STUDY OF FLOW PATTERNS AND VOID FRACTION IN VERTICAL UPWARD TWO-PHASE FLOW

By

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STUDY OF FLOW PATTERNS AND VOID FRACTION IN VERTICAL UPWARD TWO-PHASE FLOW

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NOMENCLATURE

A	Area
$a_{Shvarts}$	Constant in Shvarts et al. (1993) correlation, equation (2.110)
$a_{1\,Shvarts}$	Constant in Shvarts et al. (1993) correlation, equation (2.113)
$a_{2\,Shvarts}$	Constant in Shvarts et al. (1993) correlation, equation (2.113)
$B_{1Chexal}$	Parameter in Chexal et al. (1992) correlation, equation (2.116)
$b_{1Shvarts}$	Constant in Shvarts et al. (1993) correlation, equation (2.111)
$b_{2Shvarts}$	Constant in Shvarts et al. (1993) correlation, equation (2.111)
$b_{3Shvarts}$	Constant in Shvarts et al. (1993) correlation, equation (2.111)
b_{Yeh}	Constant in Yeh and Hochreiter (1980) model, equation (2.138)
C	Constant in flooding mechanism, equation (2.8)
C_1	Constant in Mukherjee (1979) correlation, equation (2.104)
C_2	Constant in Mukherjee (1979) correlation, equation (2.104)
C_3	Constant in Mukherjee (1979) correlation, equation (2.104)
C_4	Constant in Mukherjee (1979) correlation, equation (2.104)
C_5	Constant in Mukherjee (1979) correlation, equation (2.104)
C_6	Constant in Mukherjee (1979) correlation, equation (2.104)
$C_{2Chexal}$	Constant in Chexal et al. (1992) correlation, equation (2.115)
$C_{3Chexal}$	Constant in Chexal et al. (1992) correlation, equation (2.115)
$C_{4\,Chexal}$	Constant in Chexal et al. (1992) correlation, equation (2.115)
$C_{5\,Chexal}$	Constant in Chexal et al. (1992) correlation

$C_{7\ Chexal}$	Constant in Chexal et al. (1992) correlation
$C_{9\ Chexal}$	Constant in Chexal et al. (1992) correlation, equation (2.115)
$C_{1Sylvester}$	Constant in Sylvester model, equation (2.51)
$C_{2Sylvester}$	Constant in Sylvester model, equation (2.52)
$C_{3Sylvester}$	Constant in Sylvester model, equation (2.52)
C_o	Distribution Parameter
$C_{o1Ishii}$	Distribution Parameter 1 for Ishii (1977b) correlation, equation (2.135)
$C_{o2Ishii}$	Distribution Parameter 2 for Ishii (1977b) correlation, equation (2.135)
$C_{oMishimaishii}$	Constant in Mishima and Ishii (1984) model, equation (2.4)
$C_{o1OhkawaLahey}$	Distribution Parameter 1 for Ohkawa and Lahey (1980) correlation, equation (2.141)
$C_{o2\ OhkawaLahey}$	Distribution Parameter 2 for Ohkawa and Lahey (1980) correlation, equation (2.141)
C_{Beggs1}	Constant in Begg's (1972) correlation, equation (2.30)
C_{Beggs2}	Constant in Begg's (1972) correlation, equation (2.43)
C_L	Constant in Brauner and Barnea (1986) model, equation (2.12)
C_W	Constant in Orell and Rembrand (1986) correlation, equation (2.67)
D	Diameter of pipe
D_H	Hydraulic diameter
D_H^*	Dimensionless hydraulic diameter
$D_{Takeuchi}$	Dimensionless diameter in Takeuchi et al. (1992) correlation
E	Liquid Entrainment
E_{NY}	Constant in Yamazaki and Yamaguchi (1976) correlation, equation (2.88)

f	Friction factor
F_1	Constant in Premoli et al. (1970) correlation, equation (2.92)
F_2	Constant in Premoli et al. (1970) correlation, equation (2.92)
F_{Wilson}	Constant in Wilson et al. (1961) correlation, equation (2.98)
$F_{Takeuchi}$	Constant in Takeuchi et al. (1992) correlation, equation (2.107)
F_{Madsen}	Constant in Madsen (1975) correlation, equation (2.108)
Fr	Froude number
G	Mass Velocity
g	Acceleration due to gravity
j_G^*	Dimensionless gas flux in Dimentiev et al. (1959) correlation, equation (2.96)
K	Constant in $K\alpha_H$ model
k	Constant in equation of film thickness derived by Wallis (1969), equation (3.23)
$k_{Bankoff}$	Constant in Bankoff (1960) correlation, equation (2.84)
$k_{Bonnecaze}$	Constant in Bonnecaze et al. (1971) correlation, equation (2.122)
k_{Chen}	Constant in Chen (1986) correlation, equation (2.74)
k_{Chexal}	Constant in Chexal et al. (1992) correlation, equation (2.114)
k_{Hugh}	Constant in Hughmark (1962) correlation, equation (2.85)
k_{NY}	Constant in Nishino and Yamazaki (1963) correlation, equation (2.87)
$k_{Shvarts}$	Constant in Shvarts et al. (1993) correlation, equation (2.110)
k_{Smith}	Constant in Smith (1969) correlation, equation (2.70)
$k_{1SpeddingChen}$	Constant in Spedding and Chen (1984) correlation, equation (2.105)

$k_{2SpeddingChen}$	Constant in Spedding and Chen (1984) correlation, equation (2.105)
$k_{3SpeddingChen}$	Constant in Spedding and Chen (1984) correlation, equation (2.105)
$k_{Takeuchi}$	Constant in Takeuchi et al. (1992) correlation
$k_{Velocity}$	Velocity ratio
Ku	Kutaletatdze number
L	Length
L_{Chexal}	*Parameter* in Chexal et al. (1992) correlation, equation (2.114)
m	Mass flow rate
m_1	Constant in equation of film thickness derived by Wallis (1969) , equation (2.23)
$\mathrm{m}_{\mathrm{JayantiHewitt}}$	Constant in Jayanti and Hewitt (1992) model, equation (2.14)
$m_{Takeuchi}$	Constant in Takeuchi et al. (1992) correlation, equation (2.107)
n	Constant in Brauner and Barnea (1986) model, equation (2.12)
N_{FR}	Froude number in Begg's (1972) correlation, equation (2.31)
N_{GV}	gas velocity number in Mukherhee (1979) correlation, equation (2.104)
N_{LV}	liquid velocity number in Begg's (1972) and Mukherhee (1979) correlation, equation (2.44)
$N_{\mu L}$	Viscosity number in Kataoka and Ishii (1987) correlation, equation (2.55)
P	Pressure
$P_{Gardner}$	Constant in Gardner (1980) correlation, equation (2.100)
Q	Volume flow rate
R_{BCR}	Critical bubble radius in Yeh and Hochreiter (1980) model, equation (2.140)

Re	Reynolds number
Re_{Chexal}	Reynolds number in Chexal et al. (1992) correlation, equation (2.116)
Re_{Hugh}	Reynolds number in Hughmark (1962) correlation
$Re_{Premoli}$	Reynolds number in Premoli et al. (1970) correlation
R_L	Liquid hold up
r_{Chexal}	*Parameter* in Chexal et al. (1992) correlation, equation (2.114)
U	Velocity
U^*	Dimensionless velocity in flooding mechanism
U_0	Rise velocity of small bubbles, equation (2.49)
$U_{0\infty}$	Rise velocity of a single bubble
U_B	Velocity of small bubbles in liquid slug
U_{BCR}	Critical bubble velocity in Yeh and Hochreiter (1980) model, equation (2.139)
U_{CSG}	Critical vapor velocity in Hasan and Kabir (1990) model, equation (2.78)
$U_{GM1Ishii}$	Drift velocity1 for Ishii (1977b) correlation, equation (2.136)
$U_{GM2Ishii}$	Drift velocity 2 for Ishii (1977b) correlation, equation (2.136)
$U_{GM1OhkawaLahey}$	Distribution Parameter 1 for Ohkawa and Lahey (1980) correlation, equation (2.142)
$U_{GM2OhkawaLahey}$	Distribution Parameter 2 for Ohkawa and Lahey (1980) correlation, equation (2.142)
U_{TTB}	Gas velocity inside Taylor Bubble
U_{GM}^*	Dimensionless drift velocity in Kataoka and Ishii (1987) correlation, equation (2.55)

V	Volume
We	Weber number
$We_{Premoli}$	Weber number in Premoli et al. (1970) correlation
x	Quality
$X_{OhkawaLahey}$	Parameter in Ohkawa and Lahey (1980) model
X_{tt}	Lockhart and Martinelli parameter
$Y_{OhkawaLahey}$	Parameter in Ohkawa and Lahey (1980) model
y	Constant in Premoli et al. (1970) correlation, equation (2.92)
Z_{Hugh}	Parameter in Hughmark correlation

Greek Symbols

α	Void fraction
α_m	Void fraction over Taylor bubble region in Mishima and Ishii (1984) theory
$\alpha_{Shvarts}$	Intermediate void fraction in Shvarts et al. (1993) correlation, equation (2.110)
β_S	Dimensionless liquid slug length
β_T	Dimensionless length of Taylor bubble
δ	Liquid film thickness
ϕ	Constant in Wallis (1969) Equation, equation (2.76)
ψ	Parameter in Ohkawa and Lahey (1980) model
λ	*Parameter* in Begg's (1972) and Greskovich and Cooper (1975) correlations, equations (2.31) and (2.127)
λ_{NY}	Constant in Nishino and Yamazaki (1963) correlation , equation (2.88)

λ_{Hugh}	Constant in Hughmark (1962) correlation
μ	Dynamic Viscosity
v	Kinematic viscosity
ρ	Density
$\pi_{Shvarts}$	Ratio in Shvarts et al. (1993) correlation, equation (2.113)
θ	Angle of inclination of tube
σ	Surface tension of liquid

<u>Subscripts</u>

atm	Atmospheric
c	Outer diameter of annulus
Cr	Critical
E	Entry
F	Film
G	Gas phase
GM	Drift
H	Homogeneous
L	Liquid phase
LS	Liquid slug
M	Mixture
psia	pounds per square inches absolute
S	Superficial
Sm	Sauter mean
SU	Slug unit

t	Inner diameter of annulus
TB	Taylor bubble

CHAPTER I

INTRODUCTION

Gas-liquid two-phase flow is simultaneous flow of gas and liquid through pipes. It is a commonly occurring phenomenon in variety of industries such as chemical, petrochemical, power and refrigeration. Two types of two-phase flows are encountered – boiling and non-boiling. Boiling two-phase flow is observed when a liquid evaporates because of heat transfer to the liquid. It is a single component two-phase flow. Examples of boiling two-phase flow are steam-water flow in power plants, refrigerant vapor-liquid flow refrigeration plants. Non-boiling two-phase flow is a two component two-phase flow in which gas and liquid are two different substances. For example, flow of natural gas and crude oil through pipes.

Two-phase flow is studied extensively throughout the world because of its wide range of applications. History of two-phase flow goes back to 1930's. Therefore, a vast literature is available in this area of study. There are a variety of studies done in the field of two-phase flow. For example, some researchers have studied flow patterns in two-phase flow. Others have studied pressure drop in two-phase flow. Some have concentrated on a particular orientation of two-phase flow. Many researchers have developed correlations for prediction of design parameters (For example, heat transfer, void fraction) of two-phase flow. But, more work is needed in some specific areas. Such areas which are relevant to this study are discussed next.

As mentioned above, different flow patterns are observed during two-phase flow because of the different ways in which the two phases position themselves inside the pipe. It is important to note that gas phase is compressible whereas liquid phase is incompressible. Their properties (such as density, viscosity) also vary depending upon pressure and temperature of the system. Liquid phase also exhibits surface tension. Therefore, the two phases behave differently inside the pipe. One or more of these factors affect the flow pattern inside the pipe. Knowledge of flow patterns is important because parameters such as void fraction, pressure drop and heat transfer in two-phase flow depend upon the type of flow pattern. Some researchers have studied flow patterns, have developed flow pattern maps and have found the dependence of parameters such as void fraction, pressure drop and heat transfer on them. For example, Sujumnong (1997) developed a flow pattern map for vertical two-phase flow and studied void fraction values for different gas and liquid mass flow rates. Similarly, Taitel et al. (1980) developed flow pattern map based on their study of flow patterns in only vertical upward (+90° to horizontal) two-phase flow and suggested flow pattern transition theories. Many other researchers studied flow patterns in vertical two-phase flow and suggested a flow pattern map or flow pattern transition theories. But, till date there is no universal flow pattern map available for vertical upward flow. There is no agreement on the number of significant flow patterns and their definitions. Many researchers (For example, Shoham (1982)) have not taken into consideration the effect of operating pressure while developing their flow pattern map. Effect of gas phase density and diameter on flow pattern map is also an unresolved issue.

Similar to flow patterns, void fraction (volumetric fraction of gas in a two-phase flow) is important because it affects pressure drop and heat transfer in two-phase flow. Therefore, knowledge of void fraction value is essential. To achieve this, many researchers have developed correlations for prediction of void fraction. For example, Fernandes (1981) studied void fraction in slug flow pattern (a type of flow pattern) and developed a correlation for its prediction. Some researchers (For example, Gomez et al. (2000)) recommended void fraction correlations for all flow patterns. Other researchers tried to eliminate the effect of flow pattern inside pipe. For instance, Woldesemayat and Ghajar (2007) suggested a flow pattern independent correlation for prediction of entire range of void fraction and orientations from horizontal to vertical. But, there is no general consensus on either approach. Flow pattern specific void fraction correlations have a limitation because of absence of a universal flow pattern map and there is no generally accepted flow pattern independent correlation for prediction of void fraction in vertical upward two-phase flow. There is no large scale comparison of vertical void fraction correlations available in the literature.

Considering the above points, a detailed study of flow patterns and void fraction was carried out for upward vertical two-phase flow. The principal objective of this study was to recommend the best correlation for prediction of void fraction. But, as discussed above, different areas in the study of two-phase flow are interrelated. Therefore, other complementary tasks were carried out to get a better insight of the behavior of two-phase flow. The first step was to recognize the number of significant flow patterns and variation of void fraction with flow patterns. Therefore, accurate experimental data for flow patterns and void fraction was collected rather than depending upon the data of other researchers. The void fraction data was collected for a wide range of void fraction values and with considerable representation of all the flow patterns. The data was taken with the help of experimental facility in Two-phase Flow Laboratory at Oklahoma State University. Based on the data for flow patterns, a flow pattern map was developed for the experimental setup. The transition boundaries of the flow pattern map were compared with the prediction of flow pattern transition theories proposed in the literature. It was observed that the effect of two parameters: gas phase density and diameter, on the flow patterns (and therefore void fraction) was significant, which prompted further study of the effect of these two parameters. Using the void fraction data collected in the present study and the data from literature, comparisons of the flow pattern dependent and flow pattern independent correlations were carried out and the best correlations were recommended.

Each of the area of study mentioned above is elaborated in different chapters of this document. In Chapter 2, the vast literature studied in the present work is presented. In Chapter 3, details of the experimental set up and its validation with respect to flow patterns and void fraction is presented. Chapter 4 explains the flow visualization studies i.e. details about different types of flow patterns observed during the present study. It also presents the flow pattern map developed during present study and evaluates flow pattern transition theories based on flow pattern data. In Chapter 5, effect of diameter and gas phase density on flow pattern map is presented. In Chapter 6, trend of void fraction values depending on mass flow rate and flow pattern is discussed. Chapter 6 also covers a detailed analysis of flow pattern specific void fraction correlations with respect to different flow pattern specific data sets in the literature. Performance of flow pattern independent void fraction correlations with respect to different data sets and void fraction ranges is discussed in Chapter 7. In Chapter 8, conclusions and recommendations based on the results obtained in Chapters 4 to 7 are presented. Details of the data sets used in the present study are given in Appendix A.

CHAPTER II

REVIEW OF LITERATURE

Two-phase flow was studied since 1930's and a large amount of literature is available. This facilitated the access to lot of good works in this area but also posed a problem of choosing relevant articles from the abundant number of studies covering different aspects of two-phase flow.

As discussed in the Chapter 1, this work is divided into three major areas: flow patterns and flow pattern transition theories, effect of diameter and gas phase density on flow pattern transitions and void fraction correlations for vertical upward two-phase flow. Thorough literature search was carried out to study most of the literature related to these three areas. In addition to this literature, previously done experimental work was referred to gather experimental data on flow patterns and void fraction. This was the most challenging task because experimental data was not openly shared.

This literature review is divided into the three sections discussed above. Literature related to each section is discussed in the following paragraphs.

2.1 Flow Patterns and Flow Pattern Transition Theories

2.1.1 Flow Patterns

A lot of work is done in vertical two-phase flow patterns and including all the work here

A lot of work is done in vertical two-phase flow patterns and including all the work here will result in repetition of information. Therefore only some of the work from the literature is discussed here.

Nicklin and Davidson (1962) carried out experiments in a 1.02 inch (0.026 m) diameter tube in vertical co-current air-water flow. They observed bubble, slug, semi-annular, annular and mist flow patterns. Bubble flow was characterized by very small bubbles compared to tube diameter, slug flow was characterized by large bubbles with round nose, semi-annular flow was characterized by to and fro motion of liquid building up and breaking down again. In annular flow, they observed a central gas core surrounded by liquid annulus at the wall. Interface between gas and liquid phase was wavy. Mist flow was observed when gas flow rate was increased beyond the flow rate for annular flow. Liquid was carried as droplets in the mist flow.

Oshinowo and Charles (1974) reported six flow regimes – bubble, quiet slug, dispersed slug, frothy slug, froth and annular. Bubble flow was defined as the flow in which the gas phase dispersed in the form of bubbles. Quiet slug and dispersed slug flows were observed to have bullet shaped bubbles. Froth formation was observed in the trailing part of bubble in dispersed slug flow whereas in quiet slug flow, no froth formation was observed. Frothy-slug was a transition region between slug and froth with froth observed over the entire boundary of gas bubbles. Froth flow was characterized by a highly turbulent mixture of liquid and gas bubbles. Annular liquid film and liquid droplets entrained in central gas core were observed in annular flow.

Spedding and Nguyen (1980) carried out extensive work on flow patterns from vertically upward to vertically downward for air-water flow in a 0.0455 m diameter pipe. For vertical upward flow, they observed seven flow patterns – bubble, slug, slug-froth, annular-slug, annular, annular-roll wave and annular-droplet. But, they did not report the definitions of the seven flow patterns in this work. They stated that annular-slug flow observed in their study was similar to churn or semi-annular flow reported in other studies.

Mukherjee (1979) also carried out experiments from vertical upward to vertical downward orientations. He used air and kerosene as the two fluids in a pipe of diameter 0.0381 m. He divided vertical upward data in only three flow regimes – bubble, slug and annular mist. Bubble flow was observed in the form of discrete bubbles for low liquid flow rates. At high liquid flow rates, a homogeneous mixture of uniformly distributed small gas bubbles and liquid was observed. Slug flow was characterized by cap shaped bubbles and annular mist flow was characterized by concentric central gas core and no slip between the two phases.

Taitel et al. (1980) observed four flow patterns in vertical two-phase flow during their study with air and water in 0.025 and 0.05 m pipes. They observed bubbly, bubble, slug, churn and annular flow regimes. Bubble flow was defined as the flow with discrete bubbles in a continuous liquid phase. Slug flow was defined as the flow with bullet shaped bubbles with diameter equal to pipe diameter and continuous liquid phase bridging the pipe and containing small gas bubbles. Churn flow was characterized by alternating direction of motion of liquid. Alternating direction of liquid was due to formation and destruction of liquid bridges in the pipe. Their description of churn flow matched the description of semi-annular flow of Nicklin and Davidson (1962). Annular flow was observed with a continuous gas phase along the pipe and wavy liquid flim at the wall. Liquid drops were entrained in the central gas core. They proposed that bubbly flow cannot exist in a pipe diameter below 0.05 m. They suggested that the existence of either dispersed bubble or bubbly flow pattern was dependent on turbulent energy of the flow. At higher turbulent energy finely dispersed flow would be observed, otherwise bubbly flow would exist.

Yamaguchi and Yamazaki (1984) tried to come up with combined flow pattern map for co-current and counter-current flow in vertical tubes. They observed only bubble and slug flow in their study with air and water in pipes of diameter 0.04 and 0.08 m. This could be due to velocity ranges covered in the study. The ranges of liquid and gas superficial velocities in their study were 0 to 1 m/s and 0 to 1.2 m/s, respectively.

Aggour and Sims (1984) observed bubble, slug, churn, froth and annular flows in their study with air, helium and Freon 12 (gas phase) and water (liquid phase). Bubble, churn, slug and annular flows were defined in the same way as the literature discussed so far. They reported that Govier and Aziz (1973) defined froth flow similar to definition of churn flow in the literature. In their study, froth flow was observed at high liquid flow rates, after bubble flow. It was characterized by high turbulence and milky appearance.

McQuillan and Whaley (1985) observed only four flow patterns – bubble, plug, churn and annular in their study. Bubble flow was defined as a flow pattern with discrete bubbles in the shape of distorted spheres flowing in liquid continuum. Plug flow was distinguished by the bullet shaped bubbles having the same diameter as tube (similar to slug flow observed by other researchers). Churn flow was distinguished from plug flow with the help of following differences

1) narrower and irregular gas plugs

2) repeatedly destroyed liquid slugs due to regions of high gas concentration
3) falling film surrounding gas plugs

Annular flow was defined as the flow with central gas core and liquid in the form of liquid film at the wall and liquid droplets in the central gas core.

Mao and Dukler (1993) challenged the existence of ‘churn’ flow pattern in vertical flow. They concluded that churn flow was just an extension of the slug flow. They came up with many evidences to support their idea.

Spedding et al. (1998) observed bubble, slug, churn, semi-annular and annular flow regimes during their experiments with air and water in a 0.026 m diameter tube. They reported that bubble flow was observed at high liquid flow rates and had a frothy appearance. Definition of slug flow by Spedding et al. (1998) matched the definition of slug flow by Taitel et al. (1980). Churn flow observed by them had an oscillatory instability but semi-annular flow had no oscillatory up and down motion. Annular flow was distinguished by the clear central gas core.

Manabe et al. (2001) reported four (bubbly, dispersed bubble, intermittent and annular) flow patterns for vertical upward two-phase flow. Bubbly flow was defined as the flow with uniformly distributed bubbles in a continuous liquid phase. Dispersed bubble flow was defined as a homogeneous flow in which both phases move with the same velocity. Their definition of intermittent flow was similar to definition of slug flow by Spedding et al. (1998) or definition of plug flow by McQuillan and Whalley (1985). Annular flow was characterized by central gas core with a wavy liquid film and liquid droplets in the gas core.

Zhihua et al. (2006) used probability density function from optical probe signals to distinguish between flow patterns. They studied air-water flow in a 0.05 m diameter pipe and observed bubble, slug, churn and annular flow regimes. The definitions of flow patterns given by Zhihua et al. (2006) matched with the definitions of Taitel et al. (1980). The technique of flow pattern identification used in this study needed a horizontal rod to be placed inside the pipe. Therefore, technique was instrusive and it affected flow pattern transitions as reported by Zhihua et al. (2006).

Schmidt et al. (2008) conducted experiments with highly viscous liquid (Luviskol®) and water in a 0.0545 m diameter pipe. They observed bubble, slug, churn and annular flow in their study. But, they did not report definitions of the flow patterns.

From literature review on flow patterns in vertical two-phase flow, it is observed that there is lack of agreement on definitions of some of the flow patterns. Number of important flow patterns in vertical two-phase flow is not yet finalized. Some researchers have distinguished only four while some have distinguished as many as seven flow patterns for vertical upward flow. Existence of some of the flow patterns is also challenged by some researchers. There is an agreement on the definition of bubble, slug and annular flow patterns. But, sometimes slug, churn and froth are together called as slug or intermittent flow. Slug flow is called as plug or intermittent flow by some researchers. Definitions of churn and froth flow patterns are not yet standardized.

2.1.2 Flow Pattern Transition Theories

Flow pattern transitions generally reported in the literature are – bubble-slug, slug-churn and churn-annular. But, only slug-churn and churn-annular transitions are predominantly discussed in this section.

Taitel et al. (1980) were the pioneers in the work on flow pattern transitions. They suggested theoretical models for prediction of bubble-slug, dispersed bubble-bubbly, slug-churn and churn-annular transitions. They performed experiments with air and water in 0.025 m and 0.05 m diameter pipes and suggested a flow pattern map. They observed that churn flow was an entrance phenomenon and a stable slug flow occurred downstream of the pipe. They also reported that the entry length for the churn flow (the length at which flow changes to slug flow) depends upon the flow rates of fluids and the pipe diameter. Their proposed equation of slug-churn transition is

$$\frac{L_E}{D} = 40.6\left(\frac{U_M}{\sqrt{gD}} + 0.22\right) \tag{2.1}$$

Where, L_E is the entrance length in which the churn flow is observed, before a stable slug flow is seen downstream.

The churn-annular transition model of Taitel et al. (1980) was based upon the concept that annular flow cannot take place till the velocity of gas phase is sufficient to lift the entrained liquid droplets. If the velocity is not sufficient, the droplets drop down and form churn flow by accumulation. This idea was originally reported by Turner et al. (1969) in their work on gas lift operations. In the formulation of the model, Taitel et al. (1980) used maximum size of entrained droplet reported by Hinze (1955) and proposed the following equation

$$\frac{U_{SG}\rho_G{}^{1/2}}{\left(\sigma g\left(\rho_L - \rho_G\right)\right)^{1/4}} = 3.1 \tag{2.2}$$

The non-dimensional group on left hand side of equation is called *Kutateladze number (Ku)*. Equation (2.2) is independent of pipe diameter.

Taitel et al. (1980) compared results from their theory with experimental transition boundaries available in the literature. But, results from their theory were not in good agreement with the experimental transitions for bubble-slug and slug-churn transition. For churn-annular transition, the theory of Taitel et al. (1980) and experimental transitions were in good agreement.

Weisman and Kang (1981) suggested an equation for transition to annular flow as given below

$$Fr^{0.2}Ku^{0.18} = 1.9\left(\frac{U_{SG}}{U_{SL}}\right)^{1/8} \tag{2.3}$$

Where, Fr is *Froude number* and Ku is *Kutateladze number.*

They presented transition data of Freon 113 on a flow pattern map with gas and liquid mass flux as coordinates. But, comparison of theoretical and experimental transition was not carried out.

Mishima and Ishii (1984) used void fraction as the basis of flow pattern transition. They proposed that the slug-churn transition takes place because of the instability in the liquid slug due to wake effect of bubble, when the void fraction over the entire slug region (Taylor bubble + liquid slug) exceeds void fraction in only Taylor bubble region. At this point, the liquid slugs get destroyed and form again. The equations for the void fractions were derived by Mishima and Ishii (1984). The equation for void fraction in the Taylor bubble region is

$$\alpha_m = 1 - 0.813\left[\frac{(C_{oMishimaIshii} - 1)U_M + 0.35\sqrt{\frac{(\rho_L - \rho_G)gD}{\rho_L}}}{U_M + 0.75\sqrt{\frac{(\rho_L - \rho_G)gD}{\rho_L}\left(\frac{(\rho_L - \rho_G)gD^3}{\rho_L {v_L}^2}\right)^{1/18}}}\right]^{0.75} \tag{2.4}$$

Where,

$$U_M = U_{SG} + U_{SL} \tag{2.5}$$

The procedure followed to derive this equation is very complicated.

The expression for void fraction over the entire region is

$$\alpha = \frac{U_{SG}}{C_{omishimsishii} U_M + 0.35\sqrt{\frac{(\rho_L - \rho_G)gD}{\rho_L}}} \tag{2.6}$$

According to Mishima and Ishii (1984), transition occured when α became greater than α_m.

Churn-annular transition suggested by Mishima and Ishii (1984) is

$$U_{SG} = \sqrt{\frac{(\rho_L - \rho_G)gD}{\rho_G}}(\alpha - 0.11) \tag{2.7}$$

Where, α should be in such a range that flow is churn flow (and not slug or bubble). Thus, expression of transition by Mishima and Ishii (1984) requires void fraction as an input parameter.

Mishima and Ishii (1984) compared their transition theory with their air-water, steam-water data by other researchers and flow transition theories by other reseacrehrs. Comparison of their theory with other researchers and data was not satisfactory. They attributed the discrepancies in prediction to different methods of observation and different definitions of flow patterns.

Flooding mechanism suggested by Nicklin and Davidson (1962) was the basis for transition from slug to churn flow, proposed by McQuillan and Whalley (1985). Nicklin and Davidson (1962) suggested that the transition takes place because the gas flow rate in the bubbles increases and causes flooding of the falling film surrounding them. McQuillan and Whalley (1985) used the following equation for flooding reported by Wallis (1961).

$$\sqrt{U^*_{SG}} + \sqrt{U^*_{SL}} = C \tag{2.8}$$

Where,

$$U^*_{SG} = \frac{U_{SG}\rho_G^{1/2}}{\left(gD\left(\rho_L - \rho_G\right)\right)^{1/2}} \tag{2.9}$$

and

$$U^*_{SL} = \frac{U_{SL}\rho_L^{1/2}}{\left(gD\left(\rho_L - \rho_G\right)\right)^{1/2}} \tag{2.10}$$

The value of the constant *C,* suggested by McQuillan and Whalley (1985) was 1.

They used the expression for volumetric flow rate in plug suggested by Davis and Taylor (1950) and expression for falling film thickness reported by Smith et al. (1984) for modeling the slug-churn transition.

McQuillan and Whalley (1985) observed that churn-annular transition depends upon the relative dominance of gravity effects on the liquid and drag force on the liquid droplets by the gas. They suggested equation (2.11) for the transition.

$$U^*_{SG} \geq 1 \tag{2.11}$$

U^*_{SG} is the modified Froude number, implying relative importance of gravity and inertia forces.

McQuillan and Whalley (1985) compared their transition theories with 1399 experimental data points for air-water, steam-water, Refrigerant-11, Refrigerant-12 and Refrigerant-113. They could predict 70.1% of the data points correctly. Performance of prediction for bubble and annular flows was better than for slug and churn flows. This was the only study in which high number of data points was used for comparison.

Brauner and Barnea (1986) suggested that slug-churn transition takes place when the void fraction inside liquid slug reaches a value equal to maximum bubble volumetric packing. Brauner and Barnea (1986) proposed that the gas bubbles inside the liquid slug behave like dispersed bubbles. At the maximum value of bubble volumetric packing (0.52), suggested by Brauner and Barnea (1986) (taken from Taitel et al. (1980) dispersed bubble-slug transition theory), the liquid slug disintegrates, the liquid falls down and is again lifted by the gas phase and hence the churn flow occurs. The equation for the transition is

$$2\left(\frac{0.4\sigma}{(\rho_L-\rho_G)g}\right)^{1/2}\left(\frac{\rho_L}{\sigma}\right)^{3/5}\left(\frac{2}{D}C_L\left(\frac{D}{\nu_L}\right)^{-n}\right)^{2/5}U_M{}^{2(3-n)/5}=0.725+4.15(\alpha)^{0.5} \tag{2.12}$$

U_M is actually the mixture velocity, but as explained by Brauner and Barnea (1986), the velocity of mixture inside the slug and U_M are equal. Values of C_L and n are 0.046 and 0.2, respectively. It should be appreciated that this theory definitely gives a reason for pulsating / oscillating nature of the churn flow.

