark (1965)	4.76%	12.12%	51.52%

Huq & Loth (1992)	72.29%	84.85%	88.74%
Inoue et al. (1993)	34.20%	75.76%	89.18%
Jowitt[4]	2.16%	9.52%	39.39%
Kawaji et al. (1987)	83.12%	88.31%	90.91%
Kokal & Stanislav (1989)	5.19%	13.85%	45.45%
Kowalczewski, (1964)[2]	79.22%	87.88%	91.77%
Kutucuglu[2]	66.67%	81.82%	86.15%
Lockhart & Martinelli (1949)	78.79%	85.71%	89.18%
Loscher & Reinhardt (1973)1	60.61%	83.55%	88.74%
Madsen (1975)	2.60%	6.49%	10.39%
Maier (1997)	53.25%	83.98%	90.48%
Mattar & Gregory (1974)	0.00%	0.87%	3.03%
Woldesemayat & Ghajar (2007)	80.09%	90.04%	93.07%
Minami & Brill (1987)	74.46%	87.88%	92.21%
Moussali[2]	53.25%	78.79%	84.42%
Mukherjee (1979)	73.16%	86.15%	90.48%
Neal & Bankoff (1965)	0.43%	1.30%	2.16%
Nicklin et al. (1962)	5.19%	13.85%	45.89%
Nishino & Yamazaki (1963)	78.79%	85.71%	90.04%
Petalaz & Aziz (1997)	1.73%	3.90%	5.19%
Premoli et al. (1970)	53.25%	78.79%	84.42%
Rouhani & Axelsson (1970) Rouhani I	36.36%	89.61%	93.07%
Rouhani & Axelsson (1970) Rouhani II	3.90%	9.96%	17.32%
Smith (1969)	72.73%	84.42%	88.31%
Spedding & Chen (1984)	77.92%	86.58%	90.91%
Spedding & Spence (1989)	77.92%	86.58%	90.91%
Sterman (1956)	40.69%	54.98%	60.17%
Sun et al. (1980)	3.46%	10.39%	35.06%
Tandon et al. (1985)	75.32%	88.74%	94.81%
Thom (1964)	62.34%	80.95%	86.15%
Morooka et al. (1989) (called as Toshiba)	20.78%	83.98%	95.24%
Turner & Wallis (1965)	47.62%	76.19%	89.18%
Wallis (1969)	79.65%	87.45%	89.18%
Wilson et al. (1961)	11.26%	22.08%	28.57%
Zhao et al. (2000)	23.81%	44.16%	55.41%
Zivi (1964)	68.40%	84.42%	90.04%

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

Performance of all correlations for plug flow

Correlation	Percentage of data predicted within			
	± 5%	± 10%	± 15%	± 20%
Abdul-Majeed (1996)	0.00%	0.00%	1.52%	1.52%
Armand – Massena[3]	12.12%	25.76%	37.88%	57.58%
Armand (1946)	12.12%	25.76%	37.88%	57.58%
Bankoff (1960)	4.55%	6.06%	7.58%	21.21%
Baroczy (1966)	0.00%	0.00%	0.00%	3.03%
Beggs (1972)	13.64%	27.27%	37.88%	46.97%
Bestion[4]	0.00%	0.00%	0.00%	0.00%
Bonnecaze et al. (1971)	3.03%	7.58%	16.67%	22.73%
Chen (1986)	27.27%	54.55%	71.21%	77.27%
Chisholm & Laird (1958)	0.00%	0.00%	0.00%	0.00%
Chisholm (1973)	7.58%	24.24%	50.00%	68.18%
Chisholm(1983), Armand(1946)	7.58%	22.73%	48.48%	68.18%
Czop et al. (1994)	0.00%	1.52%	3.03%	4.55%
Dimentiev et al.[5]	7.58%	13.64%	24.24%	27.27%
Dix (1971)	9.09%	18.18%	33.33%	46.97%
El-Boher et al. (1988)	15.15%	27.27%	39.39%	51.52%
Fauske (1961)	0.00%	0.00%	0.00%	0.00%
Filimonov et al. (1957)	4.55%	6.06%	9.09%	15.15%
Flanigan (1958)	0.00%	0.00%	1.52%	1.52%
Fujie (1964)	4.55%	16.67%	34.85%	54.55%
Gardner (1980) - Gardner -1	0.00%	0.00%	1.52%	3.03%
Gardner (1980) - Gardner -2	3.03%	4.55%	4.55%	10.61%
Gomez et al. (2000)	0.00%	0.00%	0.00%	0.00%
Graham et al. (2001)	7.58%	13.64%	27.27%	39.39%
Gregory & Scott (1969)	10.61%	27.27%	39.39%	59.09%
Greskovich & Cooper (1975)	27.27%	48.48%	75.76%	87.88%
Guzhov et al. (1967)	1.52%	16.67%	27.27%	46.97%
Hamersma & Hart (1987)	0.00%	0.00%	0.00%	0.00%
Hart et al. (1989)	0.00%	0.00%	0.00%	0.00%
Homogeneous	30.30%	48.48%	74.24%	87.88%
Hoogendroon (1959)	0.00%	0.00%	0.00%	0.00%
Hughmark (1962)	4.55%	7.58%	19.70%	28.79%
Hughmark (1965)	7.58%	21.21%	33.33%	56.06%
Huq & Loth (1992)	7.58%	12.12%	22.73%	51.52%
Inoue et al. (1993)	0.00%	0.00%	0.00%	3.03%
Jowitt[4]	0.00%	0.00%	0.00%	1.52%

Kawaji et al. (1987)	1.52%	3.03%	3.03%	3.03%
Kokal & Stanislav (1989)	3.03%	7.58%	16.67%	22.73%
Kowalczewski, (1964)[2]	0.00%	0.00%	0.00%	1.52%
Kutucuglu[2]	1.52%	1.52%	1.52%	3.03%
Lockhart & Martinelli (1949)	3.03%	4.55%	10.61%	19.70%
Loscher & Reinhardt (1973)1	0.00%	0.00%	0.00%	0.00%
Madsen (1975)	0.00%	0.00%	0.00%	0.00%
Maier (1997)	0.00%	0.00%	0.00%	0.00%
Mattar & Gregory (1974)	0.00%	0.00%	0.00%	0.00%
Woldesemayat & Ghajar (2007)	12.12%	30.30%	43.94%	62.12%
Minami & Brill (1987)	9.09%	27.27%	37.88%	46.97%
Moussali[2]	22.73%	43.94%	57.58%	68.18%
Mukherjee (1979)	21.21%	33.33%	40.91%	51.52%
Neal & Bankoff (1965)	1.52%	1.52%	4.55%	4.55%
Nicklin et al. (1962)	3.03%	7.58%	16.67%	22.73%
Nishino & Yamazaki (1963)	0.00%	0.00%	3.03%	6.06%
Petalaz & Aziz (1997)	1.52%	4.55%	9.09%	9.09%
Premoli et al. (1970)	3.03%	7.58%	7.58%	15.15%
Rouhani & Axelsson (1970) Rouhani I	1.52%	4.55%	10.61%	19.70%
Rouhani & Axelsson (1970) Rouhani II	3.03%	7.58%	16.67%	24.24%
Smith (1969)	7.58%	18.18%	31.82%	56.06%
Spedding & Chen (1984)	7.58%	12.12%	15.15%	18.18%
Spedding & Spence (1989)	3.03%	4.55%	6.06%	6.06%
Sterman (1956)	0.00%	0.00%	0.00%	0.00%
Sun et al. (1980)	0.00%	4.55%	6.06%	18.18%
Tandon et al. (1985)	1.52%	1.52%	3.03%	3.03%
Thom (1964)	0.00%	0.00%	1.52%	3.03%
Morooka et al. (1989) (called as Toshiba)	1.52%	4.55%	6.06%	12.12%
Turner & Wallis (1965)	0.00%	0.00%	0.00%	1.52%
Wallis (1969)	12.12%	28.79%	40.91%	62.12%
Wilson et al. (1961)	0.00%	3.03%	7.58%	9.09%
Zhao et al. (2000)	0.00%	0.00%	0.00%	0.00%
Zivi (1964)	0.00%	0.00%	1.52%	1.52%

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

Performance of all correlations for slug flow

Correlation	Percentage of data predicted within		
Abdul-Majeed (1996)	± 5%	± 10%	± 15%
Armand – Massena[3]	37.68%	60.87%	75.85%
Armand (1946)	30.43%	71.01%	89.86%
Bankoff (1960)	29.95%	69.08%	89.86%
Baroczy (1966)	7.25%	32.85%	57.97%
Beggs (1972)	14.98%	41.06%	48.31%
Bestion[4]	14.01%	33.82%	48.31%
Bonnecaze et al. (1971)	28.02%	49.28%	58.94%
Chen (1986)	34.30%	63.29%	81.16%
Chisholm & Laird (1958)	30.43%	63.29%	90.82%
Chisholm (1973)	0.48%	3.38%	9.66%
Chisholm(1983), Armand(1946)	32.37%	66.18%	89.86%
Czop et al. (1994)	30.43%	67.63%	90.34%
Dimentiev et al.[5]	40.10%	49.28%	65.22%
Dix (1971)	14.49%	29.95%	48.31%
El-Boher et al. (1988)	49.76%	73.91%	84.54%
Fauske (1961)	14.98%	66.18%	87.92%
Filimonov et al. (1957)	0.00%	3.86%	6.28%
Flanigan (1958)	24.64%	32.85%	42.51%
Fujie (1964)	12.08%	28.02%	39.13%
Gardner (1980) - Gardner -1	12.08%	29.95%	44.93%
Gardner (1980) - Gardner -2	12.56%	28.50%	38.65%
Gomez et al. (2000)	27.05%	49.28%	57.00%
Graham et al. (2001)	0.97%	0.97%	0.97%
Gregory & Scott (1969)	21.26%	45.41%	60.39%
Greskovich & Cooper (1975)	28.02%	68.60%	90.82%
Guzhov et al. (1967)	11.11%	26.57%	36.23%
Hamersma & Hart (1987)	42.51%	65.22%	85.99%
Hart et al. (1989)	0.48%	4.83%	11.59%
Homogeneous	6.76%	16.43%	22.22%
Hoogendroon (1959)	10.63%	26.09%	35.75%
Hughmark (1962)	22.71%	40.58%	49.28%
Hughmark (1965)	24.15%	71.50%	83.09%
Huq & Loth (1992)	37.20%	67.15%	87.44%
Inoue et al. (1993)	34.30%	56.52%	80.68%
Jowitt[4]	21.26%	51.69%	73.91%