Brauner and Barnea (1986) compared their theory with experimental air-water data of Shoham (1982) and Luninsky (1981). Their prediction was satisfactory for low water velocities, but was inaccurate for high water velocities. They also compared the transitions with other slug-churn transition theories, but there was a disagreement between the two predictions.

Bilicki and Kestin (1987) also studied flow pattern transitions in vertical upward flow. They suggested equations for bubble-slug and slug-froth transitions, based on experimental data collected in their study. Froth-annular transition, suggested by Bilicki and Kestin (1987) was based on the results reported by Wallis and Makkenokery (1974) and Pushkina and Sorokin (1969). The idea behind the transition was having sufficient momentum in the air flow to support the liquid film at the walls. According to Bilicki and Kestin (1987), annular flow was possible when *Kutateladze number (Ku)* becomes greater than 3.2.

$$Ku = \frac{U_{SG}\rho_G^{\ 1/2}}{\left(g\sigma\left(\rho_L - \rho_G\right)\right)^{1/4}} \tag{2.13}$$

Jayanti and Hewitt (1992) tested the following four mechanisms for slug-churn transition

1) Taitel et al. (1980): Entrance effect mechanism
2) Mishima and Ishii (1984): Wake effect / relative void fraction mechanism
3) McQuillan and Whalley (1985): Flooding mechanism
4) Brauner and Barnea (1986): Bubble coalescence mechanism

They compared the transitions predicted by each mechanism with the experimental data reported by Owen (1986). The data was taken at 2.4 bar pressure in a 0.0318 m diameter and 18 m length (L/D = 560) pipe. McQuillan and Whalley (1985) and Brauner and Barnea (1986) theories did better than the other two, but they did not predict all the transition points satisfactorily. Hence, Jayanti and Hewitt (1992) proposed one more theory for prediction of slug-churn transition based on flooding mechanism.

Jayanti and Hewitt (1992) suggested improvements in the flooding mechanism by McQuillan and Whalley (1985) and proposed equation (2.14) for slug-churn transition.

$$\sqrt{U^*_{SG}} + m_{JayantiHewitt}\sqrt{U^*_{SL}} > 1 \tag{2.14}$$

Where,

$$m_{JayantiHewitt} = 0.1928 + 0.01089\left(\frac{L}{D}\right) - 3.754\times10^{-5}\left(\frac{L}{D}\right)^2 \ for \frac{L}{D} \le 120 \tag{2.15}$$

$$m_{JayantiHewitt} = 0.96 \approx 1 \ for \frac{L}{D} > 120 \tag{2.16}$$

The expressions for U^*_{SG} and U^*_{SL} are the same as used by McQuillan and Whalley (1985). They also suggested to use equation suggested by Brotz (1954) for calculating falling film thickness instead of using Nusselt relation used by McQuillan and Whalley (1985). They compared the transition theories with experimental data of Owen (1986) and showed that their theory gave the best prediction of data.

Chen and Brill (1997) modeled a mechanism for slug-churn transition based on the wake effect of Taylor bubbles on liquid slugs with high gas content. Their work was based on the study of Brauner and Barnea (1986) and van Hout et al. (1992). They postulated that the transition from slug to churn flow occurs when,

1) The void fraction in the liquid slug (α_{LS}) reaches a maximum value of 0.52 and
2) The dimensionless liquid slug length (β_s) reaches a minimum value of 0.15.

Where,

$$\beta_s = \frac{L_{LS}}{L_{SU}} \tag{2.17}$$

They proposed five equations which need to be solved simultaneously to find out the superficial gas velocity at transition for a particular superficial liquid velocity. The five equations are listed below from (2.18) to (2.22).

$$\alpha_{TB}U_{TTB} - (1-\alpha_{TB})U_F = U_{SG} + U_{SL} = U_M \tag{2.18}$$

This equation is derived from the volumetric flow balance within a slug body.

$$U_{SG} = \alpha_{TB}(1-\beta_s)U_{TTB} + \alpha_{LS}\beta_s(U_{SG} + U_{SL}) \tag{2.19}$$

A mass balance for a slug unit is used in this equation.

When a gas flow balance is done for a slug unit, we arrive at the following equation,

$$\alpha_s(U_{TB} - U_M) = \alpha_{TB}(U_{TB} - U_{TTB}) \tag{2.20}$$

Nicklin and Davidson (1962) derived equation (2.21) for rise velocity of a Taylor bubble, which is one of the five equations in the transition theory of Chen and Brill (1997).

$$U_{TB} = 1.2U_M + 0.35\left(\frac{gD(\rho_L - \rho_G)}{\rho_L}\right)^{1/2} \tag{2.21}$$

Expression for falling film velocity used in their work is

$$U_F = 9.916\left(\frac{gD(\rho_L - \rho_G)(1-\alpha_{TB}{}^{0.5})}{\rho_L}\right)^{0.5} \tag{2.22}$$

The equation used by Chen and Brill (1997) for calculating falling film thickness was derived by Wallis (1969) (equation (2.23)).

$$\delta_F\left(\frac{(\rho_L - \rho_G)g}{\rho_L {\nu_L}^2}\right)^{1/3} = k\,\mathrm{Re}_F{}^{m_1} \tag{2.23}$$

Where,

$$\mathrm{Re}_F = 4\left(\frac{\rho_L U_F \delta_F}{\mu_L}\right) > 1000 \tag{2.24}$$

The values of *k=0.0682* and m_1*=2/3*, recommended by Fernandes et al. (1983) were used. Chen and Brill (1997) compared flow pattern transition prediction of their with air-water data of Shoham (1982). The overall trend and values of superficial gas velocity predicted by the transition theory were in good agreement with experimental data of Shoham (1982).

Tangesdal et al. (1999) developed a model for slug-churn transition based on drift flux approach using a value of void fraction observed at transition. According to Chokshi (1994), the void fraction value at transition was 0.8. As reported by Tangesdal et al. (1999), Garber and Varanasi (1997) proposed a value of 0.73 based on the data of Fernandes (1981). But, Tangesdal et al. (1999) used a value of 0.78 from the data reported by Owen (1986), in the equation (2.25).

$$\alpha = \left[\frac{U_{SG}}{1.2U_M + U_{TB}}\right] \tag{2.25}$$

They derived a new expression for relation between velocity of Taylor bubble and superficial gas velocity, given by equation (2.26)

$$U_{SG} = 12.19(1.2U_{SL} + U_{TB}) \tag{2.26}$$

Taylor bubble rise velocity (U_{TB}) was calculated based on the work of Bendiksen (1984)

$$U_{TB} = (0.35\sin\theta + 0.54\cos\theta)\sqrt{\frac{gD(\rho_L - \rho_G)}{\rho_L}} \tag{2.27}$$

The final relation for superficial gas velocity at transition was derived, given by equation (2.28).

$$U_{SG} = 12.19\left(1.2U_{SL} + (0.35\sin\theta + 0.54\cos\theta)\sqrt{\frac{gD(\rho_L - \rho_g)}{\rho_L}}\right) \tag{2.28}$$

Tangesdal et al. (1999) compared their theory with data of Shoham (1982) for 0.025 and 0.05 m diameter pipes and showed that the slug-churn transition was predicted very well by the relation. But, they did not compare the results with data of Fernandes (1981) and data collected by Owen (1986), available to them.

Spedding et al. (1998) conducted experiments with air-water in 0.026 m pipe. They studied flow pattern maps from literature and concluded that it is unlikely to design a commonly acceptable flow pattern map. They also proposed transition theories for slug-churn and churn-annular transitions. But, those are difficult to implement because of the presence of undefined 'Heaviside Function' in their equations.

The transition theories discussed above are listed in Table 2.1 for quick reference.

Table 2.1 - Flow Transition Theories from the Literature

Slug-churn Transition Theories
Taitel et al. (1980) Mishima and Ishii (1984) McQuillan and Whalley (1985) Brauner and Barnea (1986) Jayanti and Hewitt (1992) Chen and Brill (1997) Tangesdal et al. (1999)
Churn-annular Transition Theories
Taitel et al. (1980) Weisman and Kang (1981) Mishima and Ishii (1984) McQuillan and Whalley (1985) Bilicki and Kestin (1987)

The important points from the literature review for flow patterns and flow pattern transitions are:

1) Except for slug-churn transition comparison by Jayanti and Hewitt (1992), no independent comparison of flow pattern transitions is done in the literature. Comparison of Jayanti and Hewitt (1992) for slug-churn transition is limited to only 5 theories, but there are more theories available in the literature. For churn-annular theory, no independent comparison is done in the literature studied.
2) Most of the researchers have come up with a theory, have compared their results with other theories or experimental data and have claimed that transition theory proposed by them is generally good. Quantitative analysis and reasoning for trends in flow pattern transitions is not carried out in the literature.
3) Some of the researchers have compared their theories with data of Shoham (1982). But, this data does not contain pressure values and therefore effect of gas phase density on transition cannot be analyzed using this data.
4) In some studies, dependence of gas phase density and diameter on flow pattern is considered while some researchers have proposed flow transition theories which are independent of pipe diameter and gas phase density.
5) Some of the researchers have not compareed their transition theory with experimental data.

2.2 Effect of Diameter and Gas Phase Density on Flow Pattern Transitions

There is a lesser amount of literature available which exclusively deals with the effect of gas phase density (due to changes in operating pressure) and diameter on flow pattern transitions.

Govier and Short (1958) studied air and water flow in 0.016, 0.026, 0.0381 and 0.0635 m diameter pipes. Pressure was kept constant (36 psia) so that the air density remains constant throughout the entire work. They reported that there is an effect of diameter on flow patterns. But, they only presented the data for different diameters and did not come up with a factor or mathematical equation for dependence of flow patterns on diameter.

Hosler (1958) carried out diabatic experiments with steam-water in a rectangular channel (⅛ inch x 1inch x 24 inch) at pressures 150, 300, 600, 800, 1400 and 2000 psia. He studied the effects of pressure, mass velocity, heat flux and inlet temperature on the flow patterns. He observed that the increase in pressure pushes the transitions from bubble to slug and slug to annular at higher values of quality. This effect was attributed to decrease in specific volume (i.e. increase in density) of steam.

Lin and Hanratty (1987) studied flow patterns in pipes of 0.0254 and 0.0953 m diameters. They used air and water as working fluids and presented two flow pattern maps for both the pipe diameters. But, exact effect of diameter on flow patterns cannot be determined from the two flow pattern maps.

Watson and Hewitt (1999) studied the effect of pressure on slug-churn transition boundary. They conducted experiments in a 0.032 m and 12.6 m long pipe, with air and water. Effect of pressure on slug-churn transition was analyzed by performing experiments at different pressures. They compared their data with slug-churn transition theories suggested by different researchers. The transitions were captured with the help of a conductance probe used to obtain probability histogram of void fraction, from which the slug, churn and transition flows could be discerned. With the help of their data they showed that superficial gas velocity at transition decreases with the increase in pressure.

Chen et al. (2006) conducted experiments with R134a in tubes of 0.0011, 0.00201, 0.00288 and 0.00426 m diameters. Diameters of 0.0011m and 0.00201m are not discussed in the present study, because according to Chen et al. (2006), they are small diameter tubes. They showed that increase in diameter causes decrease in superficial gas velocity at transition.

Omebere-Iyari and Azzopardi (2007) studied high pressure (20 and 90 bar) flow of naptha and nitrogen in a pipe of 0.189 m diameter and 52 m length. They observed that flow pattern transition theories for small diameter tubes failed to predict transitions in their study. The flow map in the case of large diameter pipe was entirely different from that of small diameter pipes.

It can be seen that there are limited studies on effect of gas phase density (or system pressure) and pipe diameter on flow pattern transitions. Most of the studies have given qualitative recommendations and a mathematical analysis of the effect is absent.

2.3 Void Fraction Correlations for Vertical Upward Two-phase Flow

This section concentrates on correlations proposed for prediction of void fraction in upward vertical two-phase flow. Four types of void fraction correlations are available in the literature, based on theory or methodology followed to develop them.

1. Slip ratio
2. Drift flux
3. $K\alpha_H$
4. General or Empirical

Details about these types are discussed in Woldesemayat (2006) and are not reiterated in this study.

In this study, correlations are divided into four categories, irrespective of the theory or methodology used to develop them.

- **Flow pattern specific correlations** – These are the correlations developed for a particular flow pattern in vertical upward two-phase flow.
- **Flow pattern independent correlations for vertical upward orientation** – These are the correlations which are independent of flow pattern and developed only for upward vertical orientation.
- **Flow pattern independent correlations applicable to variety of flow orientations including vertical upward flow** – These correlations are developed for different angles of inclination or orientation. For example, correlation developed for 0 to 90 degrees angle of inclination.
- **Correlations not developed for but applicable to vertical upward flow** – There are correlations in the literature which are not developed specifically for vertical flow, but are studied and recommended by researchers for prediction of void fraction in vertical flow. It was observed that these correlations perform well for vertical upward data. For example, Bonnecaze et al. (1971) correlation was developed for slug flow for ±10° inclination from horizontal. But, as reported by Woldesemayat and Ghajar (2007), its prediction for vertical two-phase flow in all the flow patterns was excellent.

These four categories will be discussed in the following sections.

2.3.1 Flow pattern specific correlations

These correlations are developed for specific flow pattern occurring in vertical upward two-phase flow. For example, correlation of Sylvester (1987) developed for slug flow. This correlation takes into consideration dynamics of slug flow and is not applicable to any other flow. If applied to void fraction data of other flow patterns, it will not produce good results. Hence, it is not reasonable to apply this correlation to any data other than slug flow data.

Bubble Flow Correlations

An empirical correlation was proposed by Ellis and Jones (1965) for void fraction calculation in bubble flow. The correlation as reported by Kaminaga (1992) is

$$\frac{U_{SG}}{\alpha} = \left(0.8 + 5.51\left(U_{SG} + U_{SL}\right)^{0.7}\right) \left[\frac{U_{SG}}{0.2U_{SL} + 0.03}\right]^{1/6} \tag{2.29}$$

Beggs (1972) studied two-phase air-water flow from horizontal to vertical flow in a 0.0381 m diameter pipe. Based on the data collected, he developed correlations for segregated (wavy, stratified and annular), intermittent (slug and plug) and distributed (bubble and mist) flows. The correlation for liquid hold up in bubble flow for vertical orientation is

$$\frac{R_L(\theta)}{R_L(0)} = 1 + C_{Beggs1}\left[\sin(1.8\theta) - \frac{1}{3}\sin^3(1.8\theta)\right] \tag{2.30}$$

Where,

$$C_{Beggs1} = 0 \ \textit{for upward distribute d flow}$$

$$R_L(0) = \frac{1.065\lambda^{0.5824}}{N_{FR}^{0.609}} \ \textit{for distributed flow} \tag{2.31}$$

$$\lambda = \frac{U_{SL}}{U_{SL} + U_{SG}}$$

$$N_{FR} = \frac{{U_M}^2}{gD}$$

Equation for void fraction in bubble flow becomes

$$\alpha(\theta) = 1 - R_L(\theta) \tag{2.32}$$

But, the correlations proposed by Beggs (1972) were not tested against independent data of other researchers.

Kabir and Hasan (1990) presented equations for flow pattern, void fraction and pressure drop in bubble, slug, churn and annular flows in vertical wells. They proposed a drift flux correlation for prediction of void fraction in bubble flow. Expressions for distribution parameter and drift velocity are given below.

$$C_0 = 1.2 + 0.371 \frac{D_t}{D_c} \tag{2.33}$$

D_t and D_c are inner and outer diameters in case of annulus.

$$U_{GM} = 1.5 \left[g\sigma \left(\frac{\rho_L - \rho_G}{\rho_L^{\;2}} \right) \right]^{0.25} \tag{2.34}$$

Value of C_0 was proposed as 1.2 for a circular pipe.

Kabir and Hasan (1990) did not elaborate on the performance of any of their flow specific void fraction models. They did not test their correlation against experimental void fraction data.

Gomez et al. (2000) proposed a mechanistic model for prediction of liquid hold up (void fraction) in bubble flow, which was a part of their work on unified model for prediction of flow pattern, liquid hold up and pressure drop for all flow patterns in horizontal to vertical two-phase flow.

Gomez et al. (2000) modified bubble flow model of Hasan and Kabir (1988) to cover a wide range of orientations by introducing inclination angle into the model.

$$\frac{U_{SG}}{1 - R_L} = \left(C_0 U_M + U_{0\infty} \sin\theta \, R_L^{\;0.5} \right) \tag{2.35}$$

Where, $U_{0\infty}$ is the rise velocity of a single bubble, suggested by Harmathy (1960) and is give as

$$U_{0\infty} = 1.53\left(\frac{g\sigma(\rho_L - \rho_G)}{\rho_L{}^2}\right)^{0.25}$$

Value of $C_0 = 1.15$ was used.

Gomez et al. (2000) did not compare their prediction of void fraction with experimental data. Therefore, the reliability of their model is not known.

Hibiki and Ishii (2002) developed a drift flux correlation for bubble flow in upward vertical flow. The expressions for distribution parameter and drift velocity for the bubble flow were calculated using 214 data points. The generalized expression for drift flux correlation is

$$\alpha = \frac{U_{SG}}{C_0 U_M + U_{GM}} \tag{2.36}$$

Where,

$$U_M = U_{SL} + U_{SG}$$

$$U_{GM} = U_G - U_M$$

The expression for the distribution parameter (C_0) given by Hibiki and Ishii (2002) is

$$C_0 = \left[1.2 - 0.2\left(\sqrt{\frac{\rho_G}{\rho_L}}\right)\left(1 - e^{-22(D_{Sm})/D}\right)\right] \tag{2.37}$$

D_{Sm} is sauter mean diameter of bubbles. Sauter mean diameter is defined as the diameter of a sphere having the same ratio of volume to surface area as the particle studied. This parameter is not easy to measure and requires special measurement techniques, not readily available. Therefore, expression for distribution parameter proposed by Ishii (1977a) and reported by Hibiki and Ishii (2002) could be used.

$$C_0 = \left[1.2 - 0.2\left(\sqrt{\frac{\rho_G}{\rho_L}}\right)\left(1 - e^{-18\alpha}\right)\right]$$

The expression for drift velocity (U_{GM}) was given by

$$U_{GM} = \sqrt{2}\left(\frac{g\sigma(\rho_L - \rho_G)}{\rho_L{}^2}\right)^{1/4}(1-\alpha)^{1.75} \tag{2.38}$$

This equation of U_{GM} is applicable only if $\mu_L >> \mu_G$, which is generally the case.

All the data of void fraction in bubbly flow, used by Hibiki and Ishii (2002) was taken with the help of probes.

They compared the prediction of their model with experimental data of Hibiki and Ishii (1999), Hibiki et al. (2001) and Grossetete (1995). The data was predicted with maximum average deviation of 23.1% for data of Hibiki and Ishii (1999) and minimum average deviation of 8.9% for data of Grossetete (1995).

Slug Flow Correlations

Slug flow is the most extensively pursued topic of study. There are a lot of correlations found in the literature for void fraction prediction in slug flow. Most of them are mechanistic, based on the flow mechanics of slug flow.

Nicklin and Davidson (1962) studied flow pattern transition in upward vertical slug flow using air and water as fluids. Their correlation for void fraction in slug flow is

$$\alpha = \frac{U_{SG}}{1.2U_M + 0.35\sqrt{gD}} \tag{2.39}$$

Ellis and Jones (1965) developed the following empirical correlation for void fraction in slug flow.

$$\frac{U_{SG}}{\alpha} = 0.3048\left(\frac{U_{SG}}{\alpha}\right)_M - 1.433\exp\left(-0.122U_M^{(-1/4)}\left(1.55D^2 + 5.5\right)\right) \tag{2.40}$$

Where,

$$\left(\frac{U_{SG}}{\alpha}\right)_M = 0.8 + 5.51\,U_M^{\;0.7}\ \mathit{for}\, U_{SG} \le 1.28 \tag{2.41}$$

$$\left(\frac{U_{SG}}{\alpha}\right)_M = 0.8 + 5.24\,U_M^{\;0.9}\ \mathit{for}\, U_{SG} > 1.28 \tag{2.42}$$

Bonnecaze et al. (1971) studied void fraction and pressure drop in slug flow of oil and gas in inclined (±10° to horizontal) pipes. From the 152 data points collected, they developed the following correlation for prediction of void fraction.

$$\alpha = \frac{\alpha_H}{1.2 + \dfrac{0.35\left(1 - \dfrac{\rho_G}{\rho_L}\right)}{k_{Bonnecaze}\sqrt{Fr}}} \tag{2.42}$$

Beggs (1972) proposed the following empirical correlation for intermittent (slug) flow pattern.

$$\frac{\alpha(\theta)}{\alpha(0)} = 1 + C_{Beggs2}\left[\sin(1.8\theta) - \frac{1}{3}\sin^3(1.8\theta)\right] \tag{2.43}$$

Where,

$$C_{Beggs2} = (1-\lambda)\ln\left[\frac{2.96\lambda^{0.305}N_{FR}^{\;\;0.0978}}{N_{LV}^{0.4473}}\right] \mathit{for\ vertical\ upward\ flow} \tag{2.44}$$

$$\alpha(0) = 1 - \frac{0.845\lambda^{0.5351}}{N_{FR}^{0.0173}}\ \mathit{for\ intermittent\ flow} \tag{2.45}$$

$$N_{LV} = U_{SL}\left(\frac{\rho_L}{g\sigma}\right)^{0.25} \tag{2.46}$$

As discussed already, Beggs (1972) did not carry out comparison of his correlation with independent data.

Fernandes (1981) conducted experiments with air and water in a Plexiglas pipe of 0.05074 m. Based on the experiments, a detailed physical model for slug flow was suggested by Fernandes et al. (1983) for void fraction in upward co-current two-phase flow slug flow at low pressures. The model includes 17 variables related to slug flow and 17 equations, which could be solved simultaneously to find out void fraction. The model has served as basis for many slug flow models such as Sylvester (1987), Orell and Rembrand (1986). Structure of a slug unit, as depicted by Fernandes et al. (1983) is shown in Figure 2.1.

$$\alpha_{SU} = \frac{Gas_{volume}}{Total_{volume}} = \frac{V_G}{V_{SU}} = \frac{Gas_{\ volume-Taylorbubble} + Gas_{\ volume-slug}}{V_{SU}} = \frac{V_{GTB} + V_{GLS}}{V_{SU}} \tag{2.47}$$

$$V_G = L_{TB}A_{GTB} + L_{LS}A_{GLS}$$

$$\alpha_{SU} = \beta_T\alpha_{TB} + (1-\beta_T)\alpha_{LS}$$

For a slug unit (one Taylor bubble and one liquid slug), the void fraction was calculated by

$$\alpha_{TB} = \frac{A_{GTB}}{A}\ ,\ \alpha_{LS} = \frac{A_{GLS}}{A}\ ,\ \beta_T = \frac{L_{TB}}{L}$$

The other equations were either derived by applying overall mass balance, mass balance at the nose of Taylor bubble or used from the previous literature. Overall mass balance provides

$$U_{SG} = \beta_T\alpha_{TB}U_{GTB} + (1-\beta_T)\alpha_{LS}U_{GLS}$$

$$U_{SL} = (1-\beta_T)(1-\alpha_{LS})U_{LLS} - \beta_T(1-\alpha_{TB})U_{LTB}$$

Mass balance at the nose of Taylor bubble yields

$$(U_{TB} - U_{LLS})(1-\alpha_{LS}) = (U_{TB} + U_{LTB})(1-\alpha_{TB})$$

$$(U_{TB} - U_{GLS})\alpha_{LS} = (U_{TB} - U_{GTB})\alpha_{TB}$$

The rising velocity of Taylor bubble used in their work was suggested by Collins et al. (1978) and is given by

$$U_{TB} = 1.29U_M + 0.35\sqrt{gD} \tag{2.48}$$

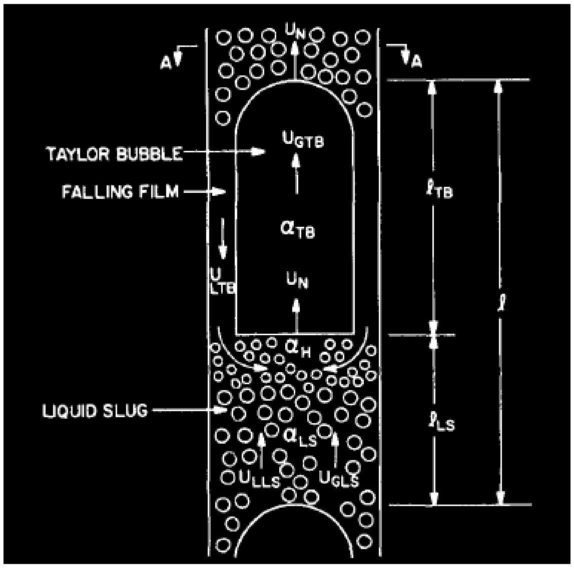


Figure 2.1 Structure of a Slug Unit (Fernandes et al. (1983))

Expression for rise velocity of a bubble in liquid was suggested by Zuber and Hench (1962) as

$$U_o = 1.53\left[\frac{\sigma g(\rho_L - \rho_G)}{\rho_L^{\ 2}}\right]^{1/4}(1-\alpha)^{1/2} \tag{2.49}$$

This expression, when used in $U_{GLS} = U_{LLS} + U_o$ gives

$$U_{GLS} = U_{LLS} + 1.53\left[\frac{\sigma g(\rho_L - \rho_G)}{\rho_L^{\;2}}\right]^{1/4}(1-\alpha_{LS})^{1/2}$$

The expression for the velocity of liquid film surrounding Taylor bubble, suggested by Brotz (1954) was used.

$$U_{LTB} = 9.916\left(gD(1-\alpha_{TB}^{\;1/2})\right)^{1/2} \tag{2.50}$$

Fernandes et al. (1983) used a value of 0.25 for α_{LS}, which was suggested by Taitel et.al. (1980). But, using α_{LS} equal to 0.25 causes a loss of accuracy because higher void fraction values are observed in the liquid slugs. For example, a void fraction value (in liquid slug) of 0.52 was reported by Brauner and Barnea (1986).

Fernandes et al. (1983) compared their model with approximately 30 experimental data points of Fernandes (1981) and achieved a prediction within ±5% error for most of the data points.

Sylvester (1987) proposed a model for slug flow. The model was based on the model of Fernandes et al. (1983). Basic equations from Fernandes et al. (1983) were used in this model with some modifications which are mentioned below.

The expression for rise velocity of Taylor bubble used by Sylvester (1987) is

$$U_{TB} = C_0(U_{SG} + U_{SL}) + C_{1Sylvester}\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2} \tag{2.51}$$

The values of C_0 and $C_{1Sylvester}$ suggested by Sylvester were: 1.2 and 0.35, respectively.

Sylvester (1987) studied the data of Fernandes (1981) and developed the following equation for void fraction in the liquid slug

$$\alpha_{LS} = \left[\frac{U_{SG}}{C_{2Sylvester} + C_{3Sylvester}(U_{SG} + U_{SL})}\right] \tag{2.52}$$

The values of $C_{2Sylvester}$ and $C_{3Sylvester}$ suggested by Sylvester were: 0.425 and 2.65, respectively.

Fernandes et al. (1983) used a constant value of 0.25 for void fraction in liquid slug (α_{LS}). But, equation (2.52) in sylvester (1987) model predicts variable values of void fraction in liquid slug depending upon changes in operating conditions. Therefore, this is an important modification made by Sylvester (1987) in Fernandes et al. (1983) model.

Sylvester (1987) did not present the accuracy of his void fraction model.

Kataoka and Ishii (1987) suggested a drift flux correlation for void fraction prediction in slug flow. The expressions for distribution parameter and drift velocity are

$$C_0 = 1.2 - 0.2\sqrt{\frac{\rho_G}{\rho_L}} \qquad (2.53)$$

$$U_{GM} = U_{GM}^{*}\left(g\sigma\left(\frac{\rho_L - \rho_G}{\rho_L^{2}}\right)\right)^{0.25} \qquad (2.54)$$

The value of U_{GM}^{*} can be found out with the help of following equations

$$U_{GM}^{*} = 0.0019\left(D_H^{*}\right)^{0.809}\left(\frac{\rho_G}{\rho_L}\right)^{-0.157} N_{\mu L}^{-0.562} \quad for \quad D_H^{*} \leq 30 \qquad (2.55)$$

$$U_{GM}^{*} = 0.03\left(\frac{\rho_G}{\rho_L}\right)^{-0.157} N_{\mu L}^{-0.562} \quad for \quad D_H^{*} \geq 30 \; and \; N_{\mu L} \leq 2.2\times10^{-3} \qquad (2.56)$$

$$U_{GM}^{*} = 0.92\left(\frac{\rho_G}{\rho_L}\right)^{-0.157} \quad for \quad D_H^{*} \geq 30 \; and \; N_{\mu L} \geq 2.2\times10^{-3} \qquad (2.57)$$

Where,

$$D_H^{*} = \frac{D_H}{\sqrt{\left(\frac{\sigma}{g(\rho_L - \rho_G)}\right)}} \quad and \quad N_{\mu L} = \frac{\mu_L}{\left(\rho_L \sigma \sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}}\right)^{0.5}}$$

Correlation of Kataoka and Ishii (1987) takes into consideration the effect of liquid and gas phase properties, diameter and pressure.

Kataoka and Ishii (1987) compared their model with air-water, air-glycerin and steam-water void fraction data of 13 other researchers. Their model achieved a prediction of void fraction within ±20% error band for nearly all the data points.

Kabir and Hasan (1990) recommended a drift flux correlation for void fraction in slug flow. Expressions for distribution parameter and drift velocity are given below.

$$C_0 = 1.18 + 0.9\frac{D_t}{D_c} \qquad (2.58)$$

D_t and D_c are inner and outer diameters in case of flow in annulus.

$$U_{GM} = 0.3 + 0.22\frac{D_t}{D_c}\left(\sqrt{g\left(D_t - D_c\right)\left(\frac{\rho_L - \rho_G}{\rho_L}\right)}\right) \qquad (2.59)$$

Gomez et al. (2000) proposed a physical model similar to that of Fernandes et al. (1983). This model is applicable to orientations from 0 to +90 degrees. The model closure relationships used by Gomez et al. (2000) are stated below.

Liquid hold-up in liquid slug (part of slug unit, other part being Taylor bubble) was predicted with the help of following equation

$$R_{LLS} = e^{-\left(7.85\times10^{-3}\theta + 2.48\frac{\mathrm{Re}_M}{10^6}\right)} \qquad (2.60)$$

Where,

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

Velocity of Taylor bubble was calculated by the equation reported by Bendiksen (1984).

$$U_{TB} = 1.2U_M + \left(0.542\sqrt{gD}\cos\theta + 0.351\sqrt{gD}\sin\theta\right) \qquad (2.61)$$

Velocity of small gas bubbles in liquid slug was calculated by the following equation suggested by Hasan and Kabir (1988)

$$U_{TB} = 1.2U_M + \left(0.542\sqrt{gD}\cos\theta + 0.351\sqrt{gD}\sin\theta\right) \tag{2.62}$$

R_{LLS} is the liquid hold up in liquid slug.

The bubble rise velocity suggested by Harmathy (1960) was used.

$$U_{0\infty} = 1.53\left(\frac{g\sigma(\rho_L - \rho_G)}{\rho_L{}^2}\right)^{0.25} \tag{2.63}$$

The length of liquid slug used was, $L_{LS} = 20D$.