Kawaji et al. (1987)	30.43%	44.44%	49.76%
Kokal & Stanislav (1989)	11.59%	23.67%	36.71%
Kowalczewski, (1964)[2]	34.30%	62.80%	81.16%
Kutucuglu[2]	20.77%	43.48%	55.07%
Lockhart & Martinelli (1949)	11.11%	24.64%	36.23%
Loscher & Reinhardt (1973)1	31.40%	54.59%	65.70%
Madsen (1975)	12.08%	25.60%	35.75%
Maier (1997)	0.00%	0.00%	0.00%
Mattar & Gregory (1974)	27.54%	52.66%	60.87%
Woldesemayat & Ghajar (2007)	0.97%	18.36%	45.89%
Minami & Brill (1987)	34.78%	80.68%	93.72%
Moussali[2]	28.02%	53.14%	87.92%
Mukherjee (1979)	14.01%	28.02%	40.10%
Neal & Bankoff (1965)	34.78%	60.39%	80.68%
Nicklin et al. (1962)	12.56%	19.81%	25.12%
Nishino & Yamazaki (1963)	34.30%	62.80%	81.16%
Petalaz & Aziz (1997)	20.77%	51.69%	60.39%
Premoli et al. (1970)	12.08%	22.71%	33.82%
Rouhani & Axelsson (1970) Rouhani I	10.63%	26.09%	35.75%
Rouhani & Axelsson (1970) Rouhani II	42.51%	71.50%	82.13%
Smith (1969)	28.99%	63.77%	79.71%
Spedding & Chen (1984)	31.40%	59.90%	85.51%
Spedding & Spence (1989)	17.87%	43.48%	56.04%
Sterman (1956)	17.87%	37.20%	41.06%
Sun et al. (1980)	5.80%	14.49%	25.12%
Tandon et al. (1985)	48.79%	61.84%	77.29%
Thom (1964)	10.63%	21.26%	31.88%
Morooka et al. (1989) (called as Toshiba)	20.77%	31.40%	44.93%
Turner & Wallis (1965)	19.81%	57.00%	80.68%
Wallis (1969)	0.00%	0.00%	0.00%
Wilson et al. (1961)	34.30%	64.73%	79.71%
Zhao et al. (2000)	13.53%	34.78%	46.86%
Zivi (1964)	0.00%	0.00%	0.00%
Zivi(1964)	13.53%	28.50%	33.82%

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

Performance of all correlations for annular flow

Correlation	Percentage of data predicted within		
	± 5%	± 10%	± 15%
Abdul-Majeed (1996)	44.83%	88.51%	98.85%
Armand – Massena[3]	56.32%	97.70%	100.00%
Armand (1946)	40.23%	58.62%	85.06%
Bankoff (1960)	0.00%	2.30%	33.33%
Baroczy (1966)	70.11%	91.95%	97.70%
Beggs (1972)	26.44%	43.68%	54.02%
Bestion[4]	45.98%	91.95%	98.85%
Bonnecaze et al. (1971)	41.38%	52.87%	81.61%
Chen (1986)	58.62%	97.70%	100.00%
Chisholm & Laird (1958)	26.44%	43.68%	54.02%
Chisholm (1973)	67.82%	97.70%	100.00%
Chisholm(1983), Armand(1946)	62.07%	97.70%	100.00%
Czop et al. (1994)	36.78%	47.13%	66.67%
Dimentiev et al.[5]	28.74%	48.28%	60.92%
Dix (1971)	86.21%	100.00%	100.00%
El-Boher et al. (1988)	34.48%	97.70%	100.00%
Fauske (1961)	21.84%	41.38%	49.43%
Filimonov et al. (1957)	42.53%	56.32%	66.67%
Flanigan (1958)	57.47%	79.31%	91.95%
Fujie (1964)	34.48%	51.72%	58.62%
Gardner (1980) - Gardner -1	64.37%	88.51%	94.25%
Gardner (1980) - Gardner -2	65.52%	94.25%	97.70%
Gomez et al. (2000)	8.05%	12.64%	14.94%
Graham et al. (2001)	82.76%	95.40%	98.85%
Gregory & Scott (1969)	40.23%	62.07%	95.40%
Greskovich & Cooper (1975)	31.03%	49.43%	57.47%
Guzhov et al. (1967)	39.08%	48.28%	70.11%
Hamersma & Hart (1987)	27.59%	43.68%	55.17%
Hart et al. (1989)	49.43%	67.82%	80.46%
Homogeneous	29.89%	48.28%	57.47%
Hoogendroon (1959)	59.77%	85.06%	96.55%
Hughmark (1962)	59.77%	98.85%	100.00%
Hughmark (1965)	40.23%	51.72%	75.86%
Huq & Loth (1992)	73.56%	96.55%	98.85%
Inoue et al. (1993)	49.43%	83.91%	100.00%
Jowitt[4]	22.99%	54.02%	55.17%

Kawaji et al. (1987)	26.44%	72.41%	93.10%
Kokal & Stanislav (1989)	41.38%	52.87%	81.61%
Kowalczewski, (1964)[2]	66.67%	95.40%	97.70%
Kutucuglu[2]	58.62%	78.16%	86.21%
Lockhart & Martinelli (1949)	80.46%	96.55%	98.85%
Loscher & Reinhardt (1973)1	77.01%	94.25%	95.40%
Madsen (1975)	0.00%	0.00%	0.00%
Maier (1997)	57.47%	94.25%	100.00%
Mattar & Gregory (1974)	0.00%	8.05%	42.53%
Woldesemayat & Ghajar (2007)	66.67%	98.85%	100.00%
Minami & Brill (1987)	50.57%	77.01%	100.00%
Moussali[2]	31.03%	49.43%	57.47%
Mukherjee (1979)	41.38%	75.86%	98.85%
Neal & Bankoff (1965)	9.20%	12.64%	16.09%
Nicklin et al. (1962)	41.38%	52.87%	81.61%
Nishino & Yamazaki (1963)	73.56%	95.40%	97.70%
Petalaz & Aziz (1997)	1.15%	2.30%	6.90%
Premoli et al. (1970)	29.89%	48.28%	57.47%
Rouhani & Axelsson (1970) Rouhani I	50.57%	90.80%	100.00%
Rouhani & Axelsson (1970) Rouhani II	28.74%	58.62%	83.91%
Smith (1969)	65.52%	96.55%	100.00%
Spedding & Chen (1984)	67.82%	93.10%	97.70%
Spedding & Spence (1989)	64.37%	80.46%	83.91%
Sterman (1956)	28.74%	44.83%	55.17%
Sun et al. (1980)	39.08%	49.43%	72.41%
Tandon et al. (1985)	35.63%	77.01%	91.95%
Thom (1964)	50.57%	80.46%	96.55%
Morooka et al. (1989) (called as Toshiba)	28.74%	93.10%	100.00%
Turner & Wallis (1965)	5.75%	17.24%	25.29%
Wallis (1969)	73.56%	95.40%	100.00%
Wilson et al. (1961)	12.64%	19.54%	27.59%
Zhao et al. (2000)	0.00%	4.60%	8.05%
Zivi (1964)	68.97%	83.91%	93.10%

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

APPENDIX 6

Performance of all correlations for void fraction range 0-0.25

Correlation	Percentage of data predicted within			RMS Error %
	± 15%	± 20%	± 30%	
Abdul-Majeed (1996)	0.00%	0.00%	0.00%	122.9
Armand – Massena[3]	31.48%	45.28%	71.70%	61.96
Armand (1946)	31.48%	45.28%	71.70%	61.48
Bankoff (1960)	31.48%	43.40%	62.26%	51.56
Baroczy (1966)	7.41%	11.32%	26.42%	53.64
Beggs (1972)	3.70%	7.55%	11.32%	333.82
Bestion[4]	9.26%	9.43%	13.21%	65.63
Bonnecaze et al. (1971)	37.04%	50.94%	67.92%	39.67
Chen (1986)	11.11%	15.09%	18.87%	143.44
Chisholm & Laird (1958)	0.00%	0.00%	0.00%	367.38
Chisholm (1973)	29.63%	41.51%	71.70%	63.17
Chisholm(1983), Armand(1946)	29.63%	39.62%	71.70%	62.51
Czop et al. (1994)	3.70%	3.77%	5.66%	176.43
Dimentiev et al.[5]	16.67%	18.87%	30.19%	128.94
Dix (1971)	27.78%	37.74%	66.04%	54.66
El-Boher et al. (1988)	18.52%	30.19%	41.51%	79.6
Fauske (1961)	0.00%	0.00%	0.00%	87.79
Filimonov et al. (1957)	20.37%	41.51%	56.60%	45.75
Flanigan (1958)	1.85%	3.77%	7.55%	79.56
Fujie (1964)	46.30%	50.94%	66.04%	67.85
Gardner (1980) - Gardner -1	9.26%	16.98%	26.42%	72.19
Gardner (1980) - Gardner -2	5.56%	13.21%	22.64%	93.02
Gomez et al. (2000)	12.96%	16.98%	24.53%	68.04
Graham et al. (2001)	31.48%	47.17%	54.72%	64.27
Gregory & Scott (1969)	31.48%	45.28%	69.81%	62.24
Greskovich & Cooper (1975)	29.63%	43.40%	56.60%	76.68
Guzhov et al. (1967)	44.44%	54.72%	73.58%	38.58
Hamersma & Hart (1987)	0.00%	0.00%	0.00%	456.91
Hart et al. (1989)	5.56%	5.66%	11.32%	75.74
Homogeneous	29.63%	41.51%	52.83%	81.1
Hoogendroon (1959)	1.85%	1.89%	7.55%	59.27
Hughmark (1962)	37.04%	52.83%	64.15%	47.45
Hughmark (1965)	33.33%	49.06%	67.92%	60.12