Orell and Rembrand (1986) developed a model for slug flow in vertical tubes based on flow structure of slug flow. Basic equations of slug flow used by Fernandes et al. (1983) were used in this model. The model is capable of predicting six variables in slug flow, including void fraction in slug unit. Downward flow of film was also taken into consideration in this model and friction factor of the film flow was used. Important equations constituting the model are listed below.

Equation suggested by Nicklin et al. (1962) was used to calculate velocity of Taylor bubble

$$U_{TB} = 1.2U_M + 0.35\sqrt{gD}$$

Film velocity U_F was found by using mass balance,

$$U_M = U_{TB}\left(1 - \frac{4\delta}{D}\right) - U_F\left(\frac{4\delta}{D}\right) \tag{2.64}$$

Where, δ is the film thickness, which can be found from

$$\delta = \frac{f_F}{2g}U_F{}^2$$

and

$$\frac{1}{\left(\frac{f_F}{2}\right)^{0.5}} = 1.75 + 5.75\log\left[\frac{\mathrm{Re}_F}{2}\left(\frac{f_F}{2}\right)^{0.5}\right]$$

Where,

$$\mathrm{Re}_F = 4\rho_L A_F \frac{U_F}{\pi D \mu_L}$$

$$A_F = f_F \pi D \frac{U_F{}^2}{2g}$$

Finally, the void fraction in slug unit was calculated by

$$\alpha = \left(1 - \frac{4\delta}{D}\right)\left(\frac{L_{TB}}{L_{SU}}\right) + \alpha_{LS}\left(1 - \frac{L_{TB}}{L_{SU}}\right) \tag{2.65}$$

Where, the ratio of Taylor bubble to total length of slug unit and void fraction in liquid slug was computed by following equations

$$\frac{L_{TB}}{L_{SU}} = \frac{U_{SG} - \alpha_{LS} U_M}{U_{TB}\left(1 - \frac{4\delta}{D}\right) - \alpha_{LS} U_M} \tag{2.66}$$

$$\alpha_{LS} = 1 - \frac{4\delta\left(U_F + U_{TB}\right)}{0.6 C_W D \left\{\left(U_F + U_{TB}\right) - 2g\left(0.6 C_W R^2 - D\delta\right)^{0.5} + D\right\}^{0.5}} \tag{2.67}$$

Value of C_W was recommended as 0.29.

Orell and Rembrand (1986) compared their model with approximately 70 data points of other researchers and achieved a prediction within ±10% for all the data points.

Annular Flow Correlations

Use of Lockhart and Martinelli (1949) correlation for prediction of void fraction in annular flow was reported by Woldesemayat (2006). It is a slip-ratio correlation with the following equation.

$$\alpha = \frac{1}{1 + 0.28\left(\frac{1-x}{x}\right)^{0.64}\left(\frac{\rho_G}{\rho_L}\right)^{0.36}\left(\frac{\mu_L}{\mu_G}\right)^{0.07}} \tag{2.68}$$

But, Woldesemayat (2006) compared Lockhart and Martinelli (1949) correlation with data for all flow patterns and therefore accuracy for Lockhart and Martinelli (1949) correlation for annular flow data is not known.

Fauske (1961) conducted experiments with steam-water system for quality range 0.01 to 1, mass velocities from 500 to 4200 lb/s-ft^2 and pressure range of 40 to 360 psia. Diameters of 0.125 (0.003175 m), 0.269 (0.006833 m) and 0.5 inch (0.0127 m) were used in these experiments. He proposed the following correlation for void fraction prediction in annular flow

$$\alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.5}} \tag{2.69}$$

However, he did not present the error analysis for his correlation and the accuracy of data collected during his study was also not reported.

Smith (1969) suggested a correlation for prediction of void fraction in annular flow. This was reported by Tandon et al. (1985) and its expression is

$$\alpha = \left(1 + \frac{\rho_G}{\rho_L}\left(\frac{1-x}{x}\right) \left\{ k_{Smith} + \left(1 - k_{Smith}\right) \sqrt{\frac{\left(\frac{\rho_L}{\rho_g} + k_{Smith}\left(\frac{1-x}{x}\right)\right)}{1 + k_{Smith}\left(\frac{1-x}{x}\right)}} \right\} \right)^{-1} \tag{2.70}$$

Value of k_{Smith} suggested by Smith (1969) was 0.4.

Another correlation for prediction of void fraction in annular flow was proposed by Zivi (1964) as reported by Tandon et al. (1985).

$$\alpha = \frac{1}{1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)^{2/3}} \tag{2.71}$$

Tandon et al. (1985) proposed an analytical expression for void fraction in annular flow. They used von Karman's velocity distribution for annular liquid film to arrive at void fraction in annular flow. Equations for the model are as follows

$$\alpha = 1 - 1.928\,\mathrm{Re}_{SL}^{-0.315}\left[F(X_{tt})\right]^{-1} + 0.9293\,\mathrm{Re}_{SL}^{-0.63}\left[F(X_{tt})\right]^{-2} \quad for\ \mathrm{Re}_{SL} < 1125 \tag{2.72}$$

$$\alpha = 1 - 0.38\,\mathrm{Re}_{SL}^{-0.088}\left[F(X_{tt})\right]^{-1} + 0.0361\,\mathrm{Re}_{SL}^{-0.176}\left[F(X_{tt})\right]^{-2} \quad for\ \mathrm{Re}_{SL} \geq 1125 \tag{2.73}$$

Where,

$$\left[F(X_{tt})\right] = 0.15\left(X_{tt}^{-1} + 2.85 X_{tt}^{-0.476}\right)$$

Tandon et al. (1985) compared their model and the models of Smith (1969) and Zivi (1964) with the data of Rouhani and Becker (1963), in which range of quality from 0.01 to 0.31 and range of pressure from 700 to 2100 kN/m^2 was used. Tandon et al. (1985) and Smith (1969) models predicted most of the data within ±10%, but model of Zivi (1964) did not perform well and under-predicted most of the data.

Chen (1986) suggested a semi-empirical model for void fraction in annular flow.

$$\alpha = \frac{k_{Chen}}{k_{Chen} + X_{tt}^{\ 2/3}} \tag{2.74}$$

Where,

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

k_{Chen} is a parameter depending upon diameter of pipe, system pressure and gas-liquid interfacial characteristics. Chen (1986) provided a graph for k_{Chen} as a function of pressure, from which value of k_{Chen} can be calculated. But, constant k_{Chen} adds rigidity to this model because it must be chosen from graph provided in the paper.

Chen (1986) used steam-water data of Rouhani and Becker (1963) and Isbin et al. (1957) and analyzed the correlations of Tandon et al. (1985), smith (1969), Zivi (1964) and Chen (1986). He concluded that for most of the data, his correlation performed better than the other three. But, he did not present any statistical analysis to reinforce his conclusion and depended mainly on graphs of void fraction (both predicted and measured values of void fraction on y-axis) versus quality for each correlation.

Yao and Sylvester (1987) also suggested a physical model for annular–mist flow in vertical pipes. The equations for the model are

$$\alpha = 1 - \frac{EV_L}{EV_L + V_G} \tag{2.75}$$

Liquid entrainment E was calculated with the help of Wallis (1969) equation reported by Yao and Sylvester (1987) as

$$E = 1 - e^{\left(-0.125(\phi - 1.5)\right)} \tag{2.76}$$

Where,

$$\phi = 3048 \times U_{SG}\mu_G \frac{\sqrt{\frac{\rho_G}{\rho_L}}}{\sigma}$$

But, the prediction performance of this model is not known because Yao and Sylvester (1987) did not compare void fraction prediction of their model with any experimental data.

Kabir and Hasan (1990) proposed a model for calculating void fraction in annular flow. The model was based on the flow structure and took into consideration void fraction in the central gas core of annular flow. Expression for void fraction is

$$\alpha = \frac{U_{SG}}{U_{SG} + EU_{SL}} \tag{2.77}$$

Where, *E* is liquid entrainment in the central gas core, which is calculated depending upon critical vapor velocity.

$$E = 0.0055\left(U_{CSG} \times 10^4\right)^{2.86} \quad for\, U_{CSG} \times 10^4 \le 4 \tag{2.78}$$

$$E = 0.857LOG\left(U_{CSG} \times 10^4\right) - 0.2 \quad for\, U_{CSG} \times 10^4 > 4 \tag{2.79}$$

Critical vapor velocity was defined as

$$U_{CSG} = U_{SG}\mu_G \frac{\sqrt{\frac{\rho_G}{\rho_L}}}{\sigma} \tag{2.80}$$

A similar approach was followed by Gomez et al. (2000). Void fraction in annular flow was calculated using equation (2.77). Liquid entrainment *E* was calculated with the help of the following expression, suggested by Wallis (1969).

$$E = 1 - e^{(-0.125(\phi - 1.5))} \tag{2.81}$$

Where,

$$\phi = 10^4 \times U_{SG}\mu_G \frac{\sqrt{\frac{\rho_G}{\rho_L}}}{\sigma}$$

As discussed earlier, both Kabir and Hasan (1990) and Gomez et al. (2000) have not mentioned the accuracy of their models.

Churn Flow Correlations

Churn flow is not studied as extensively as other flows and therefore void fraction correlations available for this flow are scarce in the literature.

Ellis and Jones (1965) correlation for slug flow (Equation (2.40)) can be used for prediction of void fraction in churn flow, as reported by Kaminaga (1992).

Kabir and Hasan (1990) suggested a drift flux correlation for churn flow. They used a value of 1.15 for distribution parameter. The expression for drift velocity is given by following equation

$$U_{GM} = 0.3 + 0.22\frac{D_t}{D_c}\left(\sqrt{g(D_t - D_c)\left(\frac{\rho_L - \rho_G}{\rho_L}\right)}\right) \tag{2.82}$$

Tangesdal et al. (1999) studied churn flow and developed with drift flux correlation for prediction of void fraction. With the help of Schmidt (1977) data, they determined the value of distribution parameter to be 1. Equation for drift velocity for the correlation is

$$U_{GM} = 0.28\left(\sqrt{gD\left(\frac{\rho_L - \rho_G}{\rho_L}\right)}\right) \tag{2.83}$$

However, statistical analysis of predicted and measured void fraction was not done by Tangesdal et al. (1999).

Froth Flow Correlations

From the literature studied, no correlations for froth flow were found.

The flow specific correlations from the literature studied are listed in Table 2.2.

Table 2.2 – Flow Pattern Specific Correlations from Literature

Researcher
Bubble Flow Correlations
Ellis and Jones (1965) Beggs (1972) Kabir and Hasan (1990) Gomez et al. (2000) Hibiki and Ishii (2002)
Slug Flow Correlations
Nicklin and Davidson (1962) Ellis and Jones (1965) Beggs (1972) Fernandes et al. (1983) Sylvester (1987) Kataoka and Ishii (1987) Gomez et al. (2000) Orell and Rembrand (1986) Bonnecaze et al. (1971) Kabir and Hasan (1990)
Annular Flow Correlations
Lockhart and Martinelli (1948) Fauske (1961) Smith (1969) Zivi (1964) Tandon (1985) Chen (1986) Yao and Sylvester (1987) Kabir and Hasan (1990) Gomez et al. (2000)
Churn Flow Correlations
Kabir and Hasan (1990) Ellis and Jones (1965) Tangesdal et al. (1999)

2.3.2 Flow Pattern Independent Correlations Developed for Upward Vertical Orientation

Bankoff (1960) suggested a $K\alpha_H$ type correlation for steam-water two-phase flow. The correlation is

$$\alpha = k_{Bankoff}\ \alpha_H \tag{2.84}$$

Where,

$$k_{Bankoff} = 0.71 + 0.0001 P_{psia}$$

and α_H is homogeneous void fraction given by following equation.

$$\alpha_H = \frac{U_{SG}}{U_{SG} + U_{SL}}$$

Bankoff (1960) mentioned that the model is proposed for bubble flow, but the void fraction limit for bubble flow, suggested by Bankoff (1960) was up to 0.8, which is a very high value. He also mentioned that annular and homogeneous (two phases mixed completely) flows could be considered as special cases of bubble flow. Bankoff (1960) compared prediction of his correlation with vertical upward steam-water flow data of other researchers, but he only presented void fraction versus quality curves and did not analyze the accuracy with which void fraction was predicted.

Hughmark (1962) suggested a correlation for void fraction in vertical gas liquid flow, which is given by

$$\left(\frac{1}{x}\right) = 1 - \left(\frac{\rho_L}{\rho_G}\right)\left(1 - \frac{k_{Hugh}}{\alpha}\right) \tag{2.85}$$

Hughmark (1962) plotted values of k_{Hugh} with a parameter Z_{hugh}

Where,

$$Z_{Hugh} = \frac{\mathrm{Re}_{Hugh}^{\ 1/6}\, Fr^{1/8}}{\lambda_{Hugh}^{1/4}}$$

$$\mathrm{Re}_{Hugh} = \frac{GD}{(1-\alpha)\mu_L + \alpha\mu_G}$$

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

$$\lambda_{Hugh} = \frac{\frac{m_L}{\rho_L}}{\frac{m_L}{\rho_L} + \frac{m_L}{\rho_G}} = \frac{U_{SL}}{U_{SG} + U_{SL}}$$

He did not give a relation between k_{Hugh} and Z_{hugh}, but values of k_{Hugh} for various values of Z_{hugh} were provided. Therefore, an equation fit was done between k_{Hugh} and Z_{hugh}, which is given by

$$k_{Hugh} = Z_{Hugh}\left(\frac{0.9733}{3.1645 + Z_{Hugh}}\right) + 0.0155\left(\frac{Z_{Hugh}}{Z_{Hugh} - 2.3609}\right) \tag{2.86}$$

Quantitative error analysis for void fraction prediction was not done by Hughmark (1962). It should also be noted that most of the experimental data points were at void fraction values greater than 0.4. Therefore, the applicability of this correlation for lower void fraction data is questionable.

Nishino and Yamazaki (1963) suggested an empirical correlation for void fraction based on their study of steam-water boiling systems in vertical upward pipes. They used a factor (k_{NY}), which relates velocity difference between steam and water, and superficial steam velocity. The correlation is

$$\frac{\alpha}{(1-\alpha)(1-k_{NY}\alpha)} = \frac{\rho_L}{\rho_G}\frac{x}{1-x} \tag{2.87}$$

Where,

$$k_{NY} = \frac{U_G - U_L}{U_{SG}}$$

As reported by Nishino and Yamazaki (1963), value of k_{NY} could be approximated as 1 for the entire range of quality (0 to 1) and pressure (from atmospheric to critical pressure).

Nishino and Yamazaki (1963) compared the prediction of their correlation with experimental data and achieved an accuracy of ±10% for nearly all the data points. But, they did not test their correlation against a void fraction value of higher than 0.8.

Yamazaki and Yamaguchi (1976) recommended values of k_{NY} as follows

$$k_{NY} = 1 \ for \ E_{NY}\lambda_{NY} \geq 2\times10^{-6} \quad and \ k_{NY} = 0.57 \ for \ E_{NY}\lambda_{NY} < 2\times10^{-6} \tag{2.88}$$

Where,

$$E_{NY} = \frac{(\rho_L - \rho_G)gD^2}{\sigma}$$

$$\lambda_{NY} = \frac{{\nu_L}^2 \rho_L}{D\sigma}$$

They tested their correlation against experimental data of 13 other researchers. Most of the data was predicted within error of ±15%. Entire range of void fraction values was used for this comparison.

Thom (1964) also suggested a correlation for vertical upward flow of boiling water. Gamma rays were used for measuring void fraction in the tube cross section.

$$\alpha = \frac{1}{1+\left(\frac{1-x}{x}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.89}\left(\frac{\mu_L}{\mu_G}\right)^{0.18}} \tag{2.89}$$

But, Thom (1964) did not compare predicted and measured void fraction and only presented trend of void fraction with increasing quality.

Baroczy (1966) formulated a correlation using vertical flow data, as reported by Chishom (1973a). The correlation is given by

$$\alpha = \frac{1}{1+\left(\frac{1-x}{x}\right)^{0.74}\left(\frac{\rho_G}{\rho_L}\right)^{0.65}\left(\frac{\mu_L}{\mu_G}\right)^{0.13}} \tag{2.90}$$

The correlations of Baroczy (1966) and Thom (1964) are slip ratio correlations.

Neal and Bankoff (1965) studied co-current mercury-nitrogen flow and suggested a correlation for void fraction. Simplified version of the correlation was reported by Woldesemayat (2006).

$$\alpha = 1.25\left(\frac{U_{SG}}{U_M}\right)^{1.88}\left(\frac{U_{SL}^2}{gD}\right)^{0.2} \tag{2.91}$$

Premoli et al. (1971) developed a correlation for vertical two-phase flow (as reported by Woldesemayat and Ghajar (2007)). The correlation is given by

$$\left(\frac{1-\alpha}{\alpha}\right)\left(\frac{x}{1-x}\right)\left(\frac{\rho_L}{\rho_G}\right) = 1 + F_1\left\{\frac{y}{1+yF_2} - yF_2\right\}^{1/2} \tag{2.92}$$

Where,

$$F_1 = 1.578\,\mathrm{Re}_{Premoli}^{-0.19}\left(\frac{\rho_L}{\rho_G}\right)^{0.22}$$

$$F_2 = 0.0273\,We_{Premoli}\,\mathrm{Re}_{Premoli}^{-0.51}\left(\frac{\rho_L}{\rho_G}\right)^{-0.08}$$

$$y = \frac{\alpha_H}{1-\alpha_H}$$

$$\mathrm{Re}_{Premoli} = \frac{GD}{\mu_L}$$

$$We_{Premoli} = \frac{G^2 D}{\sigma \rho_L g}$$

This correlation has a drawback in the right hand side term of equation (2.92). If the value of term yF_2 becomes greater than $\frac{y}{1 + yF_2}$, the term in the bracket on right hand side of equation (2.92) becomes negative and its square root cannot be calculated.

El-Boher et al. (1988) formulated a correlation based on the data of water-air, mercury-steam and lead-bismuth alloy-steam. The work was carried with focus on liquid metals. Their correlation for void fraction is

$$\alpha = \frac{1}{\left[1 + 0.27 \alpha_H^{-0.69} \left(Fr_{SL}\right)^{-0.177} \left(\frac{\mu_L}{\mu_G}\right)^{0.378} \left(\frac{Re_{SL}}{We_{SL}}\right)^{0.067}\right]} \tag{2.93}$$

Where, Fr_{SL} and We_{SL} are Froude and Weber number based on superficial liquid velocity.

$$Fr_{SL} = \frac{U_{SL}^{\ 2}}{gD}$$

$$We_{SL} = \frac{\rho_L U_{SL}^{\ 2} D}{\sigma}$$

El-Boher et al. (1988) compared their correlation with 7029 experimental data points and predicted data with an 11.97% RMS error. However, the performance of correlations in terms of percentage error was not analyzed. The maximum value of void fraction from the experimental data was limited to 0.8. The maximum diameter and superficial liquid velocity used in the comparison were 0.23 m and 2.58 m/s, respectively.

Czop et al. (1994) performed experiments in a 0.0198 m diameter vertical helical tube with water and SF_6 as working fluids. Their correlation for void fraction is

$$\alpha = -0.285 + 1.097\alpha_H \tag{2.94}$$

But, they stated that the correlation may not produce good results if applied to conditions other than those used in their work. They compared approximately 40 experimental data points with their correlation and found an agreement between predicted and measured values to within ±10%.

The following few paragraphs explain some of the pool void fraction correlations available in the literature.

Sterman (1956) proposed a correlation for steam bubbling through water (pool void fraction). Apart from his own data, he used data of Behringer (1934), Kolokol'tsev (1952) and Margulova (1955). The data ranged from 1 to 190 atmospheric pressure and included column diameters of 52 to 300 mm. The correlation is

$$\alpha = 1.07\left(\frac{U_{SG}{}^{2}}{gD}\right)^{0.4}\left(\frac{D}{\sqrt{\frac{\sigma}{\rho_L - \rho_G}}}\right)^{0.15}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{0.17} \tag{2.95}$$

Sterman (1956) compared prediction of his correlation with the experimental data of Behringer (1934), Kolokol'tsev (1952) and Margulova (1955). There was close agreement between measured and predicted values. But, Sterman (1956) did not state the accuracy of the prediction.

Dimentiev et al. (1959) also proposed a correlation for pool void fraction, which is given by the following equations.

$$\alpha = 1.07 j_G^{*0.8} D_H^{*-0.25}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{-0.23} \quad for\ j_G^{*}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{-0.5} \leq 3.7 \tag{2.96}$$

$$\alpha = 1.9 j_G^{*0.34} D_H^{*-0.25} \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{0.09} \quad for\ j_G^* \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{-0.5} > 3.7 \tag{2.97}$$

Where,

$$D_H^* = \frac{D_H}{\sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}}} \quad and \quad j_G^* = \frac{U_{SG}}{\left(\frac{\sigma g(\rho_L - \rho_G)}{\rho_G{}^2} \right)^{0.25}}$$

Correlation by Wilson et al. (1961) for pool void fraction is

$$\alpha = 0.68 F_{Wilson}{}^{0.62} \left[\left(\frac{\sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}}}{D} \right) \right]^{0.1} \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{0.17} \quad for\ F_{Wilson} \le 2 \tag{2.98}$$

$$\alpha = 0.88 F_{Wilson}{}^{0.44} \left[\left(\frac{\sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}}}{D} \right) \right]^{0.1} \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{0.17} \quad for\ F_{Wilson} > 2 \tag{2.99}$$

$$F_{Wilson} = U_{SG} \left(\frac{\rho_L - \rho_G}{g\sigma} \right)^{0.25}$$

The correlation was based on the data collected by bubbling steam in water columns of diameters 4 to 19 inch.

Based on steam-water and Freon-12 data in diameters ranging from 0.063 m to 1.219 m, Gardner (1980) proposed two pool void fraction correlations, which are

$$\alpha = (1-\alpha)^{0.5} \times 1.7 \times \left[\left(\frac{U_{SG} \rho_L{}^2 P_{Gardner}{}^{0.16}}{((\rho_L - \rho_G) g\sigma)^{0.25}} \right) \right]^{2/3} \quad Referred\ to\ as\ Gardner-I \tag{2.100}$$

$$\alpha = (1-\alpha)^{0.5} \times 11.2 \times \left[\left(\frac{U_{SG} \rho_L{}^2 P_{Gardner}{}^{0.3}}{((\rho_L - \rho_G) g\sigma)^{0.25}} \right) \right]^{2/3} \quad Referred\ to\ as\ Gardner-II \tag{2.101}$$

Where,

$$P_{Gardner} = \frac{\rho_G {v_L}^2 \left(\left(\rho_L - \rho_G\right) g\right)^{0.5}}{\sigma^{3/2}}$$

It should be noted that correlations of Dimentiev et al. (1959), Sterman (1956), Wilson et al. (1961) and Gardner (1980) were developed for large diameter pipes and steam-water mixtures. The accuracy of the four correlations was not stated by the respective authors.

Dix (1971) drift flux correlation was developed with the help of vertical upward flow data sets, as reported by Chexal et al. (1991). The expressions for distribution parameter and drift velocity are

$$C_0 = \frac{U_{SG}}{U_M}\left(1 + \left(\frac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}}\right) \tag{2.102}$$

$$U_{GM} = 2.9\left(\frac{g\sigma\left(\rho_L - \rho_G\right)}{\rho_L^2}\right)^{0.25} \tag{2.103}$$

Dix (1971) correlation was among the top three correlations in the comparison carried out by Chexal et al. (1991), which included approximately 1500 data points of vertical upward steam-water system.

Mukherjee (1979) conducted experiments with air and kerosene at inclination angles from horizontal to vertical. His empirical correlation developed for upward vertical flow is

$$\alpha = 1 - \exp\left(C_1 + C_2 \sin\theta + C_3 \sin^2\theta + C_4 N_L\right)\frac{N_{GV}^{C_5}}{N_{LV}^{C_6}} \tag{2.104}$$

Where,

$$N_{GV} = \frac{\mu_L}{\left(\rho_L \sigma^3\right)^{0.25}}$$

$$N_{GV} = U_{SG}\left[\frac{\rho_L}{g\sigma}\right]^{0.25}$$

$$N_{LV} = U_{SL}\left[\frac{\rho_L}{g\sigma}\right]^{0.25}$$

Values of constants C_1 to C_6 suggested by Mukherjee (1979), are given in the Table 2.3.

Table 2.3 – Values of Constants for Mukherjee (1979) Correlation for Upward Vertical Flow.

C_1	C_2	C_3	C_4	C_5	C_6
-0.380113	0.129875	-0.119788	2.343227	0.475686	0.288657

Mukherjee (1979) tested his correlation against 35 of his air-kerosene data points for vertical upward flow and reported an average percentage error of -2.95% with a standard deviation of 16.8. But, he did not compare his correlation with data of other researchers.

Spedding and Chen (1984) suggested a correlation for vertical two-phase flow taking into consideration changing superficial liquid velocity. They considered a variety of gas-liquid combinations like air-water, argon-water and gas-oil in their study. Their correlation is

$$\frac{\alpha}{1-\alpha} = \frac{1}{0.2 + k_{1SpeddingChen}\dfrac{U_{SL}}{U_{SG}}} \quad for \ \frac{\alpha}{1-\alpha} \le 4$$

$$\frac{\alpha}{1-\alpha} = k_{2SpeddingChen}\left(1 - e^{\left(-k_{3SpeddingChen}\frac{U_{SG}}{U_{SL}}\right)}\right)\left(\frac{U_{SG}}{U_{SL}}\right)^{0.65} \quad for \ \frac{\alpha}{1-\alpha} > 4 \ to \ 275 \tag{2.105}$$

Where,

$$\ln(k_{1SpeddingChen}) = -1.44\ln(U_{SL}) - 0.007$$

$$k_{2SpeddingChen} = 0.14\ln(U_{SL}) + 1$$

$$k_{3SpeddingChen} = 0.97\ln(U_{SL}) - 3$$

Where, expression $\frac{\alpha}{1-\alpha} \leq 4$ in equation (2.105) is correlation proposed by Armand (1946).

Morooka et al. (1989) proposed a drift flux correlation based on steam-water two-phase flow data in vertical 4x4 rod bundle (12.3 mm tube diameter tubes). Void fraction was measured with the help of a CT scanner. This correlation is also referred to as Toshiba correlation by many researchers. For developing the equation for void fraction, they plotted U_{SG}/α against U_M and came up with a straight line fit. Calculated values of distribution parameter and drift velocity were $C_0 = 1.08$ and $U_{GM} = 0.45$. Morooka et al. (1989) mentioned that prediction of void fraction by their correlation, for void fraction value of greater than 0.8 will result in under-prediction, because the correlation was developed by using void fraction data below 0.8. They reported an accuracy of 1.68% and standard deviation of 1.8% for the prediction of void fraction, but number of experimental data points considered for comparison were limited in number.

Takeuchi et al. (1992) devised a drift flux correlation for vertical two-phase flow. Equations for distribution parameter and drift velocity are

$$C_0 = 1.11775 + 0.45881\,\alpha - 0.57656\,\alpha^2 \tag{2.106}$$

$$U_{GM} = F_{Takeuchi} C_0 (1 - C_0 \alpha) \left(\frac{\sqrt{\frac{gD(\rho_L - \rho_G)}{\rho_L}}}{m_{Takeuchi}{}^2 + C_0 \alpha \sqrt{\frac{\rho_L}{\rho_G} - m_{Takeuchi}{}^2}} \right) \tag{2.107}$$

Where,

$$F_{Takeuchi} = \sqrt{\frac{k^2{}_{Takeuchi}}{D_{Takeuchi}}}$$

$$k_{Takeuchi} = \sqrt{D_{Takeuchi} \cdot \min\left(\frac{1}{2.4}, \frac{10.24}{D_{Takeuchi}} \right)}$$

$$D_{Takeuchi} = D \sqrt{g \left(\frac{\rho_L - \rho_G}{\sigma} \right)}$$

Value of *m* recommended by Takeuchi et al. (1992) was 1.367. The accuracy of their correlation was not mentioned.

2.3.3 Flow Pattern Independent Correlations Applicable to Variety of Flow Orientations Including Vertical Upward Flow

Madsen (1975) suggested a flow pattern independent correlation for vertical and horizontal orientations.

$$\alpha = \frac{1}{1 + \left(\frac{\rho_L}{\rho_G} \right)^{0.5} \left(\frac{1-x}{x} \right)^{F_{Madsen}}} \tag{2.108}$$

Where,

$$F_{Madsen} = \frac{0.5\, LOG \frac{\rho_L}{\rho_G} - LOG\left(\frac{\alpha_H}{1-\alpha_H} \right)}{LOG \frac{\rho_L}{\rho_G} - LOG\left(\frac{\alpha_H}{1-\alpha_H} \right)}$$

Madsen (1975) compared his prediction with experimental data I which pressure range was from 101 to 14480 kN/m^2 and quality range was from 0.001 to 0.525. Prediction of his correlation was within ± 10% for void fraction of 0.3 and above. But, for lower values the correlation consistently over-predicted the void fraction values.

Chisholm (1983) suggested a correlation which is applicable to horizontal to vertical orientations. The equation for the correlation is

$$\alpha = \frac{1}{\alpha_H + (1-\alpha_H)^{0.5}} \alpha_H \tag{2.109}$$

This correlation was not compared with any experimental data.

Shvarts et al. (1993) used data of steam-water systems in which pressure ranged from 0.1 up to 12 MPa and mass velocities ranged from 100 to 5150 kg/m^2-s. The tube diameters ranged from 7.8 to 60 mm. Their correlation is applicable for inclination angles ranging from 15° to 90° and pressures up to 22 MPa. Equations used in their correlation are

$$\alpha = k_{Shvarts} \alpha_{Shvarts} \tag{2.110}$$

$$k_{Shvarts} = 1 - b_{1Shvarts} \pi_{Shvarts}^{\ b_{2Shvarts}} U_M^{\ -b_{3Shvarts}} \left(1 - \frac{\theta}{90}\right) \tag{2.111}$$

$$\alpha_{Shvarts} = \frac{\alpha_H}{1 + \dfrac{a_{Shvarts}}{U_M}} \tag{2.112}$$

$$a_{Shvarts} = a_{1Shvarts} - a_{2Shvarts} \pi_{Shvarts} \tag{2.113}$$

Where,

$$\pi_{Shvarts} = \frac{P}{P_{Cr}}, P_{Cr} = 22.1\, MPa,$$

$$a_{1Shvarts} = 0.72 \ and \ a_{2Shvarts} = 0.87 \ if \ 0.53 \geq \pi_{Shvarts} \geq 0.004$$

$a_{1Shvarts} = 0.47 \; and \; a_{2Shvarts} = 0.44 \; if \; \pi_{Shvarts} > 0.53$

$b_{1Shvarts} = 0.51, b_{2Shvarts} = 0.51, b_{3Shvarts} = 0.51 \; if \; U_M \le 0.5\, m/s$

$b_{1Shvarts} = 0.23, b_{2Shvarts} = 0.07, b_{3Shvarts} = 0.91 \; if \; U_M > 0.5\, m/s$

Shvarts et al. (1993) did not find accuracy of the correlation by comparing it with experimental data.