Huq & Loth (1992)	35.19%	50.94%	73.58%	57.32
Inoue et al. (1993)	1.85%	5.66%	22.64%	54.32
Jowitt[4]	5.56%	7.55%	20.75%	48.76
Kawaji et al. (1987)	12.96%	13.21%	18.87%	636.88
Kokal & Stanislav (1989)	37.04%	50.94%	67.92%	39.63
Kowalczewski, (1964)[2]	0.00%	0.00%	0.00%	100.13
Kutucuglu[2]	0.00%	0.00%	0.00%	100.79
Lockhart & Martinelli (1949)	27.78%	41.51%	60.38%	91.86
Loscher & Reinhardt (1973)1	0.00%	0.00%	1.89%	186.47
Madsen (1975)	0.00%	0.00%	0.00%	98.46
Maier (1997)	0.00%	0.00%	1.89%	61.09
Mattar & Gregory (1974)	1.85%	1.89%	11.32%	53.17
Woldesemayat & Ghajar (2007)	16.67%	28.30%	43.40%	68.41
Minami & Brill (1987)	29.63%	41.51%	64.15%	58.01
Moussali[2]	31.48%	39.62%	67.92%	72.08
Mukherjee (1979)	12.96%	16.98%	37.74%	78.33
Neal & Bankoff (1965)	1.85%	1.89%	1.89%	68.4
Nicklin et al. (1962)	37.04%	50.94%	67.92%	39.51
Nishino & Yamazaki (1963)	11.11%	18.87%	33.96%	50.58
Petalaz & Aziz (1997)	0.00%	0.00%	0.00%	560.51
Premoli et al. (1970)	38.89%	49.06%	54.72%	78.06
Rouhani & Axelsson (1970) Rouhani I	35.19%	47.17%	66.04%	41.72
Rouhani & Axelsson (1970) Rouhani II	44.44%	56.60%	69.81%	41.39
Smith (1969)	29.63%	43.40%	73.58%	59.8
Spedding & Chen (1984)	37.04%	49.06%	66.04%	43.15
Spedding & Spence (1989)	14.81%	16.98%	22.64%	555.32
Sterman (1956)	0.00%	1.89%	1.89%	77.38
Sun et al. (1980)	31.48%	49.06%	64.15%	40.97
Tandon et al. (1985)	9.26%	9.43%	18.87%	401.6
Thom (1964)	7.41%	13.21%	16.98%	69.17
Morooka et al. (1989) (called as Toshiba)	24.07%	37.74%	54.72%	45.02
Turner & Wallis (1965)	1.85%	7.55%	13.21%	73.51
Wallis (1969)	0.00%	5.66%	9.43%	140.78
Wilson et al. (1961)	14.81%	24.53%	37.74%	63.27
Zhao et al. (2000)	0.00%	0.00%	1.89%	93.84
Zivi (1964)	5.56%	5.66%	7.55%	78.34

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

Performance of all correlations void fraction range 0.25 – 0.50

Correlation	Percentage of data predicted within			RMS Error %
	± 10%	± 15%	± 20%	
Abdul-Majeed (1996)	9.36%	15.20%	18.13%	68.2815
Armand – Massena[3]	25.73%	39.77%	56.73%	29.22089
Armand (1946)	25.73%	39.77%	57.89%	28.64034
Bankoff (1960)	28.07%	35.67%	43.86%	25.22126
Baroczy (1966)	12.28%	18.13%	27.49%	36.28955
Beggs (1972)	31.58%	50.88%	59.06%	66.22833
Bestion[4]	2.92%	8.19%	12.28%	51.26379
Bonnecaze et al. (1971)	29.24%	46.20%	62.57%	21.1948
Chen (1986)	29.82%	38.60%	43.86%	51.03812
Chisholm & Laird (1958)	0.00%	0.00%	0.00%	132.4631
Chisholm (1973)	29.24%	49.71%	61.99%	26.65711
Chisholm(1983), Armand(1946)	29.82%	49.12%	62.57%	26.08972
Czop et al. (1994)	9.94%	15.20%	23.39%	52.14719
Dimentiev et al.[5]	19.88%	26.32%	36.84%	44.43911
Dix (1971)	42.11%	54.39%	64.91%	23.06005
El-Boher et al. (1988)	38.01%	56.73%	70.18%	18.53087
Fauske (1961)	1.75%	3.51%	4.68%	77.17288
Filimonov et al. (1957)	27.49%	38.01%	50.88%	29.58796
Flanigan (1958)	2.92%	5.26%	7.60%	64.23802
Fujie (1964)	15.79%	30.99%	46.20%	37.81478
Gardner (1980) - Gardner -1	7.02%	12.87%	16.37%	52.28987
Gardner (1980) - Gardner -2	7.60%	17.54%	28.07%	45.65375
Gomez et al. (2000)	2.34%	4.68%	8.19%	72.13309
Graham et al. (2001)	36.26%	45.61%	59.06%	21.58889
Gregory & Scott (1969)	26.32%	39.77%	56.14%	29.16174
Greskovich & Cooper (1975)	29.82%	39.18%	46.20%	41.58766
Guzhov et al. (1967)	27.49%	46.20%	66.67%	21.17885
Hamersma & Hart (1987)	0.00%	0.00%	0.00%	138.8419
Hart et al. (1989)	15.20%	20.47%	26.32%	58.56956
Homogeneous	29.82%	39.77%	43.27%	44.59415
Hoogendroon (1959)	1.17%	4.09%	6.43%	51.76568
Hughmark (1962)	24.56%	39.18%	50.88%	23.6191
Hughmark (1965)	21.05%	39.77%	58.48%	27.75783
Huq & Loth (1992)	24.56%	39.18%	60.82%	24.9307
Inoue et al. (1993)	11.70%	21.05%	30.99%	39.98645

Jowitt[4]	12.28%	19.88%	28.07%	36.37327
Kawaji et al. (1987)	11.70%	14.62%	17.54%	168.077
Kokal & Stanislav (1989)	29.24%	45.61%	61.99%	21.14536
Kowalczewski, (1964)[2]	2.92%	6.43%	8.19%	84.02418
Kutucuglu[2]	4.09%	5.26%	6.43%	87.3175
Lockhart & Martinelli (1949)	10.53%	19.88%	28.07%	37.28347
Loscher & Reinhardt (1973)1	0.58%	1.75%	4.68%	127.5546
Madsen (1975)	0.00%	0.00%	0.00%	96.28418
Maier (1997)	2.34%	5.85%	11.11%	47.95161
Mattar & Gregory (1974)	3.51%	7.02%	12.28%	43.36968
Woldesemayat & Ghajar (2007)	46.78%	64.33%	76.02%	17.67395
Minami & Brill (1987)	40.94%	60.23%	75.44%	18.58761
Moussali[2]	26.32%	37.43%	49.12%	40.35704
Mukherjee (1979)	50.88%	64.33%	81.29%	15.31158
Neal & Bankoff (1965)	19.30%	30.41%	40.35%	34.76719
Nicklin et al. (1962)	27.49%	45.61%	61.99%	21.28525
Nishino & Yamazaki (1963)	14.04%	22.81%	34.50%	33.35927
Petalaz & Aziz (1997)	0.00%	0.00%	0.00%	126.3488
Premoli et al. (1970)	29.82%	39.77%	42.69%	28.88259
Rouhani & Axelsson (1970) Rouhani I	32.16%	46.20%	59.06%	22.02026
Rouhani & Axelsson (1970) Rouhani II	36.84%	49.12%	61.99%	21.18248
Smith (1969)	23.39%	44.44%	63.16%	25.6538
Spedding & Chen (1984)	16.96%	28.07%	39.18%	26.53352
Spedding & Spence (1989)	12.87%	21.05%	28.65%	134.6828
Sterman (1956)	3.51%	4.68%	4.68%	69.25203
Sun et al. (1980)	29.24%	41.52%	58.48%	23.08937
Tandon et al. (1985)	12.28%	19.88%	26.32%	63.1335
Thom (1964)	10.53%	11.70%	16.37%	49.00576
Morooka et al. (1989) (called as Toshiba)	27.49%	38.60%	46.78%	30.02357
Turner & Wallis (1965)	1.75%	4.09%	7.02%	66.4184
Wallis (1969)	31.58%	42.11%	53.80%	36.1138
Wilson et al. (1961)	11.70%	17.54%	20.47%	48.85694
Zhao et al. (2000)	0.00%	0.00%	0.00%	92.60655
Zivi (1964)	5.85%	9.94%	12.87%	61.35575

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

Performance of all correlations for void fraction range 0.50 – 0.75

Correlation	Percentage of data predicted within			RMS Error %
	± 5%	± 10%	± 15%	
Abdul-Majeed (1996)	27.87%	48.28%	60.06%	29.38
Armand – Massena[3]	24.14%	59.20%	78.16%	13.68
Armand (1946)	30.75%	65.52%	83.91%	12.25
Bankoff (1960)	20.11%	54.89%	78.45%	12.54
Baroczy (1966)	20.69%	37.36%	46.84%	22.68
Beggs (1972)	27.30%	47.70%	58.33%	23.59
Bestion[4]	15.23%	28.16%	39.94%	36.28
Bonnecaze et al. (1971)	28.16%	65.52%	81.90%	12.98
Chen (1986)	12.07%	35.92%	56.03%	20.57
Chisholm & Laird (1958)	0.00%	0.00%	0.00%	53.69
Chisholm (1973)	31.90%	60.34%	77.87%	14.14
Chisholm(1983), Armand(1946)	34.20%	62.64%	79.89%	13.55
Czop et al. (1994)	36.49%	56.03%	69.83%	15.92
Dimentiev et al.[5]	9.77%	23.28%	37.64%	28.02
Dix (1971)	36.49%	57.76%	72.70%	16.68
El-Boher et al. (1988)	20.98%	51.44%	72.41%	14.71
Fauske (1961)	2.87%	6.90%	10.06%	56.66
Filimonov et al. (1957)	20.98%	34.20%	47.99%	21.7
Flanigan (1958)	9.20%	14.94%	22.41%	51.32
Fujie (1964)	8.91%	18.68%	30.46%	24.7
Gardner (1980) - Gardner -1	8.62%	16.67%	22.70%	46.3
Gardner (1980) - Gardner -2	14.66%	27.01%	34.20%	38.98
Gomez et al. (2000)	2.59%	4.89%	8.62%	71.33
Graham et al. (2001)	25.86%	49.14%	67.82%	18.02
Gregory & Scott (1969)	29.60%	61.21%	82.18%	12.8
Greskovich & Cooper (1975)	3.45%	8.91%	18.68%	28.82
Guzhov et al. (1967)	43.97%	72.70%	85.06%	11.93
Hamersma & Hart (1987)	0.00%	0.00%	0.00%	50.38
Hart et al. (1989)	16.38%	32.47%	38.79%	36.35
Homogeneous	3.16%	8.05%	16.95%	29.99
Hoogendroon (1959)	10.92%	18.10%	25.00%	40.39
Hughmark (1962)	36.49%	69.54%	85.34%	11.11
Hughmark (1965)	36.21%	69.83%	84.77%	11.39
Huq & Loth (1992)	31.61%	54.02%	74.14%	14.72