Chexal et al. (1992) suggested a correlation using data for a wide range of fluid combinations (steam-water, air-water, hydrocarbons and oxygen), diameters up to 450 mm and horizontal to vertical orientations. The expressions for distribution parameter and drift velocity of their correlation are

$$C_0 = \frac{L_{Chexal}}{k_{Chexal} + (1 - k_{Chexal})\alpha^{r_{Chexal}}} \tag{2.114}$$

$$U_{GM} = 1.41\left(g\sigma \frac{\rho_L - \rho_G}{\rho_L^{\ 2}} \right)^{0.25} C_{2Chexal} C_{3Chexal} C_{4Chexal} C_{9Chexal} \tag{2.115}$$

Where,

$$L_{Chexal} = Min\left(1.15\alpha^{0.45}, 1\right)$$

$$k_{Chexal} = B_1 + (1 - B_1)\left(\frac{\rho_G}{\rho_L} \right)^{0.25}$$

$$r_{Chexal} = \frac{1 + 1.57\dfrac{\rho_G}{\rho_L}}{1 - B_{1Chexal}}$$

$B_{1Chexal}$ is defined as

$$B_{1Chexal} = Min\left(0.8, \frac{1}{1+e^{\left(\frac{-Re_{Chexal}}{60000}\right)}}\right) \tag{2.116}$$

$$Re_{Chexal} = Max(\mathrm{Re}_{SL}, \mathrm{Re}_{SG})$$

$$C_{2Chexal} = 0.4757\ln\left(\frac{\rho_L}{\rho_G}\right)^{0.7} \quad for \left(\frac{\rho_L}{\rho_G}\right) \leq 18$$

$$C_{2Chexal} = 1 \quad for \left(\frac{\rho_L}{\rho_G}\right) > 18 \; and \; C_{5Chexal} \geq 1$$

$$C_{2Chexal} = \frac{1}{1-e^{\left(\frac{-C_{5Chexal}}{1-C_{5Chexal}}\right)}} \quad for \left(\frac{\rho_L}{\rho_G}\right) > 18 \; and \; C_{5Chexal} < 1$$

$$C_{3Chexal} = Max\left(0.5, 2e^{\left(\frac{-\mathrm{Re}_{SL}}{60000}\right)}\right)$$

$$C_{4Chexal} = 1 \quad for \; C_{7Chexal} \geq 1$$

$$C_{4Chexal} = \frac{1}{1-e^{\left(\frac{-C_{7Chexal}}{1-C_{7Chexal}}\right)}} \quad for \quad C_{7Chexal} < 1$$

$$C_{5Chexal} = \sqrt{150\frac{\rho_L}{\rho_G}}$$

$$C_{7Chexal} = \left(\frac{0.09144}{D}\right)^{0.6}$$

$$C_{9Chexal} = (1-\alpha)^{B_{1Chexal}}$$

They compared prediction of their correlation with data from widespread sources. They selected an error band of ±10% for comparison, but the correlation did not achieve prediction within this error band for many data points. Prediction of low values of void fraction was mostly out of ±10% error band. They did not report percentage of the total data points predicted within ±10%. They also did not mention the accuracy of correlation for vertical upward flow. Chexal et al. (1992) used void fraction data with ±5% variation associated to it.

Woldesemayat and Ghajar (2007) compared 68 correlations against 2845 two-phase data points. They used data of 8 different researchers. Out of 2845 data points, 900 were for horizontal flow, 403 were for vertical upward flow and 1542 were for upward inclined flow. The study involved different gas-liquid combinations (air-water, air-kerosene and natural gas-water) and wide range of diameters (from 0.0127 to 0.10126 m). They developed a drift flux correlation as shown below

$$\alpha = \frac{U_{SG}}{U_{SG}\left(1+\left(\frac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}}\right)+2.9\left[\frac{gD\sigma(1+\cos\theta)(\rho_L-\rho_G)}{\rho_L^2}\right]^{0.25}(1.22+1.22\sin\theta)^{\frac{P_{atm}}{P_{system}}}} \tag{2.117}$$

The correlation is capable of predicting void fraction regardless of flow patterns and inclination angles. Among the correlations compared in their work, correlation of Woldesemayat and Ghajar (2007) predicted the highest percentage of data points for all the three error bands considered in their study. The correlation predicted 85.6%, 78.5% and 60.4% of the total points within ±15%, ±10% and ±5% error, respectively. But, its prediction performance for vertical upward two-phase flow was not mentioned in their work.

2.3.4 Correlations not Developed for but Applicable to Vertical Upward Flow

Homogeneous correlation, which is the most basic form of void fraction correlation, was reported by Woldesemayat and Ghajar (2007). Its expression is

$$\alpha = \frac{U_{SG}}{U_{SG} + U_{SL}} \tag{2.118}$$

Armand and Masina is a Kα_H correlation, which was reported by Woldesemayat and Ghajar (2007). Its expression is

$$\alpha = (0.833 - 0.167x)\alpha_H \tag{2.119}$$

Applicability of the above three correlations to vertical upward flow was not reported by Woldesemayat and Ghajar (2007), but these were one of the earliest coorelations in the two-phase flow study.

Filimonov et al. (1957) devised a correlation based on steam-water data, as reported by Woldesemayat (2006). They suggested a value of 1 for distribution parameter. Expressions for drift velocity are

$$U_{GM} = (0.65 - 0.0385P)\left(\frac{D}{0.063}\right)^{0.25} \quad for\ P < 12.7\ MPa \tag{2.120}$$

$$U_{GM} = (0.33 - 0.00133P)\left(\frac{D}{0.063}\right)^{0.25} \quad for\ P \geq 12.7 - 18.2\ MPa \tag{2.121}$$

It predicted more than 80% of the data points within ±15% error for all the upward vertical data sets studied by Woldesemayat (2006).

Nicklin et al. (1962) correlation was developed for slug flow. But, it predicted more than 75% of the data points for all the data sets considered in the study of Woldesemayat and Ghajar (2007).

Bonnecaze et al. (1971) studied void fraction and pressure drop in slug flow of oil and gas in inclined (±10° to horizontal) pipes. From the 152 data points collected, they developed the following correlation for prediction of void fraction.

$$\alpha = \frac{\alpha_H}{1.2 + \frac{0.35\left(1 - \frac{\rho_G}{\rho_L}\right)}{k_{Bonnecaze}\sqrt{Fr}}} \tag{2.122}$$

Value of $k_{Bonnecaze}$ for uphill flow was recommended as 1 by Bonnecaze et al. (1971). The correlation of Bonnecaze et al. (1971) predicted data for +10° angle within 11.7% deviation. The correlation was developed for slug flow, but was found to predict other data well by Woldesemayat and Ghajar (2007). It can be observed that correlation of Bonnecaze et al. (1971) for vertical orientation essentially reduces to that of Nicklin and Davidson (1962) because the multiplier $\left(1 - \frac{\rho_G}{\rho_L}\right)$ is close to unity unless gas density is very high. But, generally gas density is too low compared to liquid density.

Guzhov et al. (1967) suggested a $K\alpha_H$ correlation. The correlation, as reported by Woldesemayat and Ghajar (2007) is

$$\alpha = 0.81\alpha_H\left(1 - e^{\left(-2.2\sqrt{Fr}\right)}\right) \tag{2.123}$$

Rouhani and Axelsson (1970) proposed two drift flux correlations based on steam-water data for pressures from 19 to 138 bar. The two correlations as reported by Woldesemayat and Ghajar (2007) are

$$\alpha = \frac{\frac{\dot{x}}{\rho_G}}{\left[C_0\left(\frac{x}{\rho_G} + \frac{1-x}{\rho_L}\right) + \frac{U_{GM}}{G}\right]} \tag{2.124}$$

Where,

$$U_{GM} = \left(\frac{1.18}{\sqrt{\rho_L}}\right)\left(g\sigma\left(\rho_L - \rho_G\right)\right)^{0.25}$$

For correlation 1 (referred to as Rouhani and Axelsson - I),

$$C_0 = 1 + 0.2(1 - x)$$

For correlation 2 (referred to as Rouhani and Axelsson - II),

$$C_0 = 1 + 0.2(1 - x)(gD)^{0.25}\left(\frac{\rho_L}{G}\right)^{0.5}$$

Rouhani and Axelsson – I correlation predicted 86.6% of the total data points within ±15% error band for vertical upward data (403 points) in the study of Woldesemayat and Ghajar (2007). Rouhani and Axelsson – II correlation did not perform as good as Rouhani and Axelsson – I.

Chisholm (1973a) suggested a correlation based on velocity ratio of gas and liquid velocity for prediction of void fraction.

$$\alpha = \frac{1}{1 + k_{Velocity}\left(\frac{1 - x}{x}\right)\frac{\rho_G}{\rho_L}} \tag{2.125}$$

$$k_{Velocity} = Velocity\ Ratio = \frac{U_G}{U_L}$$

Expression for velocity ratio derived by Chisholm (1973b) was used.

$$k_{Velocity} = \frac{1}{\left(1 - x + x\frac{\rho_L}{\rho_G}\right)^{0.5}}$$

Chisholm (1973a) did not mention the accuracy of the correlation in their work.

Mattar and Gregory (1974) correlation was reported by Woldesemayat and Ghajar (2007). It is a drift flux correlation given by

$$\alpha = \frac{U_{SG}}{1.3U_M + 0.7} \tag{2.126}$$

Greskovich and Cooper (1975) suggested a correlation for upward inclined air-water slug flow based on data collected in pipe diameters ranging from 0.0254 to 0.0794 m for 1° to 10° of inclination.

$$\alpha = \frac{1-\lambda}{\left[1+0.671\left(\frac{(\sin\theta)^{0.263}}{Fr^{0.5}}\right)\right]} \tag{2.127}$$

They compared prediction of their correlation with experimental data and obtained good results but they did not report any statistical parameters (for example: percentage error, standard deviation) for the comparison and therefore accuracy of the correlation cannot be estimated.

Isbin and Biddle (1979) reported the correlations of Kowalczewski, Moussali and Kutucuglu which are presented below. All the three correlations are based on $K\alpha_H$ approach.

Kowalczewski correlation

$$\alpha = \alpha_H - 0.71(1-\alpha_H)^{0.5} Fr_L^{-0.045}\left(1-\frac{P}{P_{Cr}}\right) \tag{2.128}$$

Kutucuglu correlation

$$\alpha = \alpha_H - (1-\alpha_H)^{0.5} Fr_L^{0.2}\left(1-\frac{P}{P_{Cr}}\right)^2 \tag{2.129}$$

Moussali correlation

$$\alpha = k_{Moussali}\alpha_H \tag{2.130}$$

Where,

$$k_{Moussali} = 1 - \frac{(30.4/k_{2Moussali})+11}{60(1+1.6/k_{2Moussali})(1+3.2/k_{2Moussali})}$$

$$k_{2\,Moussali} = \frac{1-x}{x}\frac{\rho_G}{\rho_L}$$

Accuracy of none of the above correlations was reported by Isbin and Biddle (1979).

Sun et al. (1980) developed a drift flux correlation. The expressions for distribution parameter and drift velocity, as reported by Coddington and Macian (2002) are

$$C_0 = \frac{1}{0.82 + 0.18\dfrac{P}{P_{Cr}}} \tag{2.131}$$

$$U_{GM} = 1.41\left(\frac{g\sigma(\rho_L - \rho_G)}{\rho_L^2}\right)^{0.25} \tag{2.132}$$

Where, P_{Cr} is critical pressure.

Sun et al. (1980) correlation was one of the thirteen correlations selected by Coddington and Macian (2002) as wide range (applicable to wide range of experimental conditions) correlations. It predicted the data gathered by Coddington and Macian (2002) with an average absolute error of -0.041. Negative value of absolute error indicates consistent under-prediction of this correlation.

Lahey and Moody (1977) model, also known as *"Ramp model"*, was reported by Ohkawa and Lahey (1980). It is a drift flux model as given below

$$C_0 = 1.13 \; for \; \alpha \le 0.65 \text{ and } C_0 = 1.13 + \frac{0.13}{0.35}(1-\alpha) \; for \; \alpha > 0.65 \tag{2.133}$$

$$\begin{gathered} U_{GM} = 2.9\left(\frac{(g\sigma(\rho_L - \rho_G))^{0.25}}{\sqrt{\rho_L}}\right) for \; \alpha \le 0.65 \\ U_{GM} = 2.9\left(\frac{(g\sigma(\rho_L - \rho_G))^{0.25}}{\sqrt{\rho_L}}\right)\left(\frac{1-\alpha}{0.35}\right) \quad for \; \alpha > 0.65 \end{gathered} \tag{2.134}$$

Ishii (1977b) model was reported by Ohkawa and Lahey (1980). It is a drift flux model. The equations for model are given below

$$C_0 = Min\left(C_{01Ishii,} C_{02Ishii}\right) \tag{2.135}$$

$$C_{01Ishii} = \left(1.2 - 0.2\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\right)\left(1 - e^{-18\alpha}\right)$$

$$C_{02Ishii} = 1 + \frac{1-\alpha}{\left(0.8 + 4\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\right)}$$

$$U_{GM} = Min\left(U_{GM1Ishii,} U_{GM2Ishii}\right) \tag{2.136}$$

$$U_{GM1Ishii} = 1.43\frac{\left(g\sigma\left(\rho_L - \rho_G\right)\right)^{0.25}}{\sqrt{\rho_L}}$$

$$U_{GM2Ishii} = \frac{1-\alpha}{\alpha + \left(\frac{1+75(1-\alpha)}{\sqrt{\alpha}}\left(\frac{\rho_G}{\rho_L}\right)\right)^{0.5}}\left(Q_M + \left(\frac{\left(\rho_L - \rho_G\right)gD(1-\alpha)}{0.015\rho_L}\right)^{0.5}\right)$$

Where, Q_M is total volume flow rate of liquid and gas.

The accuracy of both Lahey and Moody (1977) and Ishii (1977b) models is not known because it was not reported by Ohkawa and Lahey (1980). Ishii (1977b) model was included in the comparison of Coddington and Macian (2002) and predicted void fraction with an absolute error of 0.048.

Yeh (1975) (reported in Yeh and Hochreiter (1980)) suggested a correlation for calculation of void fraction. This correlation was also included in the comparison of void fraction correlation by Chexal et al. (1991). The correlation is

$$\alpha = 0.925\left(\frac{\rho_G}{\rho_L}\right)^{0.239}\left(\frac{U_{SG}}{U_{BCR}}\right)^{b_{Yeh}}\alpha_H{}^{0.6}$$
$$\alpha = 1 \quad if\ \alpha > 1 \tag{2.137}$$

$$b_{Yeh} = 0.67\ if\ \frac{U_{SG}}{U_{BCR}} < 1$$
$$b_{Yeh} = 0.47\ if\ \frac{U_{SG}}{U_{BCR}} \geq 1 \tag{2.138}$$

Where,

$$U_{BCR} = \frac{2}{3}\left(gR_{BCR}\right)^{0.5} \tag{2.139}$$

$$R_{BCR} = \left(\frac{1.53}{\frac{2}{3}}\right)^{2}\left(\frac{\sigma}{g\rho_L}\right)^{0.5} \tag{2.140}$$

Yeh and Hochreiter (1980) compared measured void fraction and void fraction predicted by Yeh (1975) correlation, but did not report the accuracy of this model in terms of percentage or absolute error.

Ohkawa and Lahey (1980) proposed a correlation for void fraction in counter current flow limited (CCFL) conditions. The equations for distribution parameter and drift velocity for the model are

$$C_0 = C_{01OhkawaLahey}\ if\ \alpha < X_{OhkawaLahey}$$
$$C_0 = \min(C_{01\,OhkawaLahey}, C_{02OhkawaLahey})\ if\ \alpha \geq X_{OhkawaLahey} \tag{2.141}$$

$$U_{GM} = U_{GM1_{OhkawaLahey}}\ if\ \alpha < X_{OhkawaLahey}$$
$$U_{GM} = \min\left(U_{GM1_{OhkawaLahey}}, U_{GM2_{OhkawaLahey}}\right) if\ \alpha \geq X_{OhkawaLahey} \tag{2.142}$$

Where,

$$C_{01OhkawaLahey} = \left(1.2 - 0.2\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\right)\left(1 - e^{-18\alpha}\right)$$

$$C_{02OhkawaLahey} = 1 + 0.2\left(1 - \left(\frac{\rho_G}{\rho_L}\right)^{0.5}\right)\left(1 - \left(\frac{\alpha - X_{OhkawaLahey}}{1 - X_{OhkawaLahey}}\right)^2\right)$$

$$U_{GM1OhkawaLahey} = 2.9\left(\frac{\left(g\sigma\left(\rho_L - \rho_G\right)\right)^{0.25}}{\sqrt{\rho_L}}\right)$$

$$U_{GM2OhkawaLahey} = Y_{OhkawaLahey}2.9\left(\frac{\left(g\sigma\left(\rho_L - \rho_G\right)\right)^{0.25}}{\sqrt{\rho_L}}\right)\left(1 - \left(\frac{\alpha - X_{OhkawaLahey}}{1 - X_{OhkawaLahey}}\right)^2\right)$$

$$X_{OhkawaLahey} = 0.5881164 - 1.81701\psi + 2.00025\psi^2 - 3.34398\psi^3$$

$$Y_{OhkawaLahey} = Max\left(Y_{OhkawaLahey1}, 3.136\right)$$

$$Y_{OhkawaLahey1} = 4.72085 - 17.26736\psi + 56.148835\psi^2 + 113.216\psi^3 - 1250.603\psi^4 + 3039.767\psi^5 - 2431.823\psi^6$$

$$\psi = \left(\frac{\rho_G}{\rho_L}\right)^{0.5}$$

Accuracy of this model was not reported in the work of Ohkawa and Lahey (1980).

Jowitt et al. (1984) suggested a drift flux correlation with the following equations for distribution parameter and drift velocity

$$C_{Jowitt} = 1 + 0.796\exp\left(-0.061\sqrt{\frac{\rho_L}{\rho_G}}\right) \tag{2.143}$$

$$U_{GM\,Jowitt} = 0.034\left(\sqrt{\frac{\rho_L}{\rho_G}} - 1\right) \tag{2.144}$$

Jowitt et al. (1984) correlation predicted void fraction data in the study of Coddington and Macian (2002) with an average absolute error of 0.057. The correlation over-predicted void fraction data for the values of 0.5 and above.

Kokal and Stanislav (1989) conducted experiments with air and oil at inclinations up to ± 9° from horizontal in pipes of diameter 25.8, 51.2 and 76.3 mm. They suggested drift-flux correlation given by equation (2.146).

$$\alpha = \frac{U_{SG}}{1.2U_M + 0.345\left(gD\frac{(\rho_L - \rho_G)}{\rho_L}\right)^{0.5}} \tag{2.145}$$

They compared predicted void fraction and experimental void fraction and generally achieved good results. But, quantitative performance of the correlation was not reported by them.

Sonnenburgh (1989) proposed a drift flux correlation for prediction of void fraction. The expressions for distribution parameter and drift velocity for the correlation are

$$C_{Sonnenburgh} = 1 + \left(0.32 - 0.32\sqrt{\frac{\rho_G}{\rho_L}}\right) \tag{2.146}$$

$$U_{GM\,Sonnenburgh} = \frac{C_{Sonnenburgh}\left(1 - C_{Sonnenburgh}\alpha_{Sonnenburgh}\right)}{\frac{C_{Sonnenburgh}\alpha_{Sonnenburgh}}{\sqrt{\frac{gD_H(\rho_L - \rho_G)}{\rho_G}}} + \left(1 - \frac{C_{Sonnenburgh}\alpha_{Sonnenburgh}}{\sqrt{\frac{gD_H(\rho_L - \rho_G)}{\rho_L}}}\right)} \tag{2.147}$$

The expression for drift velocity for the correlation suggested by Bestion (1985) is

$$U_{GM\,Bestion} = 0.188\sqrt{\frac{gD_H(\rho_L - \rho_G)}{\rho_G}} \tag{2.148}$$

He used value of 1 for distribution parameter.

In the study of Coddington and Macian (2002), this correlation over-predicted void fraction above the value of 0.6. Average absolute error in prediction was 0.049.

Spedding et al. (1990) developed an empirical correlation for the prediction of void fraction in upward inclined tubes. The correlation is

$$\alpha = (1-\alpha)\left(0.45 + 0.08e^{-100\left(0.25-U_{SL}^{2}\right)}\right)\left(\frac{U_{SG}}{U_{SL}}\right)^{0.65} \tag{2.149}$$

Spedding et al. (1990) compared this correlation with experimental data. Average percentage errors of this correlation ranged from 0 for data points in annular+droplet flow regime to +100 for data in bubble flow regime. But, overall prediction performance of the correlation was not reported.

Huq and Loth (1992) devised a correlation that related quality to void fraction and tested it against steam-water and air-water data. They found that their simple correlation performed satisfactorily when compared to more complex correlations like Chexal and Lellouche (1986) and Ohkawa and Lahey (1980). But, they did not provide a quantitative comparison between their correlation and the correlations of Chexal and Lellouche (1986) and Ohkawa and Lahey (1980). The correlation is

$$\alpha = 1 - \frac{2(1-x)^{2}}{1-2x+\left\{1+4x(1-x)\left(\frac{\rho_L}{\rho_G}-1\right)\right\}^{0.5}} \tag{2.150}$$

Maier and Coddington (1996) developed a drift flux correlation for void fraction. The equation for distribution parameter is

$$C_{0MC} = C_{MC1}P + C_{MC2} \tag{2.151}$$

Where,

$C_{MC1} = 2.57\times10^{-3}$ and $C_{MC2} = 1.0062$

The equation for drift velocity is

$$U_{GMMC} = \left(C_{MC3}P^2 + C_{MC4}P + C_{MC5}\right)G + \left(C_{MC6}P^2 + C_{MC7}P + C_{MC8}\right) \tag{2.152}$$

Where,

$C_{MC3} = 6.73 \times 10^{-7}$, $C_{MC4} = -8.81 \times 10^{-5}$, $C_{MC5} = 1.05 \times 10^{-3}$

$C_{MC6} = 5.63 \times 10^{-3}$, $C_{MC7} = -1.23 \times 10^{-1}$, $C_{MC8} = 8 \times 10^{-1}$

It performed well in the comparison of Coddington and Macian (2002) by predicting void fraction data with an average absolute error of -0.002. It predicted data with no consistent under-prediction or over-prediction.

Inoue et al. (1993) suggested a drift flux correlation for void fraction prediction. The expressions for distribution parameter and drift velocity, as reported by Coddington and Macian (2002) are

$$C_0 = 6.76 \times 10^{-3} P + 1.026 \tag{2.153}$$

$$U_{GM} = \left(5.1 \times 10^{-3} G_M + 6.91 \times 10^{-2}\right)\left(9.42 \times 10^{-2} P^2 - 1.99P + 12.6\right) \tag{2.154}$$

Equation for distribution parameter takes into consideration the effect of pressure and equation for drift velocity considers the effect of mass flow rate and pressure. Pressure is used in MPa. In the study of Coddington and Macian (2002), this correlation gave a good performance with average absolute error of -0.003.

From the correlations discussed above, correlations of Sun et al. (1980), Lahey and Moody (1977), Ishii (1977b), Inoue et al. (1993), Yeh and Hochreiter (1980) and Ohkawa and Lahey (1980) were developed for steam-water flow. Table 2.4 lists the flow pattern independnent correlations discussed in this chapter.

Table 2.4 – Flow Pattern Independent Correlations from Literature

Flow Pattern Independent Correlations Developed for Upward Vertical Orientation	
Bankoff (1960)	Sterman (1956)
Hughmark (1962)	Dimentiev et al. (1959)
Nishino and Yamazaki (1963)	Wilson et al. (1961)
Yamazaki and Yamaguchi (1976)	Gardner (1980) – I
Thom (1964)	Gardner (1980) – II
Baroczy (1966)	Dix (1971)
Neal and Bankoff (1965)	Mukherjee (1979)
Premoli et al. (1971)	Spedding and Chen (1984)
El-Boher et al. (1988)	Morooka et al. (1989)
Czop et al. (1994)	Takeuchi et al. (1992)
Flow Pattern Independent Correlations Applicable to Variety of Flow Orientations Including Vertical Upward Flow	
Madsen (1975)	Chexal et al. (1992)
Chisholm (1983)	Woldesemayat and Ghajar (2007)
Shvarts et al. (1993)	
Correlations not Developed for but Applicable to Vertical Upward Flow	
Homogeneous	Sun et al. (1980)
Armand and Masina	Lahey and Moody (1977)
Filimonov et al. (1957)	Ishii (1977b)
Nicklin and Davidson (1962)	Ohkawa and Lahey (1980)
Bonnecaze et al. (1971)	Yeh (1975)
Guzhov et al. (1967)	Jowitt et al. (1984)
Rouhani and Axelsson (1970) – I	Kokal and Stanislav (1989)
Rouhani and Axelsson (1970) – II	Sonnenburgh (1989)
Chisholm (1973a)	Bestion (1985)
Mattar and Gregory (1974)	Spedding et al. (1990)
Greskovich and Cooper (1975)	Huq and Loth (1992)
Kowalczewski	Maier and Coddington (1996)
Kutucuglu	Inoue et al. (1993)
Moussali	

Important observations from the literature review on void fraction correlations are:

1) Many of the researchers have compared their correlations with experimental data, but have not mentioned the percentage uncertainty or error associated with the experimental data used.

2) There is no independent study on prediction performance of flow pattern specific correlations.
3) Comparison of flow pattern independent correlations considering a large number of correlations is not done.
4) There is no generally accepted void fraction correlation for vertical upward flow.

2.4 Sources of Experimental Data

The oldest void fraction data used in this study is steam-water data of Isbin et al. (1957). They carried out the experiments in a 0.875 inch (0.02215 m) vertical tube at atmospheric pressure for a range of quality from 0 to 4%. They used gamma ray absorption technique to measure void fraction. Their investigation was limited to annular flow. Therefore range of void fraction values from their work is limited (from 0.5914 to 0.9236).

Oshinowo (1971) used the technique of quick closing valves to measure void fraction in air-water and air-glycerin two-phase flows. The range of void fraction data collected for both fluid combinations was broad and void fraction data for all the flow patterns (bubble, slug, froth and annular) observed was taken. Percent uncertainty related to void fraction data was not reported.

Beggs (1972) collected air-water two-phase flow data in 0.0254 and 0.0381 m diameter pipes using quick closing valves. Though the range of void fraction was broad, the number of data points in the two pipes is only 13 and 14, respectively. This data set was taken from the work of Woldesemayat (2006).

Data of Spedding and Nguyen (1976) was reported in the work of Woldesemayat (2006). A large number of data points (224) were collected in a 0.0455 m diameter pipe with air and water as working fluids. A wide range of void fraction values was covered in this study. But, flow patterns were not reported for this data set.

Mukherjee (1979) conducted experiments with air and kerosene in a 0.0381 m diameter pipe. A wide range of void fraction values were collected in this study. Most of the data points were in slug flow region. Void fraction was measured with capacitance sensors. However, the data collected by sensors was not compared with physically collected data (for example, with data collected using quick closing valves) and the accuracy of sensors was not stated.

Using the technique of quick closing valves, Fernandes (1981) collected void fraction and flow pattern (bubble, slug, churn and annular) data in a 0.05074 m pipe using water and air. He collected void fraction data for a broad range. But, a constant pressure (atmospheric) was reported. Therefore, for all the data a constant value of gas phase density must be assumed for void fraction calculations. He reported some data points with liquid velocity of 0 m/s, which is not logical.

Chokshi (1994) used gamma ray densitometer to collect void fraction in a pipe of diameter 0.076 m. Air and water were used as the two fluids. Data with a wide range of void fraction values was collected. In the data reported by Chokshi (1994), flow pattern information was not given. The system pressure calculation for each run is also tough for this data, because high pressure drops are encountered between the pressure transducers. Pressure data of the 8 transducers used must be averaged to find out average system pressure.

Sujumnong (1997) collected void fraction and flow pattern data for air-water and air-glycerin systems using the method of quick closing valves in a 0.0127 m. Comprehensive data was taken which covered a wide range of void fraction values and all the flow patterns (bubble, slug, churn, froth and annular) were represented. But, the flow pattern data presented by Sujumnong (1997) does not clearly reveal the flow transition boundaries, because very few number of points are taken near flow transition boundaries.

Schmidt et al. (2008) conducted experiments with nitrogen and water in a 0.0545 m diameter pipe and measured void fraction using gamma ray densitometer. They studied flow patterns, but flow pattern information was not reported in the table containing data. The void fraction range was broad but only 20 data points were taken.

The experimental data of the above studies is briefly mentioned in Table 2.5. The details of the data are presented in Appendix A.

Table 2.5 - Details of Experimental Data from Literature

Data Source	Diameter (m)	Fluid Combination	Number of Data Points
Schmidt et al. (2008)	0.0545	nitrogen-water	20
Sujumnong (1997)	0.0127	air-water	104
Sujumnong (1997)	0.0127	air-glycerin	77
Chokshi (1994)	0.076	air-water	103
Fernandes (1981)	0.05074	air-water	88
Mukherjee (1979)	0.0381	air-kerosene	65
Spedding and Nguyen (1976)	0.0455	air-water	224
Beggs (1972)	0.0254 and 0.0381	air-water	27
Oshinowo (1971)	0.0254	air-water	153
Oshinowo (1971)	0.0254	air-glycerin	172
Isbin et al. (1957)	0.02215	steam-water	22

Important points revealed by the literature review on experimental data are:

1) Many data sources have covered a wide range of void fraction. Research is carried out with a variety of fluid combinations and diameters.

2) Only data bases in which froth flow was reported were Sujumnong (1997) and Oshinowo (1971).
3) Churn flow data is available in data sets of Fernandes (1981) and Sujumnong (1997) only.
4) None of the researcher has provided the uncertainty associated with the measurement of void fraction.
5) Many researchers have not gathered enough data points in all the flow patterns.
6) Flow pattern information is not provided in some data sets.

CHAPTER III

EXPERIMENTAL SETUP

As Discussed in Chapter 2, a lot of experimental work was carried out in the area of vertical upward two-phase flow. The three aspects of the present work – flow patterns and flow pattern transitions, effect of diameter and gas phase density on flow pattern transitions and study of void fraction correlations for vertical upward flow were also studied by some researchers. But, there are some drawbacks related to these studies. Some of the aspects of vertical upward two-phase flow are not studied in detail. The drawbacks in previous studies and aspects of two-phase flow which need more elaboration are presented below.

Drawbacks of the previous studies:

1) The definitions of flow patterns and number of significant flow patterns in vertical upward flow are not standardized. Churn and froth flows need more attention because they are considered as separate flow patterns by some researchers while other researchers use them synonymously.
2) There is only one independent comparison for flow transition theories. This comparison was done by Jayanti and Hewitt (1992) for slug-churn transition. There is no independent comparison for churn-annular transition. Even in the comparison by Jayanti and Hewitt (1992), only 5 theories were considered.

3) Other than the work of Jayanti and Hewitt (1992), researchers have come up with a transition theory, have compared their results with other theories or experimental data and have claimed that transition theory proposed by them is generally good. Others have not compared their theory with experimental data. Quantitative analysis and reasoning for trends in flow pattern transitions is not done in the literature.
4) Sometimes, data used for comparing transition theories is not complete. For example, some of the researchers (For example, Chen and Brill (1997)) have compared their theories with data of Shoham (1982). But, this data does not contain pressure data and therefore effect of gas phase density (due to change in pressure) on transition cannot be analyzed using this data.
5) Accuracy of void fraction data is not reported. Very limited data is available for churn and froth flows. Some researchers have not taken enough data points in all the flow patterns. In many data sets, flow pattern information is not provided.

Aspects of two-phase flow study which need more elaboration are :

1) Analysis of the effect of gas phase density and diameter on flow pattern transitions.
2) Variation of void fraction in different flow patterns.
3) Independent comparison work in the area of flow specific void fraction correlations.
4) Independent study of flow pattern independent correlations for void fraction in vertical upward two-phase flow, taking into consideration large number of correlations.

From the points mentioned above, it is clear that further study of flow patterns and void fraction in vertical upward two-phase flow is essential. It is also important to take independent, detailed and accurate data for flow patterns and void fraction. For this purpose, experimental work was carried out on vertical upward two-phase flow with the help of the experimental setup in Two-phase Flow Laboratory at Oklahoma State University. This setup was designed, constructed and validated by Cook (2008). The experimental set up is explained briefly in this chapter, with the help of thesis of Cook (2008). For more details, reader is advised to refer to Cook (2008).

3.1 Details of Experimental Setup

The set up is capable of taking experimental data for all the four aspects of two-phase flow – flow patterns, void fraction, pressure drop and heat transfer. Range of inclination of the experimental setup is from +90˚ to -90˚ from horizontal. Only flow patterns and void fraction were studied in the present work and details of the set up related to them are mentioned here. The experimental setup is shown in Figures 3.1 and 3.2. Figure 3.1 and Figure 3.2 show the schematic and photograph of the setup in +90˚ inclination, respectively.

The inside diameter of tube used in the experimental setup for flow pattern and void fraction studies is 0.0127 m. Material of the tubes is polycarbonate. Working fluids used for the experiments in the present study were air and purified water. Flow circuits for these two fluids are explained below.

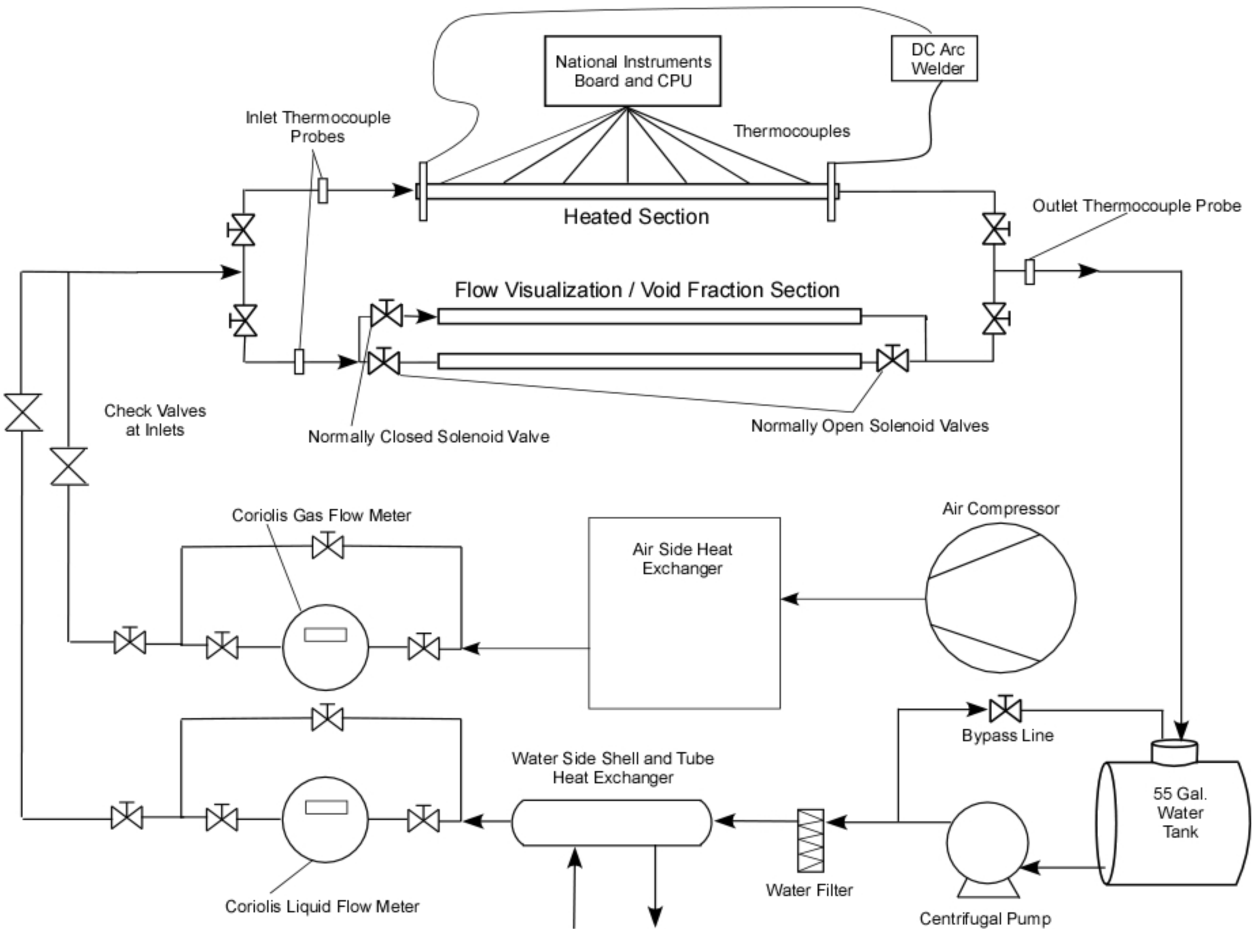


Figure 3.1 - Schematic of Experimental Setup (From Cook (2008))

Figure 3.2 - Photograph of Experimental Setup in +90 Deg Orientation (From Cook (2008))

2.3.5

3.1.1 Water Flow Circuit

As shown in Figure 3.1, purified water was stored in a cylindrical tank of 208.2L capacity. It was pulled from the tank by a centrifugal pump of Bell and Gosset (Series 1535, model number 3545 D10). At the pump outlet, water was purified by Aqua-Pure AP12T purification system. Then it was passed through a shell and tube heat exchanger (ITT model BCF 4063) and was cooled by tap water available in the test facility. Then the flow rate of water was measured with a coriolis flow meter of Emerson (Micro Motion Elite Series model number CMF 100). Flow of water was controlled by a gate valve placed after flow meter. Then water was mixed with air in the mixing section of the setup, which will be discussed later.

3.1.2 Air Flow Circuit

Compressed air was supplied by Ingersoll-Rand T30 Model 2545 air compressor. Then the air was filtered, dried and its pressure was regulated. Then air was passed through a copper coil submerged heat exchanger. The water used for cooling the air and purified water was taken from the same source which ensured that the temperatures of both purified water and air were very close before getting mixed in the mixing section. After passing through the heat exchanger, air was again dried and filtered and then the flow of air was regulated using a Parker (24NS 82(A)-V8LN-SS) needle valve. For both high and low air flow rates, Emerson (Micro Motion Elite Series model number CMF 025 and LMF 3M, respectively) flow maters were used. Then air was mixed with purified water in the mixing section, which will be discussed later.

3.1.3 Details of Test Section for Flow Visualization and Void Fraction

Details of the test section for taking flow visualization and void Fraction data are shown in Figure 3.3. It consisted of 4 components – mixing section, thermocouple array, void fraction system and flow visualization section. The four components are explained below.

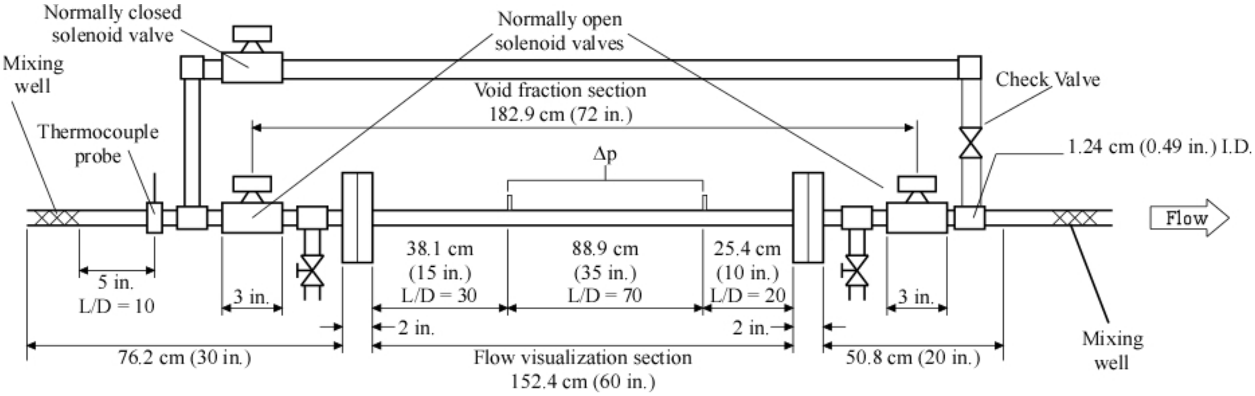


Figure 3.3 - Details of Test Section for Flow Visualization and Void Fraction (From Cook (2008))

<u>Mixing Section</u>

Two static mixers were used – one at the inlet and one at the outlet of flow visualization and void fraction section. Inlet mixer served two purposes. It ensured that the air and water flow at the inlet was mixed properly so that thermocouple sensing two-phase flow temperature at inlet measures a representative temperature of mixture. The other function of the mixer was to make sure that inlet geometry does not affect flow patterns. Mixer at the outlet served the first purpose mentioned above. Mixers at the inlet and outlet of this section were Koflo model 3/8-40C-4-3V-2.

Thermocouple Array

Thermocouple array for this section consisted of two thermocouple probes at inlet and outlet. Thermocouple probes used were Omega model TMQSS-06U-6. The two thermocouples measured inlet and outlet temperatures of the flow.

Void Fraction System

Using this void fraction system, two-phase mixture was trapped and volume of the liquid portion was measured. Volume of the void fraction section was 277.5 cc. Void fraction was then calculated by using the following equation.

$$Void\ Fraction = Volume\ of\ void\ fraction\ section - Volume\ of\ liquid\ collected$$

Three quick closing solenoid operated valves were utilized to trap two-phase mixture flowing through pipe, as shown in Figure 3.3. Two normally open valves were placed at the inlet and outlet. A normally closed valve was placed in bypass line to control entry of fluid into bypass line. When the solenoid valves were triggered, two normally open valves closed and the normally closed valve opened and two-phase flow sample was trapped in the void fraction section and air-water flow continued to flow from bypass line. Backflow from main line into the exit of bypass line was prevented by using a check valve. Quick closing valves were W. E. Anderson model ABV1DA101 pneumatic ball valves. The time of activation of these valves was 0.03 seconds. The solenoid controllers used along with the pneumatic ball valves were manufactured by Dynaquip Controls with a designation of 14570.01.

Liquid and gas mixture captured in the void fraction section was drained into an 8 L tank of high density polyethylene manufactured by Nalgene, using 3.175 mm diameter ball valves. Clear PVC tubes were connected between ball valves and the Nalgene tank, which carried the two-phase mixture from void fraction section to the tank. In order to ensure maximum collection of liquid into the tank, compressed air was passed through the PVC tubes. Length of void fraction section was 219.075 cm.

The ranges and accuracies of the equipments and instrumentations described above are given in Table 3.1.

Table 3.1 - Ranges and Accuracies of Equipments and Instrumentations

Equipment / Instrument	Range	Accuracy
Bell and Gosset series 1535 centrifugal pump (model 3545 D10)	0 – 0.226 kg/s	--
ITT model BCF 4063 shell and tube heat exchanger	0 – 19.7 kW	--
Ingersoll-Rand T30 Model 2545 air compressor	0 – 125 psi, 0 - 0.0042 kg/s	--
Micro motion coriolis flow meter for water (model CMF 100)	7.5555 kg/s	±0.05%
Micro motion coriolis flow meter for air (model LF)	0.000029 – 0.00101 kg/s	±0.5%
Micro motion coriolis flow meter for air (model CMF 025)	0.6055 kg/s	±0.35%
Absolute pressure transducer	0 – 50 psia	0.25% BSFL
Thermocouple probes used are Omega model TMQSS-06U-6	-250 to 350 ˚C	Greater of ±1 ˚C or ±0.75%

BSFL – Best Fit Straight Line

Flow Visualization Section

The central portion of void fraction section was used for flow visualization. Its length was 152.4 cm. It was made up of optically clear polycarbonate tubing. The optical clarity of tubing ensured easy flow visualization and clear photographs.

3.1.4 Data Acquisition System

Data was recorded with the help of National Instruments Data Acquisition system. The data was stored on a dedicated computer in the laboratory. The data acquisition system consisted of three major components – chassis, modules and terminal blocks.

The chassis was used as the housing for the components in data acquisition system. Model number for chassis was SCXI 1000. Modules were connected to chassis and performed the signal conditioning process. Two 32 channel analog modules and one 8 channel analog module were used. Model number for 32 channel module was SCXI 1102 and that for 8 channel module was SCXI 1125. Terminal blocks were connected to the other end of modules. Terminal blocks were connected directly to the devices being monitored. Model numbers for terminal blocks connected to 32 and 8 channel modules were SCXI 1303 32 and SCXI 13138, respectively. Finally, LabVIEW was used as graphical interface program for data acquisition process. The program was written by Jae-yong Kim (former Ph.D. student in the two-phase flow laboratory) and then modified by Clement Tang (current Ph.D. student in the Two-phase Flow Laboratory) to suit the experimental setup.

3.2 Procedure for Flow Visualization and Void Fraction Data

3.2.1 Procedure of Flow Visualization

Three methods were used for flow visualization:

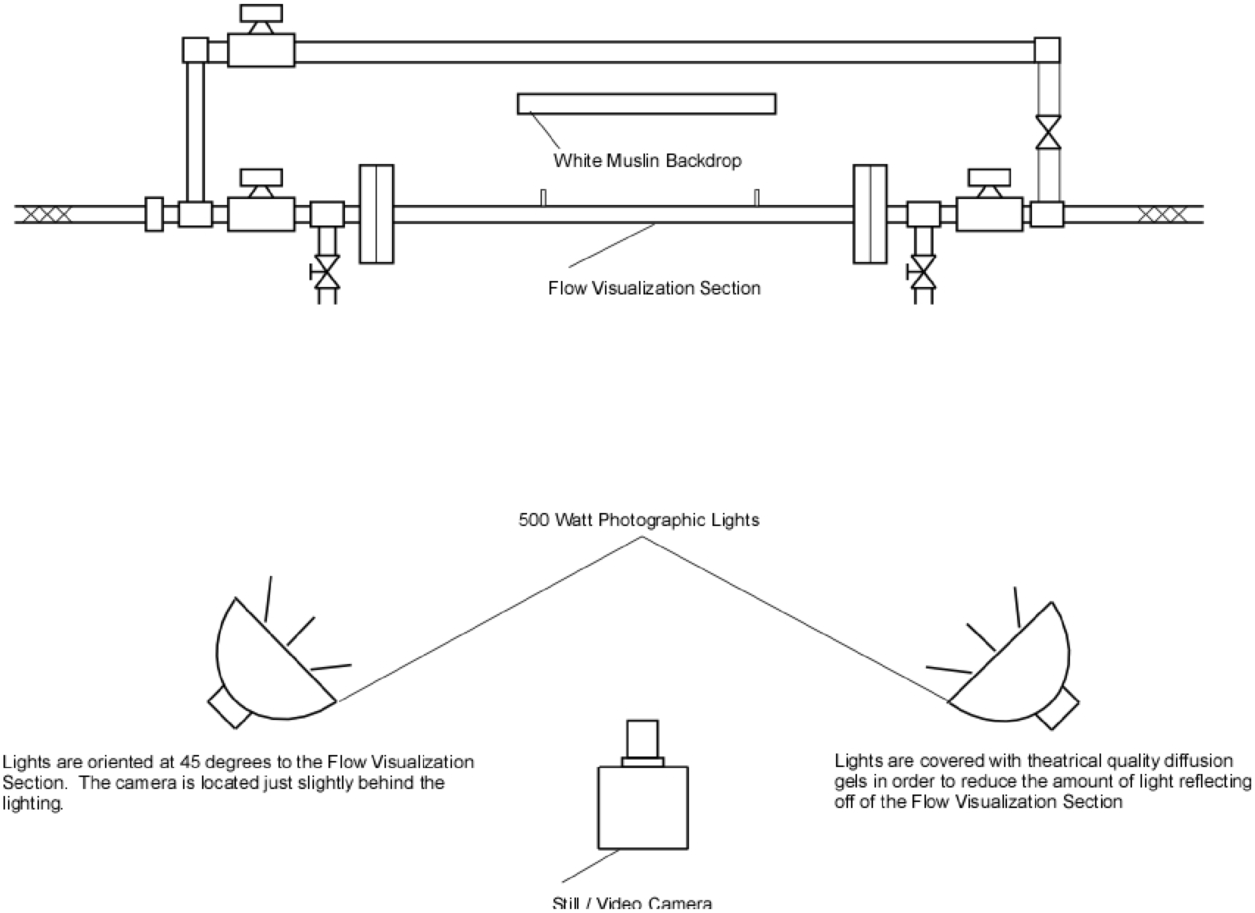
1) Visual Observation
2) Photographs
3) Videos

Visual observation was done for every reading of flow pattern and void fraction. Flow patterns were visualized more than one time and at different hours to ensure repeatability and consistency in definition of the flow patterns. Especially, flow patterns near transition were checked again and again to locate transitions. It should be noted that flow regime identification was a challenging task. Definitions of all the flow patterns were available from the literature (with some level of variation amongst various researchers) but recognizing the flow pattern flowing inside the tube was difficult. Therefore, deciding on the flow pattern for all the data points required considerable amount of time.

Photographs and videos were used as supplementary techniques. But, for high velocity two-phase flow, photographs and videos had limited utility. Even using high resolution and high frame rate cameras, photographs and videos were not convincing enough for high velocity flow patterns. Therefore, most of the decisions for flow patterns were made by visual observation. Specifications of photo and video camera are given below:

- Photography camera: Nikon D50 digital SLR, shutter speed 1/4000th of a second, 6 megapixels.
- Video Camera: Sony DCR-VX2100 digital video recorder, shutter speed 1/10,000th of a second, frame rate 1/60th of a second, 3.8 megapixels.

A detailed study on procedure for taking photographs and videos was done by Cook (2008) and therefore the procedure suggested by him was followed. Setup for taking photographs is shown in Figure 3.4.



Lights are oriented at 45 degrees to the Flow Visualization Section. The camera is located just slightly behind the lighting.

Lights are covered with theatrical quality diffusion gels in order to reduce the amount of light reflecting off of the Flow Visualization Section

Figure 3.4 – Setup for Photographs and Videos (From Cook (2008))

Two lights with 500 Watt rating were placed at 45˚ angles to the flow visualization section. For diffusing the light, Roscolux #105 Tough Spun Gel diffusers were placed in front of lights. The 45˚ angle and diffusers guaranteed that there was minimum effect of glare and shadows. Camera was placed just behind the lights so that reflections of the camera and operator were minimal. A white muslin cloth was used as backdrop for flow visualization section to ensure a bright, crisp and non-reflective background.

3.2.2 Procedure for Void Fraction Data

Elaborate procedures for pre-operations check-ups, system warm-up, flow visualization and void fraction were documented by Cook (2008). The procedures were meticulously followed for each run to ensure uniformity in each reading.

For the data collection during this study, following criteria was used.

Case 1

If two consecutive readings were within the acceptable tolerance, they were averaged to get one representative reading for the flow conditions.

Case 2

If two consecutive readings did not fall within acceptable difference, third reading was taken. If two of the three readings were within acceptable tolerance, the remaining reading was not considered and an average of the selected two was taken as one representative data point for the flow conditions.

Case 3

Due to dynamic nature of two-phase flow, acceptable difference was not achieved sometimes. Therefore, if two of the three consecutive readings were not within the acceptable tolerance, readings were taken on another day / hour with the same values of liquid and gas mass flow rates.

Acceptable tolerance or difference was decided based on an error of 5%; i.e. if the second reading was within 5% difference of the first reading, then the two readings were averaged. Therefore, for higher liquid hold up (low void fraction), absolute difference between the two readings was higher than the absolute difference between readings for low liquid hold up.

Cases 1, 2 and 3 were the only possible cases for achieving accurate values of void fraction. After deciding upon the value of void fraction, trend of void fraction was observed by plotting values of void fraction against gas mass flow rate (m_G) for constant liquid mass flow rate (m_L). Generally, void fraction increased with increase in gas mass flow rate for a constant liquid mass flow rate. If some of the data points did not follow the trend, those data points were visited again on a different day to see whether the points followed the trend. For all such cases, data points were found to follow the trend in the next iteration of void fraction.

3.3 Accuracy of Flow Pattern and Void Fraction Readings

Sophisticated equipments and instrumentation used in this experimental setup assured accurate values of void fraction. Cook (2008) carried out uncertainty analysis for void fraction data taken on the same set up. He found out that uncertainty associated with high void fraction (0.8639) data point and low void fraction (0.2836) data point was as low as 1.25% and 4.16%, respectively. In the literature studied, only Chexal et al. (1991) reported the uncertainty associated with the data used and its value was 5%. Therefore, it can be concluded that the uncertainty in the void fraction data collected was significantly low. For flow pattern, there was no parameter which could define goodness of data.

3.3.1 Accuracy of Flow Pattern Readings

Flow pattern visualization data was compared with the data of other researchers from the literature. Comparison of sample points is shown in Table 3.2.

It can be understood that exact comparison between two researchers was not possible because of the different conditions (For example, mass flow rates, velocities, temperatures) used. But, for the study of flow patterns, data from Table 3.2 shows an acceptable comparison.

Table 3.2 – Comparison of Flow Pattern Data with Other Researchers

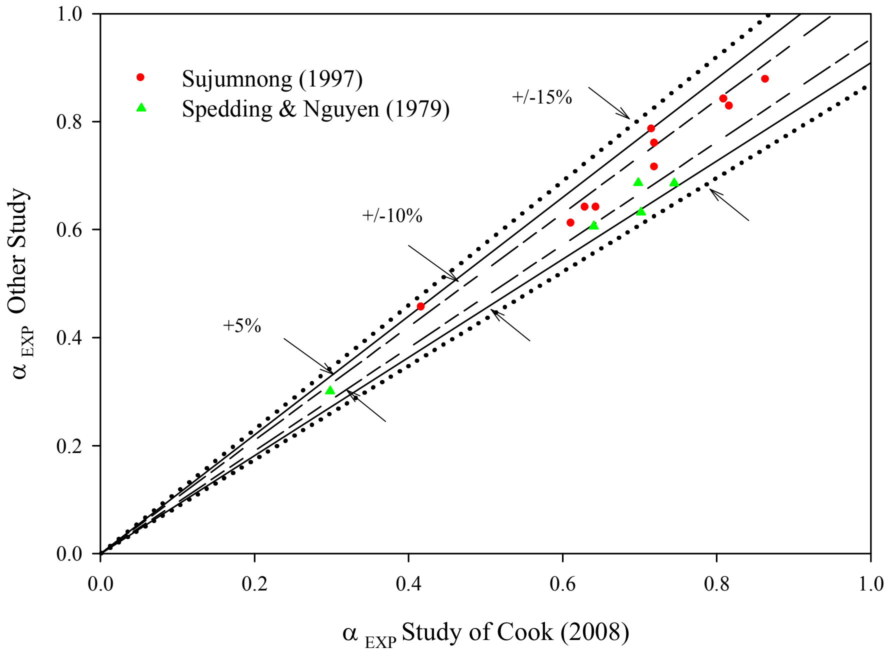
Flow Pattern	Superficial Gas / Liquid Velocity (m/s)		
	Present study	Fernandes (1981)	Sujumnong (1997)
Bubble	0.41 / 1.02	0.42 / 1.01	NA
Slug	0.6 / 0.31	0.76 / 0.322	0.59 / 0.311
Churn	2.35 / 0.084	3.5 / 0.099	2.84 / 0.116
Annular	12.3 / 0.16	13.4 / 0.1	13.945 / 0.116

NA – Comparable Gas and Liquid Velocities Were Not Available

3.3.2 Accuracy of Void Fraction Readings

Cook (2008) did the comparison between void fraction data taken on this setup and data of other researchers and correlations in the literature. He compared data collected for vertical upward orientation with the data of Sujumnong (1997) and Spedding and Nguyen (1976) and found that only 1 out of 19 data points fell outside ±15 % error. The comparison done by Cook (2008), with the data of other researchers is shown in Figure 3.5. The comparison between experimental data of Cook (2008) and Spedding and Nguyen (1976) was based on mass flow rates and that between Cook (2008) and Sujumnong (1997) was based on superficial velocities.

He also compared his experimental data (33 points) with the correlations of Rouhani and Axelsson (1970), Morooka et al. (1989), Dix (1971) and Woldesemayat and Ghajar (2007). Rouhani and Axelsson (1970) and Morooka et al. (1989) predicted 76% of the data points within ±15% and Dix (1971) and Woldesemayat and Ghajar (2007) predicted 91% of the data points within ±15% error.



3.5-Comparison of Experimental Data of Cook (2008) and Sujumnong (1997) and Spedding and Nguyen (1976)

For the data collected in this study, similar comparison was done and results were in good agreement. Comparison with the data of Spedding and Nguyen (1976) is shown in Table 3.3. Exact comparison was not possible because of the different conditions used in present and other experimental data. Comparison on the basis of gas and liquid mass fluxes was approximate, but it gave a good idea that the results were in-line with the results of other researchers.

Table 3.3 – Comparison of Void Fraction data with Spedding and Nguyen (1976)

Superficial Gas / Liquid Mass Flux (kg/s-m^2)		Void Fraction	
Present study	Spedding and Nguyen (1976)	Present study	Spedding and Nguyen (1976)
3.2 / 162.9	2.77 / 165	0.7232	0.632
6 / 157.4	5.5 / 165	0.7358	0.686
5.9 / 730. 6	5.54 / 720.3	0.6223	0.637
3.1 / 1007.4	3.4 / 974.5	0.5088	0.520
6 / 1161.8	5.5 / 1134.5	0.5484	0.572
1.7 / 1588	1.85 / 1688.3	0.3196	0.298

Comparison of 30 data points was done with the correlations of Rouhani and Axelsson – I, Dix (1971) and Woldesemayat and Ghajar (2007). These correlations are represented by equations (2.124), (2.102) and (2.117), respectively. Measured and predicted data is shown in Figure 3.6.The comparison was satisfactory for the sample considered because most of the data points were predicted within ±15% error band by all the correlations. Thus, it was ensured that the void fraction data collected was in good agreement with the established correlations in the literature.

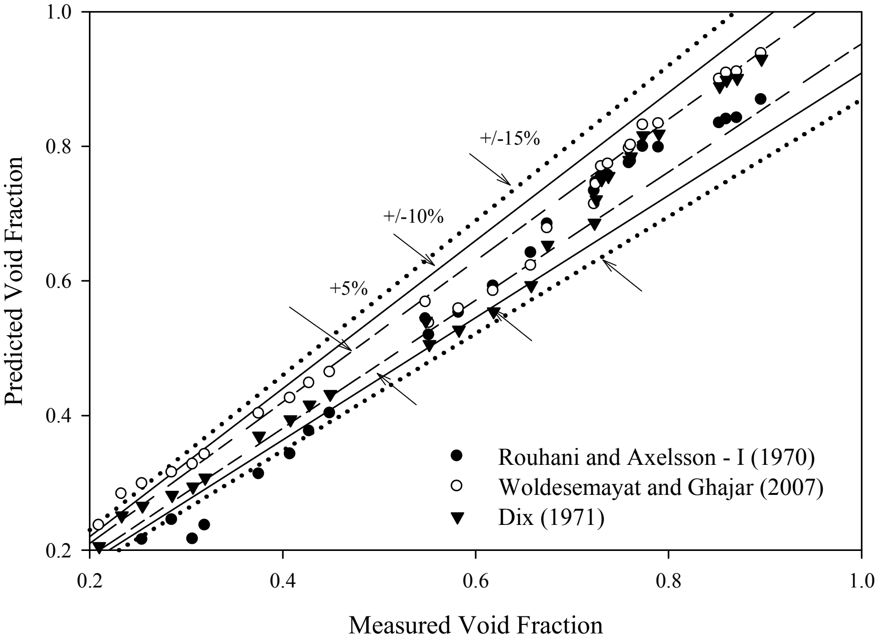


Figure 3.6 – Comparison of Experimental Data with Correlations in Literature

CHAPTER IV

FLOW VISUALIZATION AND FLOW PATTERN TRANSITIONS

Flow pattern recognition is important because behavior of void fraction, pressure drop and heat transfer depends on the type of flow pattern. Based on flow pattern observation, flow map can be developed for a given system. After developing flow map for a particular two-phase flow system, correlations for prediction of void fraction, pressure drop and heat transfer in a flow pattern can be used to calculate their values. For example, to find value of void fraction in slug flow, a correlation developed for prediction of void fraction in slug flow can be used. In this study, flow patterns were recognized by visual observation aided with photographs and videos.

Different flow patterns were identified based on the different configurations in which the two phases positioned themselves inside the tube. Five distinct flow patterns were observed during the present study: Dispersed Bubble, Slug, Churn, Froth and Annular. Moving from low gas flow rate to high gas flow rate, the two phases are separated in axial direction (slug flow) at the beginning and end up having radial separation (annular flow). For intermediate gas flow rates, liquid and gas phases are intermingled and can have radial or axial separation at the same time. If liquid flow rate is increased keeping a low gas flow rate, the two phases loose the axial separation (slug/churn flow) and gas phase gets dispersed in liquid in the form of small bubbles (dispersed bubble) or gets mixed with liquid causing the flow to move randomly inside the tube (froth). Figure 4.1 shows the flow patterns observed in the present study and vertical two-phase flow in general. In the following sections, definitions and characteristics of all the flow patterns are discussed.

4.1 Descriptions of Flow Patterns

4.1.1 Dispersed Bubble Flow

Among bubble (bubbly and dispersed bubble) flow types, only dispersed bubble flow pattern was observed during the experiments. In dispersed bubble flow pattern, gas phase is in the form of very small bubbles, dispersed uniformly throughout liquid phase. Dispersed bubble flow is observed at high liquid and low gas flow rates. There is a possibility of getting bubbly flow if gas flow rate is decreased to a very low value (less than that for slug flow) at low liquid flow rates, but it could not be achieved in the present case due to limitations of available mass flow meters (Micro Motion Elite Series CMF025 and LMF 3M) required for very low flow rates.

Taitel et al. (1980) developed an equation for the possibility of observing bubbly flow in tubes. According to them, bubbly flow cannot take place in small diameter tubes. Small tubes are defined by equation (4.1)

$$\left(\frac{\rho_L{}^2 g D^2}{(\rho_L-\rho_G)\sigma}\right)^{1/4} \leq 4.36 \tag{4.1}$$

For air-water two-phase flow, the limiting tube diameter according to the above equation is approximately 0.05 m. But, Sujumong (1997) observed bubbly flow in a 0.0127 m diameter tube. According to the observations during the present study with a 0.0127 m diameter tube, there is a possibility of occurrence of bubbly flow in the present experimental set up. Merging of small bubbles was observed in dispersed bubble flow even at high liquid flow rates. At low liquid flow rates, gas flow rate required for bubbly flow region could not be achieved, but some bubbles were observed near the start of slug flow region, at low gas flow rates.