Inoue et al. (1993)	15.80%	37.36%	52.01%	27.75
Jowitt[4]	12.64%	26.15%	32.47%	26.19
Kawaji et al. (1987)	6.90%	19.83%	31.32%	34.72
Kokal & Stanislav (1989)	28.45%	65.23%	81.90%	12.92
Kowalczewski, (1964)[2]	15.80%	31.03%	41.95%	32.63
Kutucuglu[2]	10.34%	18.68%	28.45%	50.54
Lockhart & Martinelli (1949)	24.43%	41.95%	60.34%	18.29
Loscher & Reinhardt (1973)1	3.16%	12.07%	18.97%	79.15
Madsen (1975)	0.00%	0.00%	0.00%	90.97
Maier (1997)	15.52%	32.76%	41.67%	30.27
Mattar & Gregory (1974)	2.59%	14.94%	28.45%	31.84
Woldesemayat & Ghajar (2007)	41.38%	75.29%	87.93%	11.51
Minami & Brill (1987)	33.05%	57.47%	81.32%	12.72
Moussali[2]	5.17%	13.22%	23.28%	28.29
Mukherjee (1979)	24.71%	58.91%	76.44%	13.58
Neal & Bankoff (1965)	8.91%	16.67%	23.56%	47.69
Nicklin et al. (1962)	26.44%	64.66%	81.32%	13.08
Nishino & Yamazaki (1963)	20.11%	43.97%	55.46%	18.76
Petalaz & Aziz (1997)	21.84%	41.95%	61.49%	22.57
Premoli et al. (1970)	3.16%	8.05%	16.95%	14.1
Rouhani & Axelsson (1970) Rouhani I	44.54%	71.26%	85.63%	11.32
Rouhani & Axelsson (1970) Rouhani II	24.14%	51.72%	66.67%	17.37
Smith (1969)	29.89%	56.32%	76.44%	14.74
Spedding & Chen (1984)	14.94%	33.33%	49.43%	19.8
Spedding & Spence (1989)	12.36%	25.57%	36.21%	42.96
Sterman (1956)	3.45%	9.20%	12.93%	57.42
Sun et al. (1980)	40.52%	66.95%	82.47%	12.5
Tandon et al. (1985)	18.39%	33.05%	48.56%	30.53
Thom (1964)	16.38%	31.90%	45.69%	26.1
Morooka et al. (1989) (called as Toshiba)	22.13%	45.69%	67.24%	19.88
Turner & Wallis (1965)	2.01%	3.74%	6.90%	51.46
Wallis (1969)	23.28%	50.00%	67.53%	15.11
Wilson et al. (1961)	9.48%	18.10%	27.30%	43.88
Zhao et al. (2000)	0.57%	0.57%	1.15%	78.83
Zivi (1964)	12.93%	21.84%	29.60%	35.86

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

Performance of all correlations for void fraction range 0.75 – 1

Correlation	Percentage of data predicted within			RMS Error %
	± 5%	± 10%	± 15%	
Abdul-Majeed (1996)	46.89%	83.05%	93.67%	15.93
Armand – Massena[3]	71.35%	97.32%	99.89%	4.69
Armand (1946)	20.60%	40.13%	81.22%	11.33
Bankoff (1960)	0.00%	1.61%	14.59%	22.51
Baroczy (1966)	70.49%	86.59%	93.67%	7.05
Beggs (1972)	63.09%	79.83%	87.88%	9.87
Bestion[4]	25.11%	48.07%	61.70%	22.18
Bonnecaze et al. (1971)	9.87%	23.28%	56.22%	14.93
Chen (1986)	72.10%	89.16%	97.00%	5.73
Chisholm & Laird (1958)	36.27%	57.40%	70.49%	14.37
Chisholm (1973)	75.21%	92.60%	98.93%	5.01
Chisholm(1983), Armand(1946)	68.56%	90.88%	98.61%	5.43
Czop et al. (1994)	12.98%	25.32%	56.01%	13.82
Dimentiev et al.[5]	25.21%	40.13%	51.82%	23.43
Dix (1971)	65.13%	89.38%	95.92%	9.7
El-Boher et al. (1988)	37.66%	74.36%	93.03%	9.92
Fauske (1961)	54.18%	67.49%	75.11%	16.25
Filimonov et al. (1957)	57.19%	77.36%	86.27%	11.8
Flanigan (1958)	15.02%	31.01%	45.49%	31.81
Fujie (1964)	45.06%	70.92%	83.80%	9.95
Gardner (1980) - Gardner -1	22.75%	36.80%	48.82%	30.93
Gardner (1980) - Gardner -2	32.30%	53.11%	61.91%	24.61
Gomez et al. (2000)	20.82%	27.68%	33.91%	46.11
Graham et al. (2001)	82.51%	93.88%	97.53%	7.3
Gregory & Scott (1969)	21.78%	45.49%	90.56%	10.69
Greskovich & Cooper (1975)	43.99%	68.78%	81.55%	10.74
Guzhov et al. (1967)	14.16%	27.25%	56.33%	14.89
Hamersma & Hart (1987)	39.81%	62.02%	74.79%	12.85
Hart et al. (1989)	79.72%	90.88%	95.28%	7.89
Homogeneous	42.17%	67.70%	80.58%	11.03
Hoogendroon (1959)	17.38%	34.66%	54.29%	24.99
Hughmark (1962)	39.38%	89.59%	99.03%	7.24
Hughmark (1965)	17.38%	33.15%	67.38%	12.55
Huq & Loth (1992)	73.82%	92.27%	98.39%	5.27

Inoue et al. (1993)	38.52%	67.60%	79.94%	15.1
Jowitt[4]	7.62%	13.84%	31.76%	24.89
Kawaji et al. (1987)	59.98%	79.94%	89.91%	20.08
Kokal & Stanislav (1989)	9.98%	23.50%	56.33%	14.9
Kowalczewski, (1964)[2]	65.24%	88.63%	96.78%	6.53
Kutucuglu[2]	63.95%	81.76%	90.24%	9.45
Lockhart & Martinelli (1949)	80.04%	94.64%	98.61%	4.58
Loscher & Reinhardt (1973)1	60.52%	78.00%	85.41%	29.45
Madsen (1975)	3.86%	7.73%	11.80%	60.35
Maier (1997)	44.64%	71.14%	80.69%	14.67
Mattar & Gregory (1974)	0.00%	2.04%	9.12%	26.11
Woldesemayat & Ghajar (2007)	78.54%	96.03%	97.85%	7.7
Minami & Brill (1987)	69.10%	90.77%	98.39%	6.05
Moussali[2]	42.92%	68.78%	81.76%	10.75
Mukherjee (1979)	65.56%	87.77%	96.35%	6.82
Neal & Bankoff (1965)	5.36%	9.12%	12.88%	56.85
Nicklin et al. (1962)	9.87%	23.07%	56.12%	14.97
Nishino & Yamazaki (1963)	62.55%	86.27%	94.42%	7
Petalaz & Aziz (1997)	0.32%	0.64%	3.11%	47.85
Premoli et al. (1970)	42.17%	67.70%	80.58%	4.01
Rouhani & Axelsson (1970) Rouhani I	44.53%	92.60%	98.07%	8.21
Rouhani & Axelsson (1970) Rouhani II	15.45%	36.70%	54.72%	20.63
Smith (1969)	73.82%	91.63%	98.39%	5.28
Spedding & Chen (1984)	60.84%	81.55%	90.99%	8.18
Spedding & Spence (1989)	60.30%	82.08%	92.17%	8.78
Sterman (1956)	29.83%	43.67%	53.00%	33.88
Sun et al. (1980)	10.41%	24.79%	55.04%	14.97
Tandon et al. (1985)	72.96%	91.85%	97.42%	7.08
Thom (1964)	59.23%	83.26%	93.45%	7.49
Morooka et al. (1989) (called as Toshiba)	24.14%	72.96%	88.09%	12.26
Turner & Wallis (1965)	27.58%	45.17%	58.58%	20.41
Wallis (1969)	79.08%	95.06%	98.82%	4.6
Wilson et al. (1961)	9.98%	19.21%	26.82%	36.01
Zhao et al. (2000)	17.81%	29.51%	36.59%	43.04
Zivi (1964)	70.92%	88.09%	94.74%	7.16

[1] Friedel (1977); [2] Isbin & Biddle (1979); [3] Leung (2005); [4] Coddington & Macian (2002); [5] Kataoka & Ishii (1987)

VITA

Nishant Mathure

Candidate for the Degree of

Master of Science

Thesis: STUDY OF FLOW PATTERNS AND VOID FRACTION IN HORIZONTAL TWO-PHASE FLOW

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Gwalior, India on January 27, 1985.

Education: Received Bachelor of Engineering degree in Mechanical Engineering from University of Pune, India in July 2006.

Completed the requirements for the Master of Science in Mechanical Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2010.

Professional Experience:

2006-2007, Trainee Engineer, DGP Hinoday Pvt. Ltd., Pune, India
2007-2010, Teaching Assistant, Oklahoma State University

Professional Membership:

American Society of Heating, Refrigerating and Air Conditioning Engineers, Oklahoma State University Branch.

Name: Nishant Mathure Date of Degree: December, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: STUDY OF FLOW PATTERNS AND VOID FRACTION IN HORIZONTAL TWO-PHASE FLOW

Pages in Study: 109 Candidate for the Degree of Master of Science

Major Field: Mechanical Engineering

Scope and Method of Study: A comprehensive literature review was carried out in regards to flow patterns and void fraction in horizontal two-phase flow. Data was collected in the laboratory to determine the flow pattern map for the setup. The resulting map was compared with the popular existing maps. Void Fraction data was collected in the laboratory and validated via uncertainty analysis and head-on comparison with external available data. Void fraction data collected in the laboratory was combined with data from external sources in order to evaluate a large number of void fraction correlations. The analysis was carried out by classifying the data according to flow patterns and void fraction ranges separately. Specific criteria were used for different categories in order to recommend a suite of correlations, each applicable to the respective category. Finally the best overall correlations were determined.

Findings and Conclusions: Five flow patterns were observed in the course of experimentation through the collection of 530 data points. The flow pattern map developed was shown to be comparable with the popular maps within reasonable deviations. This map may be used as a reference for future studies on the setup. 184 data points covering the void fraction range of 0.14 to 0.84 were collected. This dataset of known accuracy forms a reliable resource for future work. 69 void fraction correlations were tested against a combined database of 1505 points. Different correlations applicable to different flow patterns and void fraction ranges were determined. The best overall performing void fraction correlations were determined to be those by Woldesemayat & Ghajar (2007) and Minami & Brill (1987). The correlation of Woldesemayat & Ghajar (2007) was also found to be the best correlation for the data collected in the present study.

ADVISER'S APPROVAL: Dr. Afshin J. Ghajar