4.1.2 Slug Flow

Slug Flow occurs at low liquid mass flow rate and low gas mass flow rate. It is a very structured and calm flow. Liquid flows in the form of 'slugs' and gas flows in the form of cylindrical bubbles with nose, called 'Taylor bubbles'. Taylor bubbles, due to their higher velocity, force the liquid in front of them towards the wall and it falls down around the Taylor bubbles in the form of film. For low liquid flow rates, the length of Taylor bubbles is large and becomes smaller as the liquid flow is increased maintaining gas flow rate. This phenomenon is shown in Figure 4.2. Detailed study of length of slug unit, Taylor bubbles, liquid slugs and void fraction in liquid slugs have been done by several of researchers, but it is not a part of this study. At the upper end of gas flow for which slug flow is observed, there is small amount of churning at the bottom of the flow visualization section. Churning is a kind of "fighting" between the falling film and gas flowing upwards when they encounter each other. Gas hinders the motion of falling film. The film is held by the gas and merges with the next upward flowing liquid slug.

4.1.3 Churn Flow

Churn flow takes place when gas flow rate is increased further maintaining the liquid flow rate. There are no Taylor bubbles in case of churn flow. The gas phase is present in the form of voids which are separated by slugs of small length. Falling film is present in churn flow. It gets accumulated, bridges the pipe and forms a liquid slug of small length which is lifted upwards by high velocity gas pocket. The flow is oscillating because of the upward and downward movement of small liquid slugs, which are lifted by gas and fall down. As shown in Figure 4.1, the liquid and gas phases are still separated from each other in the axial direction.

Existence of churn flow is challenged by some of the researchers. Taitel et al. (1980) defined churn flow as an entry length phenomenon. They postulated that a stable slug flow will be observed if sufficient length of pipe is available. According to them, churn flow region is expected to shrink and finally disappear as the L/D ratio for tube increases. They reported that entry length for churn flow depends upon the flow rates of fluids and the pipe diameter. The equation proposed by Taitel et al. (1980) is

$$\frac{L_E}{D} = 40.6\left(\frac{U_M}{\sqrt{gD}} + 0.22\right) \tag{4.2}$$

So, in a pipe of 0.05 m diameter in which water flows with a superficial velocity of 1 m/s, churn flow is expected to vanish in approximately 940 diameters. But, Taitel et al. (1980) have given no experimental evidence apart from visual observation to support this theory.

Mao and Dukler (1993) also challenged the existence of ‘churn’ flow pattern. They concluded that churn flow is just an extension of the slug flow. Following evidences were provided to support their conclusion.

1) They observed that the length of the slug reduces as the gas flow is increased for constant liquid flow rate and then the flow “looks” like churn flow. They studied the axial profile of local void fraction in slug and churn flows with the help of

a) b) c) d) e)

Figure 4.1 - Flow Patterns in Vertical Two-phase Flow a) Dispersed Bubble b) Slug c) Churn d) Froth e) Annular

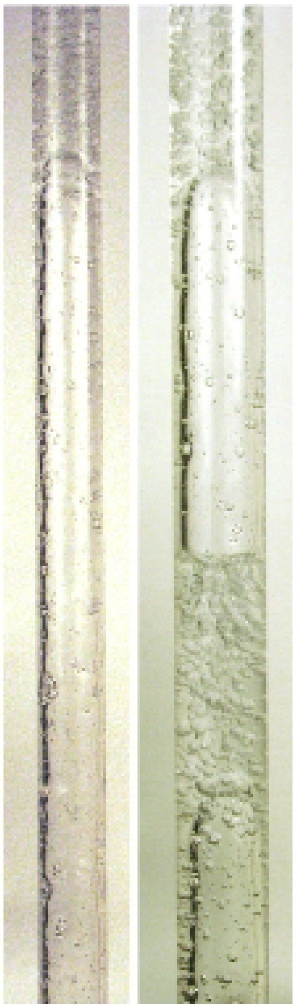


Figure 4.2 - Change in length of Taylor bubbles with increase in liquid flow

0.0506 m diameter pipe and showed that the void fraction profiles are same for both flows.

2) They used wire conductance probes to measure the average propagation velocity for more than 200 Taylor bubbles and liquid slugs. The direction (upward or downward) in which the slug moves was also determined for visually observed slug and churn flows. They showed that when churn flow was observed visually, the slugs appeared to be oscillating, but the down flow (downward movement of

slugs) for slug and churn flow was 0.9% and 1.7%, respectively; too small a difference to identify them as distinct flow patterns.

3) With the help of radio frequency probes and conductance probes, the thickness of the liquid film surrounding the Taylor bubble was compared for slug and churn flows. According to their observations, the axial profiles of film thickness were similar for both flows.
4) They used data of Fernandes (1981) and showed that the predictions of void fraction for churn flow, using the correlation for slug flow suggested by Fernandes et al. (1983), were accurate to within ±6%, with a standard deviation of 5.3%.

Mao and Dukler (1993) stated that the visual observation of the two-phase flow is very deceptive and tried to explain the probable cause of confusion between slug and churn flows. According to them, the oscillating motion of the churn flow is seen because of the shear layer formed between the downward falling film and upward moving slug. The shear layer is disturbed and contains a large amount of gas bubbles, which causes the illusion of chaotic flow. Shear layer is destroyed due to interaction with liquid-slug in slug flow, but maintains its continuity in case of churn flow, causing the illusion.

Contrary to this, many other researchers (For example, Oshinowo and Charles (1974), Bilicki and Kestin (1987), Spedding et al. (1998), Zhihua et al. (2006)) have reported churn (some researchers call it froth with same definition) flow as distinct flow pattern in their experimental work. Some researchers like Tangesdal et al. (1999) have studied churn flow exclusively.

As reported by Jayanti and Hewitt (1992), Owen (1986) observed the churn flow even at L/D=560, when the calculated entry length according to Taitel et al. (1980) theory was between L/D = 200 to 360. Thus, the entry flow mechanism proposed by Taitel et al. (1980) is challenged by this work. Jayanti and Hewitt (1992) also made an important note that practically there will be no application for which L/D will be greater than 600. Hence, churn flow should be treated as distinct flow.

Visual observation during the present study confirms that upward and downward chaotic movement of liquid-slug really takes place during churn flow. This movement is well exaggerated and cannot be confused with the shear layer, as mentioned by Mao and Dukler (1993).

Thus, it can be concluded that churn flow exists as a distinct flow pattern and it is not an entry length phenomenon.

4.1.4 Froth Flow

Froth flow takes place when gas flow rate is increased further. The gas and liquid phases are intermingled with each other and have no continuity. Flow has a frothy appearance. The overall direction of the flow is upwards only and there is no falling film. Froth flow may be considered as very high frequency churn flow. Froth flow takes place either by churn-froth or bubble-froth transition. For churn-froth transition, gas flow rate should be high enough to lift the liquid film in churn flow continuously. Increasing gas flow rate further, causes gas and liquid phases to mix with each other. For bubble-froth transition, gas content should be high enough to cause bubble coalescence. Liquid flow rate in bubble-froth transition is so high that stable cap shaped or Taylor bubbles cannot form by bubble coalescence and hence the bubbles unite and from gas pockets, which mix with the liquid and then flow as a frothy mixture. If not observed carefully, this flow could be confused with annular flow at higher gas flow rates.

Most of the researchers have reported only bubble, slug, churn and annular flow patterns. Froth flow is considered as a part of churn flow region by most of the researchers. Sometimes, froth and churn flow are used synonymously. But, frequent references to froth flow are made in the literature. Aggour and Sims (1984), Sujumnong (1997) observed froth flow in their laboratory in a 0.0127m diameter tube for air-water flow. Oshinowo and Charles (1974), Taitel et al. (1980) and Brauner and Barnea (1986) have mentioned occurrence of froth flow at high liquid flow rates. Description of semi-annular flow given by Spedding et al. (1998) is exactly similar to froth flow defined above. In the present study, froth flow has emerged as an independent flow pattern with entirely different structure than churn flow. Due to difference in flow structure; void fraction, pressure drop and heat transfer in froth flow could be entirely different than churn flow. Behavior of void fraction for froth flow is discussed in the Chapter 6. Comparison between pressure drop and heat transfer in churn and froth flows are important topics for further study. It is important to mention here that froth flow is observed over a wide range of liquid and gas flow rates.

4.1.5 Annular Flow

Annular flow takes place when the liquid and gas phases are separated in radial direction; i.e. gas forms the central core and liquid adheres to the wall in the form of a film. Annular flow takes place at very high gas flow rates. Annular flow is described or classified as annular-mist flow by Mukherjee (1979), Sujumnong (1997), Bilicki and

Kestin (1987), Hlaing et al. (2007). But, this classification is not done in the present study.

Flow patterns observed for various liquid and gas flow rates during present study are tabulated in Table 4.1.

4.2 **Transitions in Flow Patterns**

There were four transitions in flow patterns observed during present study.

1) Slug-Churn

2) Chun-Froth

3) Churn/Froth-Annular

4) Dispersed Bubble-Froth

Figure 4.3 shows experimental transitions observed during present study.

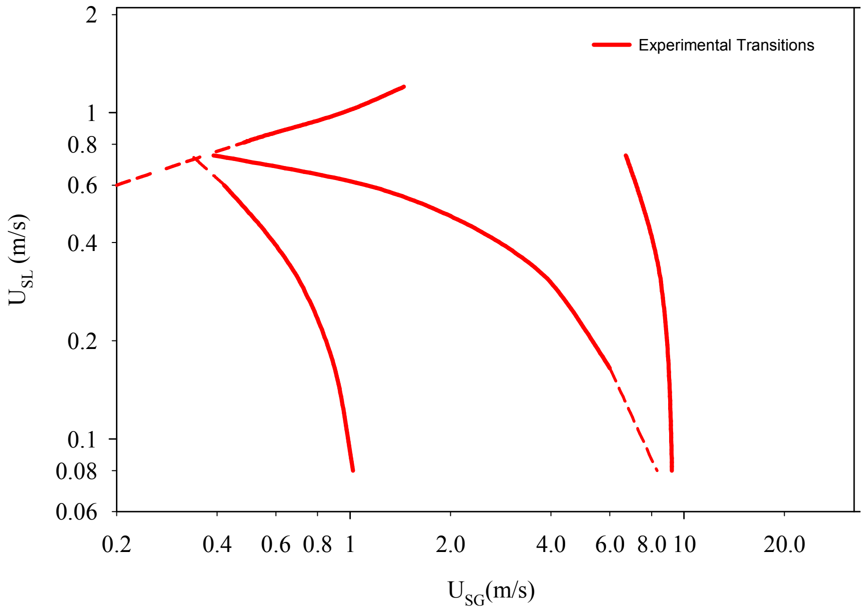


Figure 4.3 - Experimental Transition Boundaries of Flow Patterns

Experimental transitions were determined by observing flow patterns and marking the points in superficial gas velocity and superficial liquid velocity plane. Transition lines in Figure 4.3 separate two clearly identifiable flow patterns.

Out of these transitions, only slug-churn and churn/froth-annular transitions are discussed in abundance in the literature. Many theories are proposed for these two transitions. Churn-froth and bubble-froth transition were not studied by researchers in the past. In the following sections, experimental slug-churn and churn/froth-annular transitions will be compared with the theories proposed in the literature and churn-froth and bubble-froth transitions will be discussed in detail. An effort will be made to come up with underlying phenomenon behind all the transitions.

4.2.1 Slug-Churn Transition

Many researchers (For example Taitel et al. (1980), McQuillan and Whalley (1985)) have reported transition from slug to churn flow, in which the Taylor bubbles first get distorted and then no longer seen. This type of transition was also observed in the present study. When gas flow rate is increased after stable slug flow, the shape of Taylor bubbles starts to distort and then, instead of Taylor bubbles, gas voids are observed flowing along with liquid slugs. So, absence of clearly defined Taylor bubbles should be considered as the start of transition. When gas flow rate is increased further, oscillating liquid slugs of small length are observed. This oscillating flow is an indicator of end of transition and start of churn flow region.

The theoretical prediction of flow pattern transition is important as it provides a tool to decide flow patterns for given operating conditions without actually observing the flow pattern. The theories are independent of geometry of test set-up, fluids used and mass flow rates of fluids. But, till date there is no universally accepted theory for flow pattern transitions. This is because of the difference in flow pattern terminology and theories satisfying different data sets. In this section, an attempt is made to compare and contrast different theories proposed for slug-churn transition.

Table 4.1 - Observed flow patterns during present study for various liquid and gas flow rates

Liquid Mass Flow Rate (kg/min)	Liquid Superficial Velocity (m/s)	Dispersed Bubble	Slug	Churn	Froth	Annular
0.6	0.08	NA	Observed	Observed	Not Observed	Observed
1.2	0.165	NA	Observed	Observed	Observed	Observed
2.3	0.31	NA	Observed	Observed	Observed	Observed
3.4	0.46	NA	Observed	Observed	Observed	Observed
4.5	0.6	NA	Observed	Observed	Observed	Observed
5.6	0.74	Observed	Observed	Not Observed	Observed	Observed
6.1	0.81	Observed	Not Observed	Not Observed	Observed	NA
6.6	0.87	Observed	Not Observed	Not Observed	Observed	NA
7.7	1	Observed	Not Observed	Not Observed	Observed	NA
8.8	1.2	Observed	Not Observed	Not Observed	Observed	NA

NA – Not Available - Limitations on range of gas flow meters at very low and very high flow rates

4.2.2 Comparison of Slug-Churn Transition Theories with Experimental Data

In Figure 4.4, prediction of slug-churn transition by theories is compared with the present experimental results. Only Brauner and Barnea (1986), Taitel et al. (1980), McQuillan and Whalley (1985) and Jayanti and Hewitt (1992) predict correct trend of transition. Mishima and Ishii (1984), Tangesdal et al. (1999), Chen and Brill (1997) provide an incorrect prediction of slug-churn transition, predicting increasing superficial gas velocities with increasing superficial liquid velocities. Brauner and Barnea (1986) predict a transition at much higher superficial gas velocity than observed experimentally.

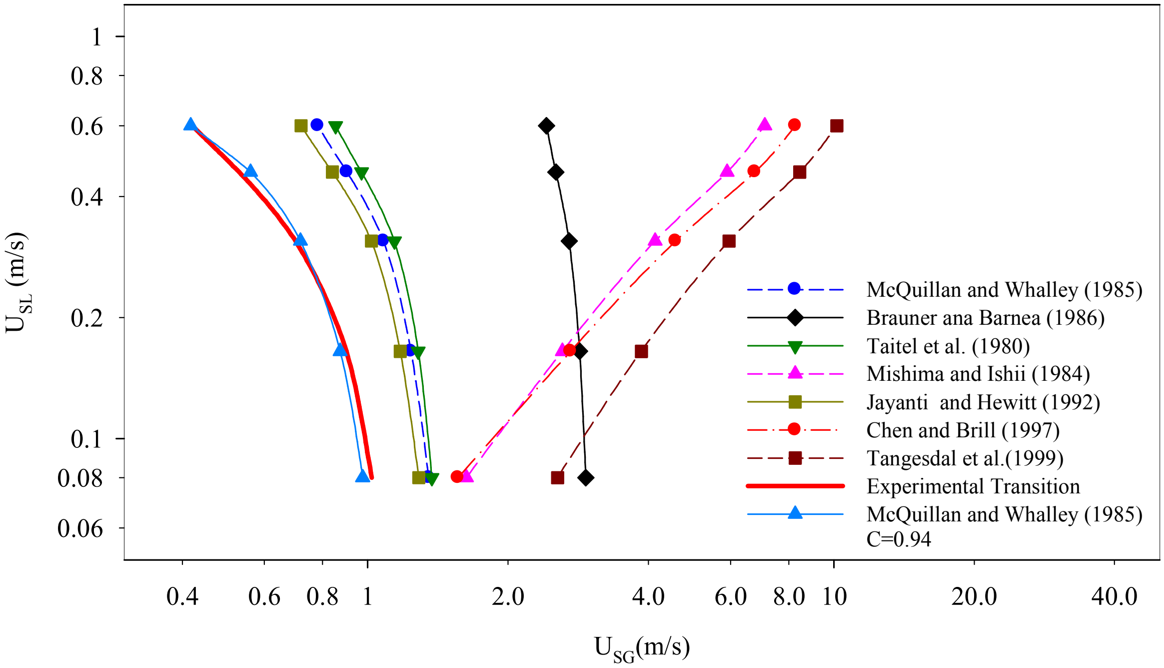


Figure 4.4 - Comparison of slug-churn transition theories with experimental data

McQuillan and Whalley (1985), Jayanti and Hewitt (1992) and Taitel et al. (1980) predict transition most satisfactorily. Experimental and predicted values of superficial gas velocities at transition for respective superficial liquid velocities are compared in Table 4.2. It can be seen that percentage errors are high even for the best prediction theories. It is also observed that absolute errors in prediction of transition velocities are not high considering the dynamic phenomenon of two-phase flow, but further analysis of the prediction is needed.

It is evident from the above data that flooding mechanism (Jayanti and Hewitt (1992), McQuillan and Whalley (1985)) gives the best prediction. Their expression for flooding mechanism is

$$\sqrt{U^*_{SG}} + \sqrt{U^*_{SL}} = C \tag{4.3}$$

Non-dimensional velocities U^*_{SG} and U^*_{SL} depend upon fluid densities, diameter and respective superficial fluid velocities. The value of constant *C* suggested by McQuillan and Whalley (1985) is 1. But, from expressions for U^*_{SG} and U^*_{SL}, it is clear that this value cannot be used for all pipe diameters.

Table 4.2 - Comparison of McQuillan and Whalley (1985), Jayanti and Hewitt (1992) and Taitel et al. (1980) Slug-churn Transition Theories with Experimental Data.

U_{SL} (m/s)	U_{SG} (m/s)				% Error in prediction		
	Experimental	Taitel et al. (1980)	McQuillan and Whalley (1985)	Jayanti and Hewitt (1992)	Taitel et al. (1980)	McQuillan and Whalley (1985)	Jayanti and Hewitt (1992)
0.0800	1.02	1.37	1.35	1.29	34.31	32.35	26.47
0.165	0.9	1.28	1.24	1.17	42.22	37.78	30.00
0.31	0.7	1.14	1.08	1.02	62.86	54.28	45.71
0.46	0.53	0.97	0.90	0.84	83.02	69.81	58.49
0.6	0.42	0.85	0.78	0.72	102.38	85.71	71.43

Hence, superficial gas velocities were calculated utilizing different values of *C*, which resulted in much more accurate prediction of transitions. For a value of *C=0.94*, the experimental and theoretical values are compared in Table 4.3. Figure 4.5 shows a comparison between experimental and theoretical transition for *C=0.94*. There is a considerable improvement in the prediction of transition boundary. Thus, the value of constant *C* has a dominant effect on prediction of transition and hence effect of value of *C* was determined for other datasets. Comparison of Taitel et al. (1980) data (0.025m diameter pipe) with McQuillan and Whalley (1985) model is shown in the Figure 4.6. Slug-churn transition is compared with theoretical transition values for different values of *C*.

Table 4.3 - Percentage Error in Prediction of Slug-churn Transition for McQuillan and Whalley (1985) using C = 0.94.

U_{SL} (m/s)	U_{SG} (m/s)		% Error
	Experimental	C=0.94 McQuillan and Whalley (1985)	
0.08	1.02	0.9754	-4.37
0.165	0.9	0.8725	-3.06
0.31	0.7	0.7171	2.44
0.46	0.53	0.5604	5.73
0.6	0.42	0.4171	-0.69

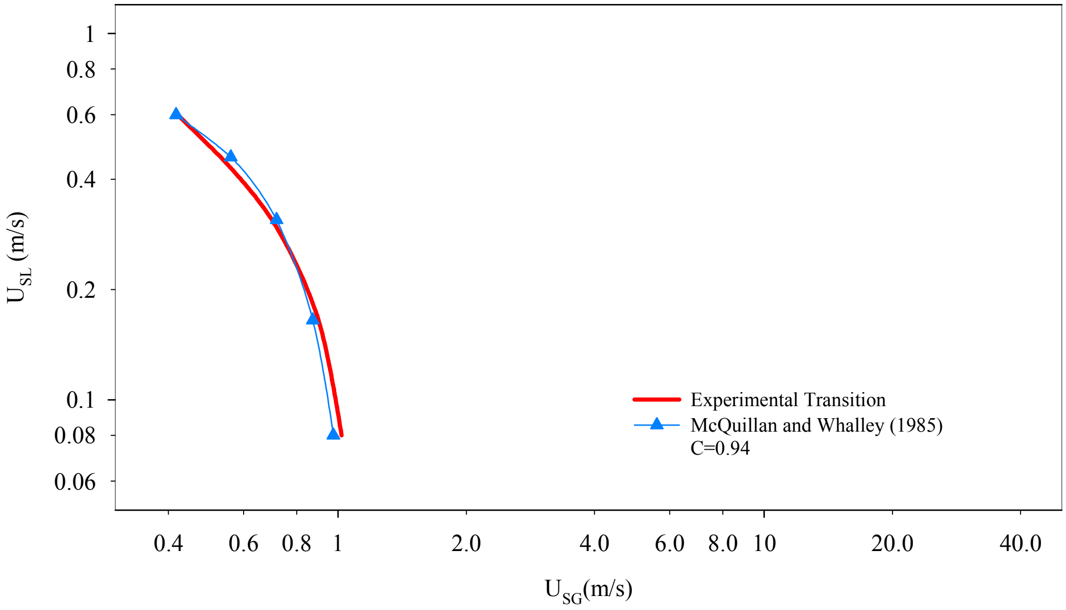


Figure 4.5 - Comparison of McQuillan and Whalley (1985) Slug-churn Transition (C=0.94), with Experimental Data

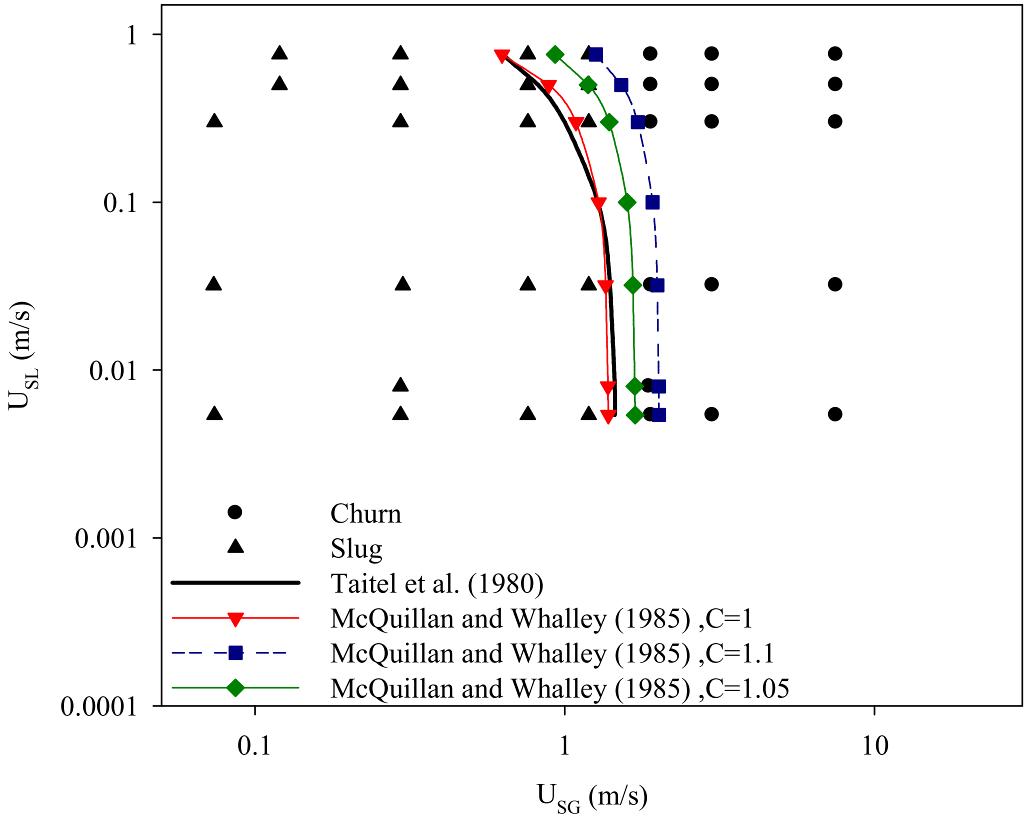


Figure 4.6 - Comparison of McQuillan and Whalley (1985) Slug-churn Transition Theory with Taitel et al. (1980) Data for 0.025 m Diameter Pipe

For *C*=1, prediction of McQuillan and Whalley (1985) is close to the theory of Taitel et al. (1980). But, there is under-prediction of transition at higher superficial liquid velocities. For *C*=1.1, theory of McQuillan and Whalley (1985) predicts transition at higher velocities than experimental transition. For *C*=1.05, prediction is optimum. Transition superficial gas velocity is correctly predicted for all the superficial liquid velocities.

Experimental data of Fernandes (1981) for slug-churn transition (0.051 m diameter pipe) is compared with prediction of McQuillan and Whalley (1985) for *C* = 1 and 1.1. The results are shown in Figure 4.7. Based on the comparison, it can be concluded that value of *C*=1.1 gives a better prediction, encompassing all the transition points. For *C*=1, theory of McQuillan and Whalley (1985) under-predicts the transitions. For *C*=1.05, the theoretical transition curve falls into experimental slug-churn transition zone, but, transition for higher superficial liquid velocities is not predicted well.

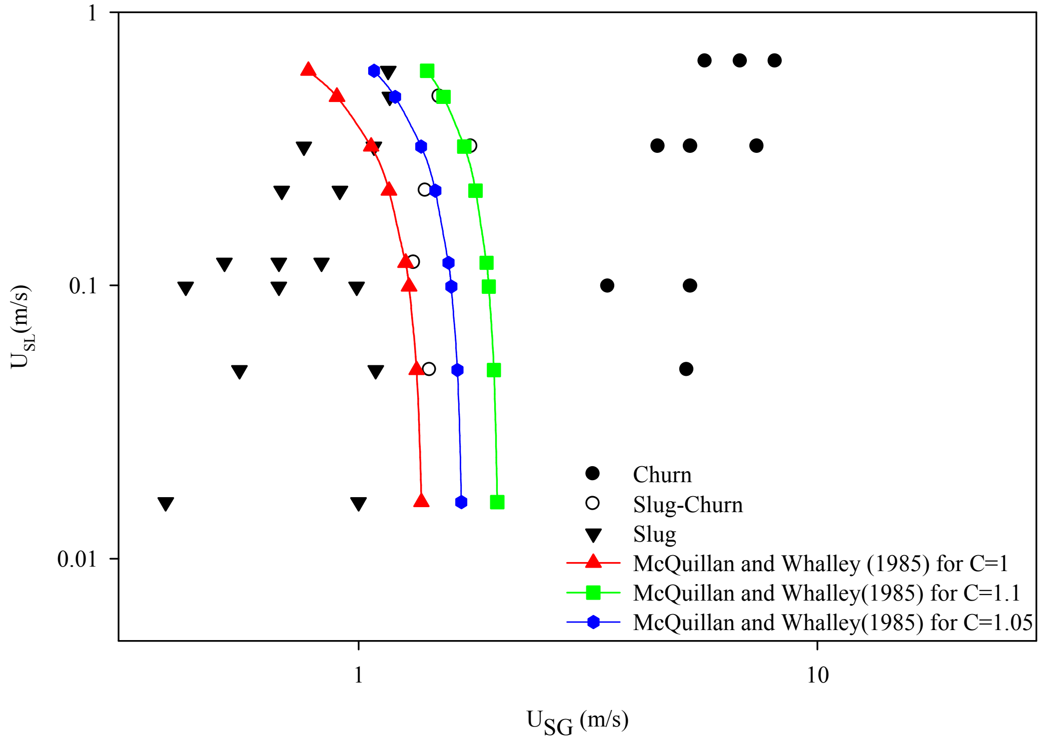


Figure 4.7 - Comparison of McQuillan and Whalley (1985) Slug-churn Theory with Fernandes (1981) for 0.051 m Diameter Pipe

Referring to Figures 4.5, 4.6 and 4.7, a trend can be seen in the value of constant *C* in McQuillan and Whalley (1985) model for slug-churn transition. As pipe diameter increases, value of *C* increases; giving a better prediction of transition. But, this trend is not supported by all the data sets. For example, for air-water data of Sujumnong (1997) in a 0.0127 m diameter pipe, as shown in Figure 4.8, constant *C* takes a value of 1.2. For the same diameter of 0.0127 m diameter, the pressures (gas densities) in the present study are higher than that of sujumnong (1997). For example, for the same superficial liquid and gas velocities of 0.31 m/s and 5.5 m/s, pressures inside the system for Sujumong (1997) and present study are 102,040 Pa and 137,933 Pa, respectively. Corresponding gas phase densities are 1.28 kg/m^3 and 1.63 kg/m^3. This causes increase in the value of parameter *C*, because of lower gas density in case of Sujumnong (1997). There is a definite effect of density on the parameter *C*. But, the difference in *C* for the two data sets is very high. This could be attributed to abnormally high gas velocities in case of air-water data of Sujumnong (1997).

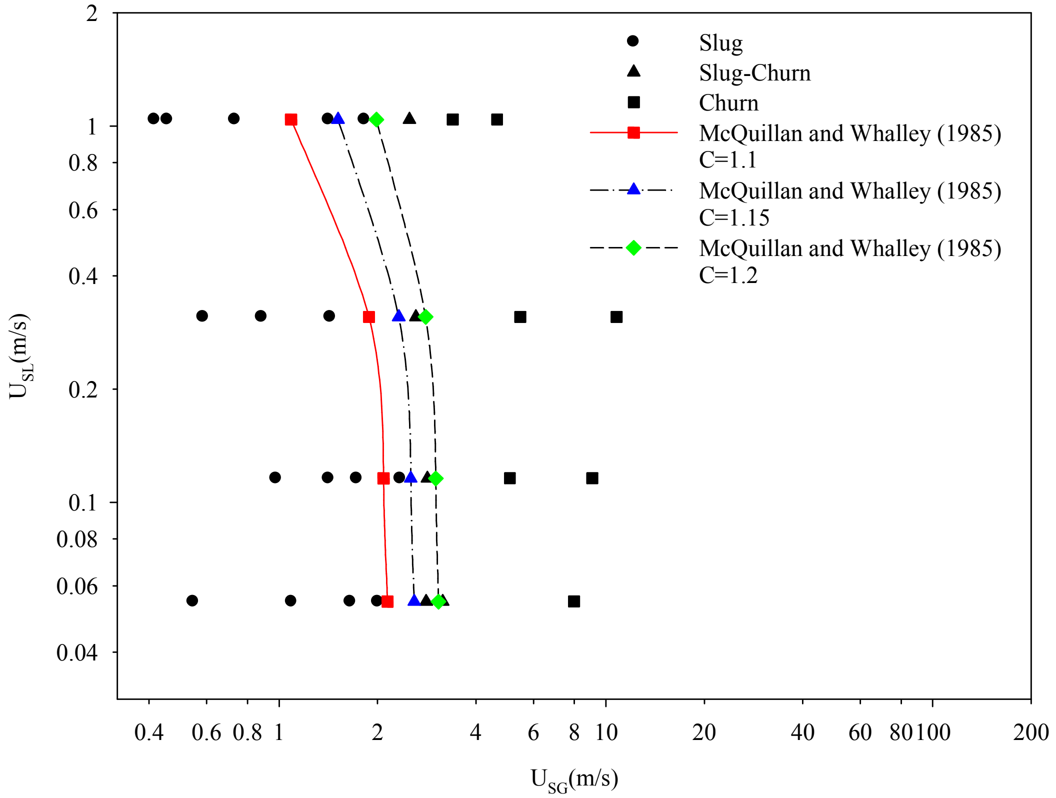


Figure 4.8 - Comparison of Sujumnong (1997) Data for 0.0127m Diameter Pipe and McQuillan and Whalley (1985) Slug-churn Transition Theory.

4.2.3 Churn/froth – Annular Transition

For lower liquid flow rates, churn-annular or froth-annular transition is characterized by formation of ring-like structures. The ring type structures may be also be present in annular flow at lower end of gas flow rates, but these rings disappear subsequently, with further increase in gas flow rate. For churn-annular transition, absence of oscillating slugs of small lengths can be considered as start of transition. As discussed earlier, annular flow is characterized by continuous gas core, which also indicates end of transition and start of pure annular flow region. Froth-annular transition is difficult to locate because both phases flow in only upward direction. Only difference between them is gas and liquid phases are interspersed in froth flow while radially separated in annular flow. At higher liquid flow rates, only froth-annular transition takes place. There are no ring like-structures observed during froth-annular transition at high liquid flow rates.

4.2.4 Comparison of Theories for Churn/Froth-Annular Transition with Experimental Data

Performance of the theories with respect to experimental data collected in the present study is shown in Figure 4.9. Prediction of Weisman and Kang (1981) theory is not included in Figure 4.9 because of high over-prediction of superficial gas velocity at transition. McQuillan and Whalley (1985) theory gives the best prediction among the theories compared. Bilicki and Kestin (1987), Taitel et al. (1980) and Mishima and Ishii (1984) predict transition at a higher superficial gas velocity.

4.3 Churn-Froth Transition

This transition takes place when gas flow rate is increased in churn flow, keeping liquid flow rate constant. In churn flow, gas and liquid phases are present alternately. Froth flow does not have any structure or pattern. The transition is characterized by change in flow direction of the falling liquid film observed in churn flow. The structure of churn flow is also disturbed and gas and liquid start mixing with each other. This is the start of transition. As the gas flow rate is increased, falling liquid film experiences more and more resistance by upward flow in gas and it eventually disappears in froth flow. No falling liquid film and frothy appearance of flow can be considered as end of transition. There are no existing models for churn-froth transition, to compare with experimental data.

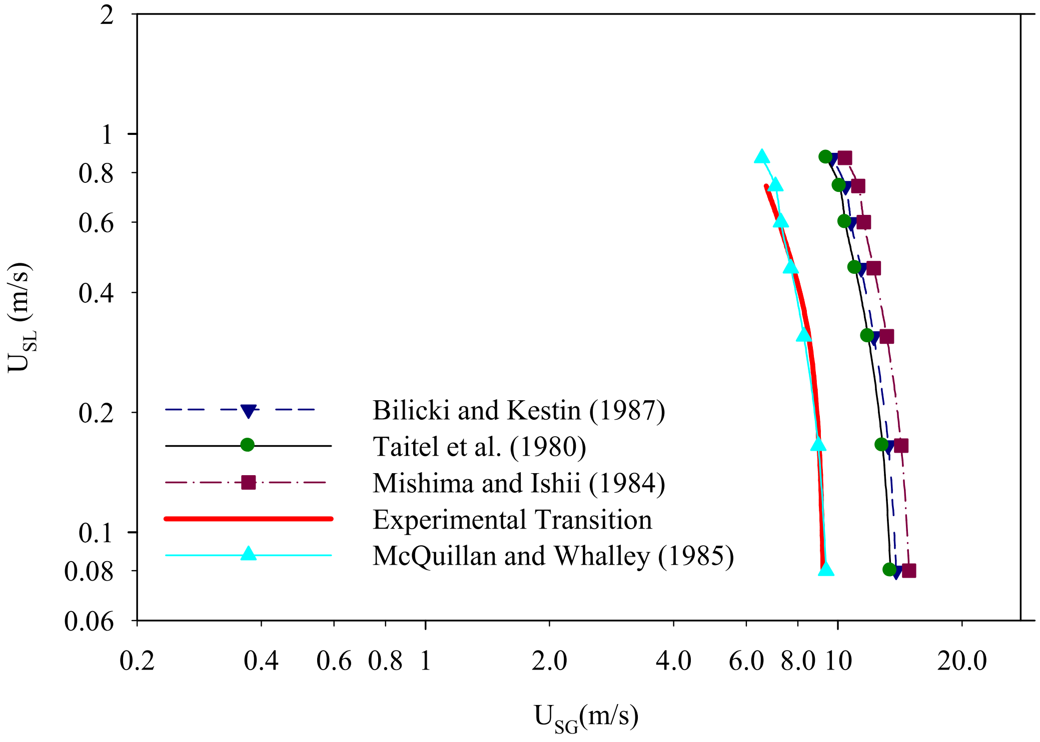


Figure 4.9 – Comparison of Churn-annular Transition Theories with Experimental Data

4.4 Dispersed Bubble-Froth Transition

When gas flow rate in increased in a dispersed bubble flow, it gets transformed into froth flow. It is difficult to observe this transition because of high liquid velocities. When gas flow rate is increased, bubbles coalesce with each other. This coalescence cannot result in Taylor bubbles because of the high turbulence level. Hence gas pockets are formed which are dispersed throughout the liquid resulting in froth flow. Absence of dispersed bubbles is the sign of end of transition. The appearance of gas pockets because of bubble coalescence indicates the start of transition. For bubble-froth transition, theoretical models are not available in the literature.

CHAPTER V

EFFECT OF DIAMETER AND GAS PHASE DENISITY ON FLOW PATTERN MAP

This chapter is related to changes in flow pattern map due to changes in diameter and pressure. Variations in gas phase density and diameter have an effect on transition boundaries between flow patterns, causing early or late transition. The gas phase density increases with the increase in system pressure. Liquid phase density is unaffected by the system pressure due to incompressible nature of liquid. This chapter is divided into two parts. First, effect of diameter is discussed followed by discussion on the effect of pressure. The published literature is scarce on the effect of pressure and diameter. Few examples of such work are: Lin and Hanratty (1987), Watson and Hewitt (1999), Omebere-Iyari and Azzopardi (2007). But, as discussed in Chapter 2, a thorough analysis taking into consideration a variety of data sets is not available. Therefore, an effort is made to bring various data sets from widespread sources together and analyze them. A major limitation on many data sets is lack of pressure data for individual data points. System pressure for the entire data set is mentioned for such experimental data and hence calculations are done based on that pressure. A definite effect of both diameter and pressure is observed during the present study. At the end of this chapter, relation between superficial gas velocity at flow pattern transition and diameter, for constant superficial liquid velocity and gas phase density is suggested. Similarly, relation between superficial gas velocity at flow pattern transition and gas phase density, for constant superficial liquid velocity and diameter is also discussed.

5.1 Effect of Diameter on Flow Pattern Map

One of the earlier studies on the effect of diameter was done by Govier and Short (1958). Their Data for slug-froth and froth-annular transitions, for different diameters is listed in Tables 5.1 and 5.2, respectively.

Table 5.1 - Data of Govier and Short (1958) for Slug- Froth Transition

Diameter (m)	Flow Pattern	Superficial Water Mass Flow Rate (kg/s)	Superficial Air Mass Flow Rate (kg/s)	Superficial Water Volume Flow Rate (m^3/s)	Superficial Air Volume Flow Rate (m^3/s)	U_{SL} (m/s)	U_{SG} (m/s)
0.0160	Slug	0.0517	0.00131	0.000052	0.0004	0.2576	2.18
0.0160	Froth	0.0517	0.00194	0.000052	0.0006	0.2576	3.24
0.0260	Slug	0.1412	0.00315	0.000141	0.0010	0.2659	2.04
0.0260	Froth	0.1412	0.00468	0.000141	0.0016	0.2659	3.02
0.0381	Slug	0.3024	0.00491	0.000303	0.0016	0.2657	1.46
0.0381	Froth	0.3019	0.00724	0.000303	0.0025	0.2657	2.2
0.0635	Slug	0.8355	0.01630	0.000838	0.0056	0.2646	1.78
0.0635	Froth	0.8355	0.02047	0.000838	0.0070	0.2646	2.23

They found out that diameter has a noticeable effect on slug-churn (slug-froth as per their definition) and churn-annular (froth-ripple as per their definition) transition, but the exact nature of the effect was not discussed in their work.

Table 5.2 - Data of Govier and Short (1958) for Churn/Froth-Annular Transition

Diameter (m)	Flow Pattern	Superficial Water Mass Flow Rate (kg/s)	Superficial Air Mass Flow Rate (kg/s)	Superficial Water Volume Flow Rate (m^3/s)	Superficial Air Volume Flow Rate (m^3/s)	U_{SL} (m/s)	U_{SG} (m/s)
0.0160	Froth	0.0517	0.002811	0.000052	0.0009	0.2576	4.70
0.0160	Ripple	0.0517	0.003425	0.000052	0.0011	0.2576	5.73
0.0260	Froth	0.1412	0.009738	0.000142	0.0033	0.2659	6.22
0.0260	Ripple	0.1411	0.011237	0.000142	0.0038	0.2659	7.29
0.0381	Froth	0.3024	0.023600	0.000303	0.0079	0.2657	7.00
0.0381	Ripple	0.3018	0.027525	0.000303	0.0095	0.2657	8.40
0.0635	Froth	0.8353	0.034571	0.000838	0.0119	0.2646	3.78
0.0635	Ripple	0.8355	0.041757	0.000838	0.0144	0.2646	4.56

The data in Tables 5.1 and 5.2 shows that there is a diameter effect, but, it is not clear. For approximately constant liquid superficial velocity of 0.26 m/s, superficial gas velocities, for first reading of froth flow are 3.24 m/s, 3.02 m/s, 2.20 m/s and 2.23 m/s for 0.016, 0.026, 0.0381 and 0.0635 m diameters, respectively. Similarly, the start of ripple flow is at 5.73 m/s, 7.29 m/s, 8.40 m/s and 4.56 m/s, respectively. Thus, there is no consistent effect of diameter. Superficial gas velocity for first froth flow reading decreases with increase in diameter, but then settles down to a constant value of approximately 2.2 m/s. Similarly, the value of superficial gas velocity for ripple flow increases with increase in diameter, but decreases suddenly for 0.0635 m diameter. But, even if there is no consistent trend in the values of superficial gas velocity at transition, mass flow rate and volume flow rate required at transition increase with the increase in diameter.

The data of Taitel et al. (1980) is shown in Table 5.3. This data is based on the flow map given in their work.

Table 5.3 - Data of Taitel et al. (1980) for Transitions

Diameter (m)	Transition	Superficial Water Velocity at Experimental Transition (m/s)	Range of Superficial Air Velocity at Experimental Transition (m/s)
0.025	Slug – Churn	0.031	1.3 to 1.7
0.025	Churn-Annular	0.031	8. 3 to 16.3
0.051	Slug – Churn	0.028	1.7 to 2.2
0.051	Churn-Annular	0.028	9.4 to 12.4

Table 5.4 - Data of Shoham et al. (1980) for Transitions

Diameter (m)	Transition	Superficial Water Velocity at Experimental Transition (m/s)	Range of Superficial Air Velocity at Experimental Transition (m/s)
0.025	Slug – Churn	0.18	2.7 to 3.4
0.025	Churn-Annular	0.18	7.1 to 8.3
0.051	Slug – Churn	0.18	4.1 to 5.4
0.051	Churn-Annular	0.18	10.4 to 13.4

In Table 5.3, equal superficial liquid velocities are chosen for comparison. Observing the values of superficial gas velocities for the same superficial liquid velocities, it is evident that increase in diameter causes increase in superficial gas velocity at transition.

Data of Shoham (1982) also shows the same trend of increasing superficial gas velocity at transition, with increase in diameter. Data of Shoham (1982) is shown in Table 5.4. It is important to note that trend of superficial gas velocity at slug-churn transition, with increasing superficial liquid velocity is opposite for Taitel et al. (1980) and Shoham (1982). Superficial gas velocity decreases with increase in superficial liquid velocity in data of Taitel et al. (1980), whereas it increases in case of Shoham (1982) data. But, both data-sets are in agreement on the effect of increase in diameter.

Values of superficial gas velocities at slug-churn and churn/froth-annular transition in the present study are tabulated in Table 5.5. Transition in flow pattern takes place over a range of gas mass flow rates (or superficial gas velocities), but approximately mean values of the range are listed in Table 5.5. They are consistent with the trend of decreasing superficial velocity with decreasing diameter.

Table 5.5 - Data of Transitions for the Present Study

Diameter (m)	Superficial Liquid Velocity at Experimental Transition (m/s)	Superficial Gas Velocity at Experimental Slug-Churn Transition (m/s)	Superficial Gas Velocity at Experimental Churn-Annular Transition (m/s)
0.0127	0.08	1.02	9.1
0.0127	0.165	0.9	8.9
0.0127	0.31	0.7	8.6
0.0127	0.46	0.53	7.7
0.0127	0.6	0.42	7.1

Chen et al. (2006) conducted experiments with R134a (approximately same density as water, with higher gas phase density) using tubes of 0.0011, 0.00201, 0.00288 and 0.00426 m diameters. The superficial gas velocities at transition, for their data at 6 bar pressure are shown in Table 5.6. Diameters of 0.0011m and 0.00201m are not presented in Table 5.6, because Chen et al. (2006) categorized them as small diameter tubes.

Table 5.6 - Data of Chen et al. (2006) for Transitions

Superficial Liquid Velocity at Experimental Transition (m/s)	Superficial Gas Velocity at Experimental Slug-Churn Transition (m/s) D=0.00426 m	Superficial Gas Velocity at Experimental Churn-Annular Transition (m/s) D=0.00426 m	Superficial Gas Velocity at Experimental Slug-Churn Transition (m/s) D=0.00288 m	Superficial Gas Velocity at Experimental Churn-Annular Transition (m/s) D=0.00288 m
1.6	0.77	1.37	0.74	1.47
2.24	0.8	1.63	0.84	1.8
2.65	0.76	1.81	0.9	2
3.6	0.72	2.45	0.95	2.74
4.55	0.65	2.50	0.92	2.74
4.92	0.57	2.51	0.85	2.77

If the data for churn-annular transition for 0.00426 m diameter tube is compared with data in the present study, the trend of decreasing superficial gas velocity with decrease in diameter is maintained. But, if data for 0.00426 m tube is compared with data for 0.00288 m tube, opposite trend is established. Based on their data, Chen et al. (2006) concluded that the superficial gas velocity increases with decrease in diameter. Increase in superficial gas velocity with decrease in diameter for Chen et al. (2006) could be because of the increased effect of surface tension in smaller diameter tube (0.00288m).

The increasing superficial gas velocity at transition with increasing diameter can be explained based on the energy required in gas flow at transition. Consider churn/froth – annular transition. In annular flow, liquid is pushed to the wall of the tube and a central gas core is formed. Energy required to push the liquid towards the wall is provided by gas flow. Hence, at same superficial liquid velocity (increased liquid mass flow rate if going from lower to higher diameter, as liquid density does not vary much with pressure and temperature), gas mass flow rate required will be higher for higher diameter, because incompressible liquid phase should be pushed at higher distance from pipe centerline and liquid film thickness will be lower for a higher diameter pipe.

Increase in superficial gas velocity with increase in diameter, at slug-churn transition can also be explained on the same lines. Many researchers (Fernandes (1981), Sujumnong (1997), Jiang and Rezkallah (1993)) have experimentally proven that void fraction increases as flow pattern changes from slug to churn. For increase in void fraction, more gas flow rate will be required. For the same value of void fraction, more gas will be required in a higher diameter tube than a lower diameter tube. Some of the researchers (Spedding et al. (1998), Oshinowo and Charles (1974), Lin et al. (1998)) have also mentioned that slug-churn transition takes place at increasing gas flow rate. This explains the increase in superficial gas velocity at transition, with increase in diameter.

Thus, referring to the above experimental data, it can be concluded that a definite trend of increasing superficial gas velocity with the increase in pipe diameter is observed. But, as mentioned above, there are few exceptions to this. Hence, a research focusing on effect of diameter will be helpful to shed more light on this phenomenon.

It should be noted that the theories for transition also consider that the gas superficial velocity will increase with increase in diameter. For example, expression for slug-churn transition by McQuillan and Whalley (1985) is

$$\sqrt{U^*_{SG}} + \sqrt{U^*_{SL}} = C \tag{5.1}$$

If U^*_{SL} is kept constant, relation between superficial gas velocities for diameter 1 and 2 is

$$\frac{U_{SG1}\rho_{G1}{}^{1/2}}{\left(gD_1\left(\rho_L-\rho_{G1}\right)\right)^{1/2}}=\frac{U_{SG2}\rho_{G2}{}^{1/2}}{\left(gD_2\left(\rho_L-\rho_{G2}\right)\right)^{1/2}} \tag{5.2}$$

Liquid density ρ_L and gas density ρ_G will be constant at constant pressure and hence

$$\frac{U_{SG1}}{U_{SG2}}=\frac{D_1{}^{1/2}}{D_2{}^{1/2}} \tag{5.3}$$

Thus, according to McQuillan and Whalley (1985) model of slug-churn transition, superficial gas velocities at transition are directly proportional to square root of diameter.

Slug-churn transition equation by Brauner and Barnea (1986) is

$$2\left(\frac{0.4\sigma}{\left(\rho_L-\rho_G\right)g}\right)^{1/2}\left(\frac{\rho_L}{\sigma}\right)^{3/5}\left(\frac{2}{D}C_L\left(\frac{D}{\nu_L}\right)^{-n}\right)^{2/5}U_M{}^{2(3-n)/5}=0.725+4.15(\alpha)^{0.5} \tag{5.4}$$

For varying diameters, with other properties constant, equation (5.4) reduces to

$$U_M=K_1D^{0.4285} \tag{5.5}$$

Or,

$$\frac{U_{SG1}}{U_{SG2}}=\left(\frac{K_1D_1^{0.4285}-U_{SL}}{K_1D_2^{0.4285}-U_{SL}}\right) \tag{5.6}$$

Theory of Taitel et al. (1980) for slug-churn transition also shows a diameter effect to the power 0.5. Taitel et al. (1980) model is

$$\frac{L_E}{D}=40.6\left(\frac{U_M}{\sqrt{gD}}+0.22\right) \tag{5.7}$$

For constant ratio of entrance length to diameter at transition, superficial gas velocity can be calculated by

$$U_{SG}=K_2\sqrt{D}-U_{SL} \tag{5.8}$$

Or,

$$\frac{U_{SG1}}{U_{SG2}} = \left(\frac{K_2 D_1^{1/2} - U_{SL}}{K_2 D_2^{1/2} - U_{SL}} \right) \tag{5.9}$$

It is seen that there is a consensus between various researchers on the effect of diameter on slug-churn transition. Superficial gas velocity at transition increases with increase in diameter. It could also be concluded that the increase in superficial gas velocity is proportional to square root of diameter.

Churn-annular transition model of McQuillan and Whalley (1985) is

$$U^*_{SG} \geq 1 \tag{5.10}$$

Equation (5.10) reduces to equation (5.11) for constant superficial liquid velocity and fluid properties.

$$\frac{U_{SG1}}{U_{SG2}} = \frac{D_1^{1/2}}{D_2^{1/2}} \tag{5.11}$$

Mishima and Ishii (1984) have proposed equation (5.12) for churn-annular transition,

$$U_{SG} = \sqrt{\frac{(\rho_L - \rho_G) g D}{\rho_G}} (\alpha - 0.11) \tag{5.12}$$

Considering high values of α (for annular flow) in the above equation, the term *(α-0.11)* will not have much effect even if transition takes place at different values of α for different diameters. Hence, for constant gas density, the effect of diameter emerges as a power of 0.5, as given by equation (5.13)

$$\left(\frac{U_{SG1}}{U_{SG2}} \right) = \left(\frac{D_1}{D_2} \right)^{0.5} \tag{5.13}$$

Churn-annular transition by Weisman and Kang and (1981) is

$$Fr^{0.2}Ku^{0.18} = 1.9\left(\frac{U_{SG}}{U_{SL}}\right)^{1/8} \tag{5.14}$$

When rearranged, it gives the following result for constant fluid properties and superficial liquid velocity.

$$U_{SG} = K_3 D^{0.39} \tag{5.15}$$

This again substantiates the effect of diameter, which appears as a power of 0.39.

Researchers such as Taitel et al. (1980) and Bilicki and Kestin (1987) have not considered the effect of diameter on churn-annular transition and have based their models on *Kutateladze number (Ku).* Taitel et al. (1980) predict only their churn-annular transition data satisfactorily. McQuillan and Whalley (1985) model predicts the present data as well as data of Taitel et al. (1980) satisfactorily. As seen from the experimental data in Tables 5.2 to 5.6, there is certainly an effect of diameter on churn-annular transition.

Based on the discussion so far, it can be concluded that the effect of increasing diameter is increase in superficial gas velocity at transition. This effect can be taken approximately as square root of diameter for both slug-churn and churn-annular transitions.

5.2 Effect of Gas Phase Density on Flow Pattern Map

Readings for churn-annular transition in the present study show that gas mass flow rate required at transition increases with increase in liquid mass flow rate. But, referring to the flow pattern map in the present study (Chapter 4), superficial velocity of gas decreases with increase in superficial liquid velocity. This is because of the effect of density. Density of gas at higher liquid and gas flow rates is higher than density of gas at lower flow rates. Hence, superficial gas velocity at transition decreases even if the gas mass flow rate increases. The increase in density is because of the increase in operating pressure. At higher liquid flow rates, the outlet pressure of pump increases and for a higher gas flow rate, the throttle valve at the outlet of compressor in experimental set up is opened, causing increase in pressure of gas flow. The increase in gas density because of increase in pressure takes place in both boiling and non-boiling two-phase flows. Many researchers do not take into consideration this effect of system pressure and collect data without recording system pressure. Examples among many are: Taitel et al. (1980), Barnea et al. (1983), who have reported only one pressure for the entire data set. The practicability of a system operating at the same pressure for the entire range of gas and liquid mass flow rates is questionable. Lack of pressure data also poses question on their flow pattern maps. Therefore, effect of pressure on flow pattern map is discussed in the following paragraphs to get a better understanding of it.

From the work of McQuillan and Whalley (1985), churn-annular transition data reported by Bergles and Suo (1966) was studied. In their work, data of churn-annular transition was obtained for steam-water system in a 0.01 m diameter pipe at 34.5 and 69 bar pressure. Plots for the two cases are shown in Figures 5.1 and 5.2, respectively.

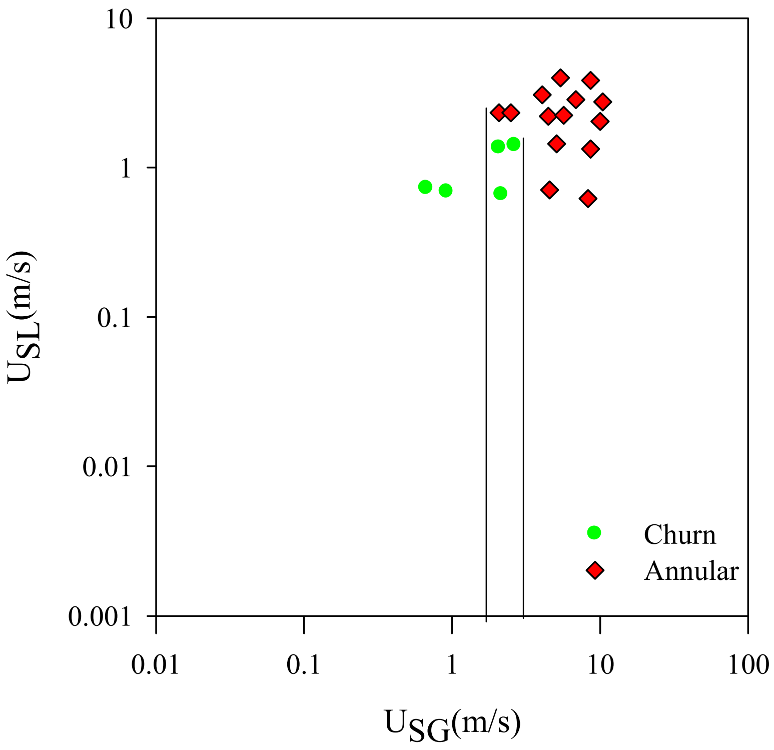


Figure 5.1 - Data reported by Bergles and Suo (1966) for slug-churn transition at 34.5 bar pressure (Taken from McQuillan and Whalley (1985))

Data points near transition are not enough, which makes it difficult to determine exact value of superficial gas velocity at transition. Therefore, two cases were considered – Superficial gas velocity at the end of churn flow and superficial gas velocity at the start of annular flow. Values of superficial gas velocities extracted by graphical method are listed in Table 5.7.

Effect of pressure is clearly observed from data in Table 5.7. As the pressure increases, superficial gas velocity at transition decreases. The effect can be studied only qualitatively because of the lack of other parameters (for example steam quality, mass flow rate) at transition.

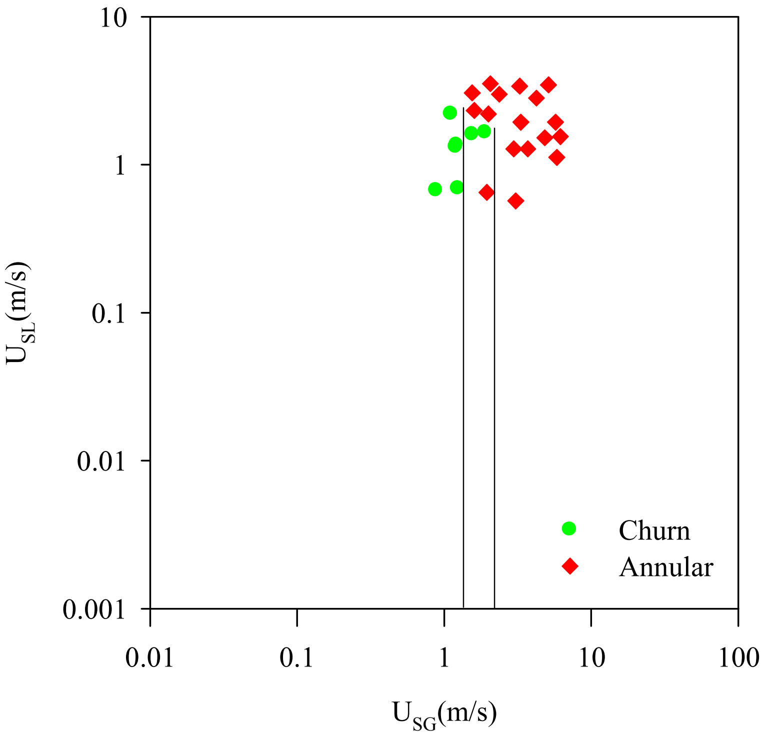


Figure 5.2 - Data reported by Bergles and Suo (1966) for churn-annular transition at 69 bar pressure (Taken from McQuillan and Whalley (1985))

Watson and Hewitt (1999) studied the effect of pressure on slug-churn transition boundary. They conducted experiments in a 0.032 m pipe at pressures of 1.2 bar, 3 bar and 5 bar.

Table 5.7 - Velocities at Churn-Annular Transition for Data Reported by Bergles and Suo (1966)

Pressure (bar)	Superficial gas velocity at the end of churn flow (m/s)	Superficial gas velocity at the start of annular flow (m/s)
34.5	3	1.7
69	2.15	1.32

Plots from their work, as shown in Figure 5.3, clearly show that the superficial gas velocity at transition decreases with the increase in pressure. Care should be taken while referring to Figure 5.3 because superficial gas velocity is plotted on y-axis to maintain consistency with graphs from Watson and Hewitt (1999).

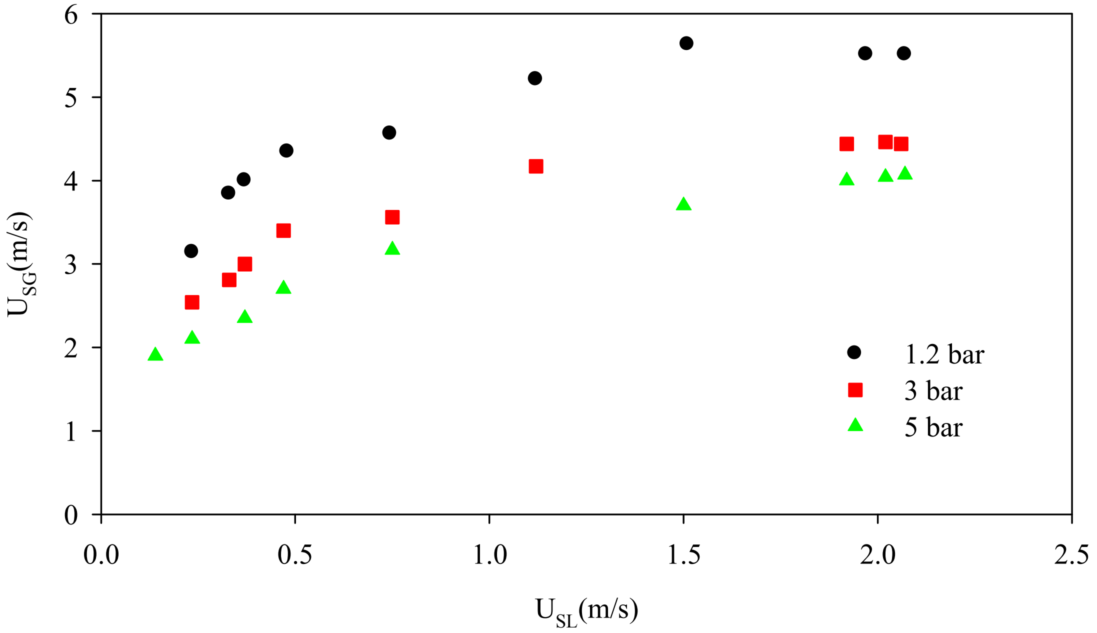


Figure 5.3 - Data of Watson and Hewitt (1999) for Slug-Churn Transition

It can be seen from Figure 5.3 that superficial gas velocity increases with increasing superficial liquid velocity, which is not consistent with the present study. This can be attributed to difference in definitions of slug and churn flow. Established definitions from the literature are used in the present study whereas definitions used by Watson and Hewitt (1999) are different from established definitions. The criterion used by Watson and Hewitt (1999) for differentiating the churn from slug was absence of low void fraction readings on conductance probes. Low void fraction readings were attributed to absence of liquid slugs. This criterion seems unreasonable because slugs are present in churn flow, as discussed in the Chapter 4. Watson and Hewitt (1999) used erroneous definition of transition and churn flow. Slug flow was defined in the same way as other researchers. But, churn flow was defined as: “The churn flow region itself is one in which the flow is highly disturbed and in which large waves flow up the channel interspersed with regions of falling film. It is the existence of these flow reversals which distinguishes churn flow from annular flow, though in both cases there is continuous gas core in the flow.” The churn flow is defined as the flow with no liquid slugs. The definition of transition flow by Watson and Hewitt (1999) actually matches with that of churn flow defined by other researchers. Transition flow was defined by Watson and Hewitt (1999) as mixture of occasional stable slug and unstable collapsing slugs with indefinite shapes and void fractions.

Hosler (1958) did diabatic experiments with steam-water. The transitions data, at various pressures and mass velocities is given in Table 5.8. It is evident that steam mass flow rate required at transition increases with the increase in pressure. The respective values of superficial gas and liquid velocities are presented in Table 5.9.

Table 5.8 - Steam Quality Data for Slug-Annular Transition for Data from Hosler (1958)

Mass velocity (lb/h-ft^2) x10^{-6}	Pressures (psia)/Quality of Steam					
100000	150/0.09	300/0.11	600/0.21	800/0.27	1400/0.34	2000/0.9
250000	150/0.067	300/0.073	600/0.11	800/0.18	1400/0.25	2000/0.58
500000	150/0.038	300/0.051	600/0.065	800/0.1	1400/0.2	2000/0.3
1000000	150/0.03	300/0.038	600/0.046	800/0.078	1400/0.11	2000/0.19
2000000	150/0.02	300/0.027	600/0.03	800/0.059	1400/0.065	2000/0.17
4000000	--	--	--	800/0.014	1400/0.06	2000/0.15

From Table 5.9, it is clear that as the pressure increases superficial gas velocity at transition decreases. For example, at approximately constant velocity of 0.42 to 0.46 ft/s, superficial velocity decreases from 7.88 ft/s to 2.85 ft/s as pressure increases from 150 psia to 2000 psia. There are some inconsistencies in the data but the trend for increasing pressure is decreasing superficial gas velocity. The data of Hosler (1958) is similar to the data collected during present study. In both cases, for churn-annular transition, mass flow rate of gas increases, but superficial gas velocity decreases because of increase in gas density.

Table 5.9 – Data of Velocities for Slug-Annular Transition from Hosler (1958)

Mass velocity (lb/h-ft^2)	Pressure (psia) U_{SL} (ft/s)/U_{SG} (ft/s)					
100000	150	300	600	800	1400	2000
	0.46/7.88	0.47/4.72	0.44/4.49	0.42/4.27	0.42/2.85	0.07/4.70
250000	150	300	600	800	1400	2000
	1.17/14.04	1.22/7.83	1.24/5.89	1.19/7.11	1.2/5.24	0.75/7.58
500000	150	300	600	800	1400	2000
	2.42/15.92	2.49/10.94	2.62/6.96	2.61/7.90	2.56/8.38	2.49/7.84
1000000	150	300	600	800	1400	2000
	4.9/20.95	5.05/16.30	5.34/9.84	5.35/12.33	5.7/9.21	5.77/9.93
2000000	150	300	600	800	1400	2000
	9.87/30.17	10.21/23.16	10.83/13.70	10.91/18.66	11.98/10.89	11.82/17.76
4000000	150	300	600	800	1400	2000
	--	--	--	22.87/8.85	24.04/20.44	24.21/31.35

Omebere-Iyari and Azzopardi (2007) conducted experiments with naptha and nitrogen in a large diameter (0.189 m) pipe. Though the flow patterns observed in their study were different from those observed in small (compared to 0.189 m) diameter pipes, flow pattern maps presented in their work show the effect of operating pressure on semi-annular to annular flow transition. The start of transition at low superficial liquid velocity (approximately 0.002 m/s) reduces from 1 m/s for 20 bar pressure to approximately 0.6 m/s for 90 bar pressure. Bubble-intermittent and intermittent-semi-annular transitions are not affected much by change in pressure.

The effect of density considered in transition theories was studied in the same manner as diameter.

Referring to equations (5.1) and (5.2) for slug-churn transition suggested by McQuillan and Whalley (1985), for a constant diameter,

$$U_{SG1}\rho_{G1}^{\;1/2} = U_{SG2}\rho_{G2}^{\;1/2} = Constant \tag{5.16}$$

The influence of gas density in the denominator of equation (5.2) can be neglected because of the high value of liquid phase density compared to gas density.

Except for flooding mechanisms of McQuillan and Whalley (1985) and Jayanti and Hewitt (1992), only Mishima and Ishii (1984) have considered effect of gas phase density. But, the effect of density is very difficult to analyze in their model (equation (5.12)) because of complex form of the transition equations. Others (Taitel et al. (1980), Brauner and Barnea (1986), Chen and Brill (1997) and Tangesdal et al. (1999)) have not considered effect of density on slug-churn transition. This explains bad prediction performance of some of the theories, as shown in Figure 4.5 of Chapter 4. Prediction of transition by Brauner and Barnea (1986), at very high superficial gas velocity is probably because of ignoring gas phase density effect. Chen and Brill (1997) and Tangesdal (1999) have also not considered the effect of gas phase density. The results obtained from their theories are also not satisfactory.

Model of Taitel et al. (1980) predicts slug-churn transition satisfactorily, even if they have not incorporated effect of gas phase density. But McQuillan and Whalley (1985) and Jayanti and Hewitt (1992) consider the effect of gas phase density and predict slug-annular transition better than Taitel et al. (1980).

For churn-annular transition, equation proposed by McQuillan and Whalley (1985) (given by equation (5.10)), at constant diameter,

$$U_{SG1}\rho_{G1}^{1/2} = U_{SG2}\rho_{G2}^{1/2} \tag{5.17}$$

Mishima and Ishii (1984) model for churn-annular transition (equation (5.12)) also gives the same result as equation (5.17) for constant diameter, neglecting the effect of gas phase density in the term ($\rho_L - \rho_G$) and the effect of void fraction (α) in the term (α-0.11).

Models of Taitel et al. (1980) and Bilicki and Kestin (1987) for churn-annular transition (equations (2.2) and (2.13)) also support this idea. The transition equations proposed by them, at constant surface tension reduce to equation (5.17).

CHAPTER VI

VARIATION OF VOID FRACTION WITH FLOW PATTERNS

As discussed in Chapter 1, void fraction, pressure drop and heat transfer in two-phase flow vary with the flow pattern in the pipe. Pressure drop and heat transfer is not included in the scope of present study. The dependence of void fraction on the flow pattern is discussed in this chapter.

In this chapter, variation of void fraction with respect to flow patterns observed in the present study is discussed first, followed by comparison of measured void fraction with void fraction predicted by flow pattern specific correlations. As discussed in Chapter 4, there were five flow patterns observed during present study; viz. Dispersed Bubble, Slug, Churn, Froth and Annular. The best correlations (from the correlations considered) for bubble, slug, churn, froth and annular flow patterns are recommended based on the comparison with data in the present study and data collected from literature.

Percentage error was used as the criterion for determining the accuracy of correlations. Comparison of various techniques for determining accuracy of the correlations was done by Woldesemayat (2006). He selected percentage error as the criterion because it was simple and provided an insight regarding the weakness of a correlation in a particular range of void fraction values. Referring to Chpater 2 in this work, it is evident that most of the researchers use percentage error as the criterion for checking the accuracy of correlations. One more reason for choosing percentage error as the criterion was to maintain a consistency in all the work done in Two-phase Flow Laboratory at Oklahoma State University.

6.1 Variation of Void Fraction with Flow Pattern in the Present Study

Ranges of mass flow rates used in the present are discussed in Chapter 4. Variation of void fraction is plotted for varying gas mass flow rate, at constant liquid mass flow rates in Figure 6.1.

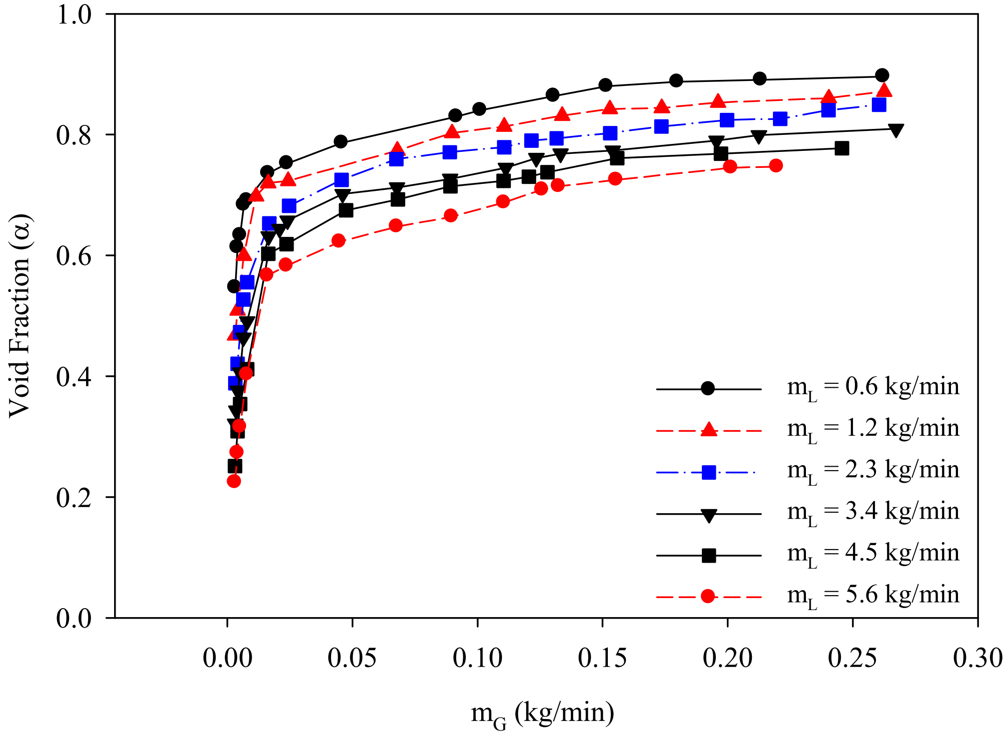


Figure 6.1 – Variation of Void Fraction with Gas Mass Flow Rate at Constant Liquid Mass Flow Rate

Liquid and gas mass flow rates were used for plotting the graph, instead of superficial gas velocity or Reynolds number, because mass and time are independent of any other physical quantity. For example, Reynolds number changes with changes in viscosity, which in turn depends upon temperature of the system. Velocity changes with mass flow rate, density and area of the pipe. But, mass flow rate, once fixed, does not vary irrespective of changes in other physical quantities. Thus, by using liquid and gas mass flow rates as coordinates, effects of operating conditions are kept minimal. Mass flow rates were recorded directly from mass flow meters specified in Chapter 3.

Referring to Figure 6.1, for constant liquid flow rate, void fraction increases with increase in gas (air in the present case) mass flow rate. The trend is followed for all liquid flow rates. This is in agreement with the observations made by Sujumnong (1997), Stanislav et al. (1986), Woods and Spedding (1999) and Jiang and Rezkallah (1993).

Starting from low gas flow rates (0.003 kg/min), void fraction profile shows a steep slope. Void fraction increases rapidly even for small change in gas flow rate. This behavior continues till a value of approximately 0.025 to 0.03 kg/min. The rapid increase in void fraction eventually subsides and the slope of void fraction profile becomes gradual. This change occurs at around 0.035 kg/min gas flow rate. With further increase in gas flow rate, the slope of void fraction profile becomes less and less steep, but, void fraction increases continuously. At high void fraction values, void fraction profile becomes nearly parallel to the gas mass flow rate (m_G) axis. This shows that, at higher void fractions, the gas flow rate required to bring about a change in void fraction value is high. It is also observed that as the liquid mass flow rate increases, the gas flow rate required to achieve a nearly flat void fraction profile increases. For the same gas flow rate, void fraction decreases with the increase in liquid flow rate. The trends mentioned above were also observed by Jiang and Rezkallah (1993) in a 0.009525 m diameter pipe. Figure 6.2 shows an extension of Figure 6.1. Variation of void fraction depending on flow patterns is demonstrated in Figure 6.2. It is evident from Figure 6.2 that the rapid change in void fraction for a small change in gas flow rate takes place in the region of dispersed bubble and slug flow. Hence, it is important to use accurate void fraction correlations in this region. Margin for error in these two flow regimes is very small. The slope starts to become gradual in the region of churn flow. In churn flow region and some

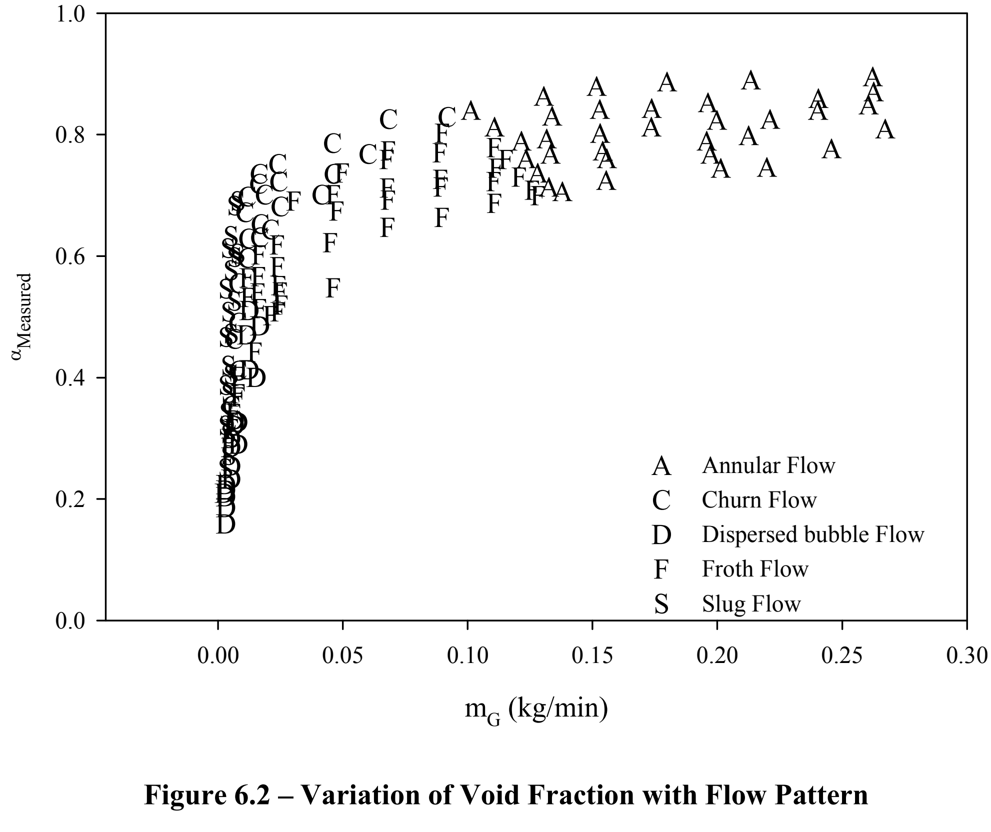


Figure 6.2 – Variation of Void Fraction with Flow Pattern

part of froth flow region, there is a moderate change in void fraction with change in gas flow. In most part of froth flow region and in the entire annular flow region, rate of change of void fraction with change in gas flow rate is low. Hence, there is a higher margin for error in prediction of void fraction in these regions. Ironically, most of the void fraction correlations predict higher values of void fraction better than lower values of void fraction. The analysis of prediction of void fraction by flow dependent void fraction correlations will be done next.

The range of void fraction values observed in the present study for different flow patterns is given in Table 6.1.

Table 6.1 – Range of Void Fraction for Flow Patterns in the Present Study

Flow Pattern	Range of Void Fraction
Dispersed Bubble	0.16 To 0.48
Slug	0.25 To 0.69
Churn	0.35 To 0.77
Froth	0.32 To 0.78
Annular	0.72 To 0.9

6.2 Comparison of Flow Dependent Void Fraction Correlations

6.2.1 Comparison of Dispersed Bubble or Bubbly Flow Correlations with Experimental Data

The correlation developed for either dispersed bubble or bubbly flow is applicable to both of these flow regimes. Hence, separate comparison for bubbly and dispersed bubble flow is not done. Both flow patterns combined are referred to as bubble flow in the discussion. There are very few correlations developed specifically for bubble flow in vertical upward two-phase flow. A total of 111 data points were used for this comparison, as shown in Table 6.2. Details of all the flow pattern specific data sets are presented in Appendix A. Predictions of the correlations for the data sets listed in Table 6.2 are tabulated in Table 6.3. None of the correlations predicts sufficient number of data points within ±5%. This is because of low void fraction values encountered in bubble flow. Hence, the error band needs to be relaxed for bubble flow correlations. For the same absolute error in the predictions, correlations of annular flow have an advantage over correlations for bubble flow, because of the high void fraction value in annular flow.

Table 6.2 - Source of Data for Bubble flow

Source of Data	Number of Data Points
Present study	25
Sujumnong (1997)	13
Fernandes (1981)	29
Mukherjee (1979)	17
Oshinowo (1971)	27

For example, consider a bubble flow data point and an annular flow data point with void fraction values of 0.15 and 0.9, respectively. For an absolute error of 0.05 in the predictions, percentage error for bubble flow data point is 33.3% and percentage error for annular flow data point is 5.5%.

There is no criterion established in the literature for acceptable percentage error in calculation of void fraction in bubble flow. Kabir and Hasan (1990) have reported average error in only pressure drop (which is as high as 24.9% for some data sets in their study), which was calculated by using void fraction values predicted by their void fraction models. Gomez et al. (2000) have reported percentage error in liquid hold up. Their model predicted data of Caetano et al. (1992) with an average percentage error of -2.3%. But, percentage error in liquid hold up should be low for bubble flow because of the high values of liquid hold up in bubble flow. Gomez et al. (2000) did not report percentage error in prediction of void fraction. Hibiki and Ishii (2002) reported percentage error in prediction of void fraction. But, they showed prediction of their correlation in only one error band (±10%) though errors in most of their predictions were more than ±10%. Kaminaga (1992) used error band of ±30% for comparison of bubble flow. In the present study, calculations were performed until one of the correlations predicted 85% of the total data points within the selected error band. This is in-line with the criteria set by Woldesemayat and Ghajar (2007) for flow pattern independent void fraction correlations in his study. They selected correlations based on criterion of 85% of the total data points predicted within ±15%. Based on the above discussion, acceptable tolerance for void fraction in bubble flow was chosen as ±30%.

From Table 6.3, it is evident that correlation of Ellis and Jones (1965) does not perform well for any of the data sets. Performance of correlations by Kabir and Hasan (1990), Gomez et al. (2000) and Hibiki and Ishii (2002) is satisfactory for all data sets, except for data of Mukherjee (1979). As shown in Table 6.4, Kabir and Hasan (1990), Gomez et al.

(2000) and Hibiki and Ishii (2002) predict the same percentage (84.7%) of data points within ±30%. This is a very good performance considering low values of void fraction. Performance of Gomez et al. (2000) for ±10% and ±5% error bands is better than Kabir and Hasan (1990) and Hibiki and Ishii (2002). Beggs (1972) correlation was also studied, but did not perform well for any of the data sets. The prediction of Beggs (1972) correlation was found to be very high and outside the logical limits of void fraction (0 to 1). Hence, Beggs (1972) was not included in Tables 6.3 and 6.4.

Table 6.3 – Prediction Performance of Correlations with Individual Data Sets for Bubble Flow

Correlation	Data Source and Percentage of Data Points Predicted Correctly																			
	Present Study				Sujumnong (1997)				Fernandes (1981)				Mukherjee (1979)				Oshinowo (1971)			
	±5%	±10%	±15%	±30%	±5%	±10%	±15%	±30%	±5%	±10%	±15%	±30%	±5%	±10%	±15%	±30%	±5%	±10%	±15%	±30%
Ellis and Jones (1965)*	0	0	0	0	0	0	0	7.7	0	0	0	0	0	0	0	0	0	0	0	0
Gomez et al.(2000)	0	20	60	92	0	15.4	69.2	84.6	24.1	41.4	69	96.5	0	11.8	23.5	29.4	28	72	88	100
Kabir and Hasan(1990)	0	0	24	88	0	0	23.1	84.6	20.7	31	51.7	100	0	0	11.8	29.4	36	56	88	100
Hibiki and Ishii (2002)	0	28	64	92	0	0	38.5	84.6	24.1	27.6	51.7	93.1	5.9	11.6	23.5	35.3	32	64	88	100

* From Kaminaga (1992)

Table 6.4 - Prediction Performance of Correlations with All Data for Bubble Flow

Correlation	Percentage of All Data Predicted Correctly			
	±5%	±10%	±15%	±30%
Ellis and Jones (1965)*	0	0	0	1
Gomez et al.(2000)	13.5	36	64	84.7
Kabir and Hasan(1990)	14.4	21.6	44.1	84.7
Hibiki and Ishii (2002)	15.3	31.5	56.8	84.7

* From Kaminaga (1992)

Considering the better performance of Gomez et al. (2000) model for lower error bands, it is recommended for void fraction prediction in bubble flow. Performances of Hibiki and Ishii (2002), Kabir and Hasan (1990) and Gomez et al. (2000) models are shown in Figures 6.3, 6.4 and 6.5, respectively.

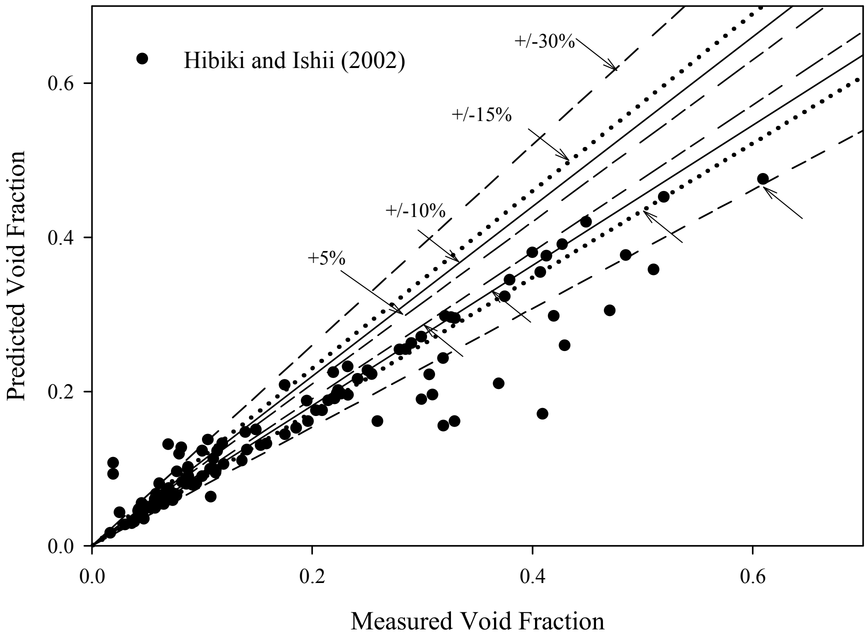


Figure 6.3 – Comparison of Hibiki and Ishii (2002) Correlation for All Bubble Flow Data

All the three correlations perform similarly. There are few points in the range of 0.25 to 0.5, which are under-predicted by the three correlations. Therefore, an improvement in prediction performance in the void fraction range of 0.25 to 0.5 is required. Performance of all the three correlations is good for lower values of void fraction.

6.2.2 Compariosn of Slug Flow Correlations with Experimental Data

A total of 175 data points were included for comparison of slug flow correlations with experimental data, as shown in Table 6.5.

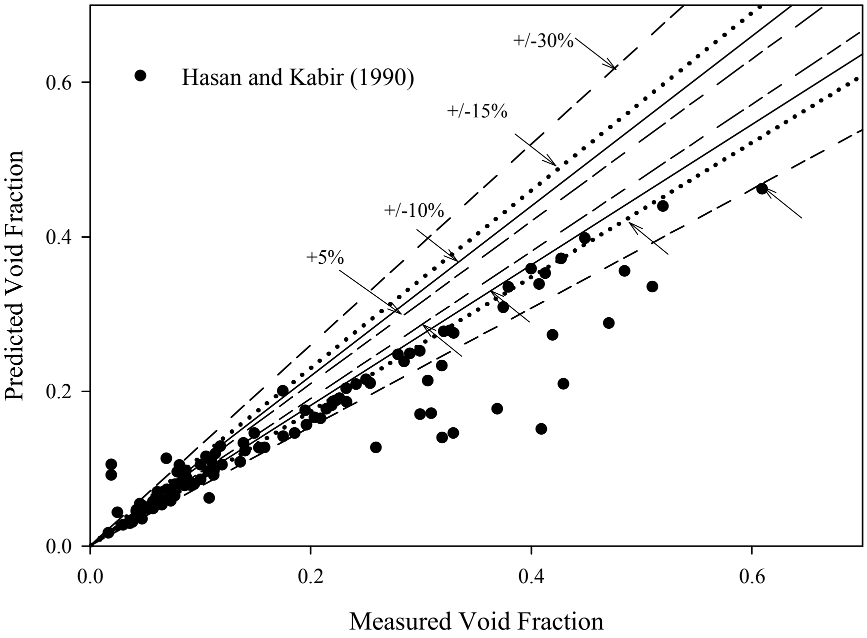


Figure 6.4 – Comparison of Kabir and Hasan (1990) Correlation with All Bubble Flow Data

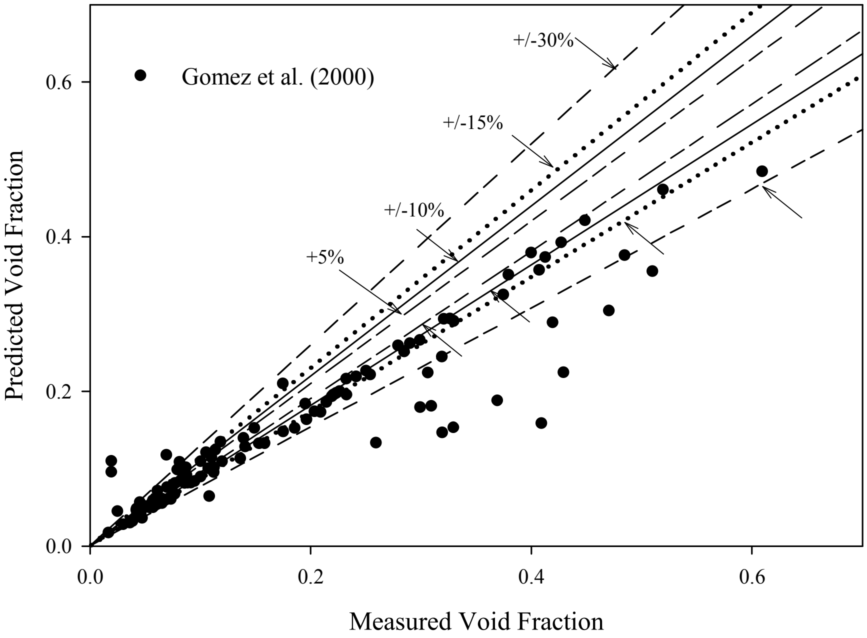


Figure 6.5 - Comparison of Gomez et al. (2000) Correlation with All Bubble Flow Data

Table 6.5 – Sources of Data for Slug Flow

Source of Data	Number of Data Points
Present study	21
Sujumnong (1997)	20
Fernandes (1981)	16
Mukherjee (1979)	32
Oshinowo (1971)	86

For slug flow, several correlations are available in the literature. Performance of the correlations considered in this study is shown in Tables 6.6 and 6.7. Correlations by Ellis and Jones (1965) and Beggs (1972) do not perform satisfactorily for most of the data sets. Considering ±15% error band, Fernandes et al. (1983), Sylvester (1987) and Kabir and Hasan (1990) perform reasonably well, but fail to predict enough data points for Oshinowo (1971) data set, which contributes 50% of the total slug flow data considered. Therefore, for overall slug flow data, these correlations predict below 80% of the data points within ±15%. It should be noted that Sylvester (1987) model gives a consistent prediction (above 85%) for all other data sets. Gomez et al. (2000) model performs well for all the data sets. Except for Oshinowo (1971) data, its prediction for ±15% error is consistently above 85%. Kabir and Hasan (1990) correlation fails badly for the data collected in the present study, but predicts above 80% of the data points within ±15% for the other data sets. Orell and Rembrand (1986), Kataoka and Ishii (1987), Nicklin and Davidson (1962) and Bonneczae et al. (1971) predict more than 80% of the entire data

Table 6.6 – Prediction Performance of Correlations with Individual Data Sets for Slug Flow

Correlation	Data Source and Percentage of Data Points Predicted Correctly														
	Present Study			Sujumnong (1997)			Fernandes (1981)			Mukherjee (1979)			Oshinowo (1971)		
	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Ellis and Jones (1965) *	57.1	90.5	100	10	35	65	0	6.25	37.5	3.1	6.3	15.6	2.3	4.6	11.6
Gomez et al. (2000)	14.3	66.7	95.2	70	85	90	87.5	93.8	100	40.6	53.1	84.4	13.9	43	68.6
Kabir and Hasan (1990)	0	0	9.5	30	60	85	25	68.8	100	21.9	43.8	81.3	31.3	75.5	89.5
Kataoka and Ishii (1987)	71.4	100	100	65	80	90	0	37.5	81.3	40.6	53.1	87.5	15.1	44.1	72
Fernandes et al. (1983)	66.67	100	100	40	70	80	87.5	100	100	31.2	46.8	78.1	22	51.1	65.1
Sylvester (1987)	57.1	95.2	100	55	80	85	68.8	100	100	40.6	81.2	87.5	8.1	17.4	47.6
Orell and Rembrand(1986)	95.2	100	100	70	90	95	81.3	93.8	100	31.2	46.8	78.1	23.2	56.9	70.9
Beggs (1972)	0	0	0	0	0	0	0	0	0	6.2	15.6	15.6	0	0	0
Nicklin and Davidson (1962)	23.8	85.7	100	60	80	90	31.3	93.8	100	28.1	43.7	75	26.7	63.9	83.7
Bonnecaze et al. (1971)	23.8	85.7	100	60	80	90	31.3	93.8	100	28.1	43.7	75	26.7	63.9	83.7

*From Kaminaga (1992)

Table 6.7 - Prediction Performance of Correlations with All Slug Flow Data

Correlation	**Percentage of All Data Predicted Correctly**		
	±5%	±10%	±15%
Ellis and Jones (1965) *	9.7	18.8	31.4
Gomez et al. (2000)	32	57.1	80
Kabir and Hasan (1990)	25.1	58.2	78.8
Kataoka and Ishii (1987)	30.8	56	81.1
Fernandes et al. (1983)	37.1	62.8	76.5
Sylvester (1987)	30.8	53.1	70.2
Orell and Rembrand(1986)	44	67.4	81.1
Beggs (1972)	1.1	2.8	2.8
Nicklin and Davidson (1962)	30.8	67.4	86.9
Bonneczae et al. (1971)	30.8	67.4	86.9

within ±15%. As discussed in Chapter 2, Bonneczae et al. (1971) and Nicklin and Davidson (1962) correlations are approximately the same for vertical upward orientation. Therefore, their performance is identical for all error bands and data sets. For the entire data set considered, Bonneczae et al. (1971) and Nicklin and Davidson (1962) correlations perform the best. But, prediction performance of Orell and Rembrand (1986) is higher than those two for the data sets of Sujumnong (1997), Fernandes (1981), Mukherjee (1979) and the data collected in the present study. Orell and Rembrand (1986) also gives the best performance for error band of ±5%, predicting 44% of the data points from the entire data set. Kataoka and Ishii (1987) predicts the same percentage of data points within ±15% as that of Orell and Rembrand (1986), but its prediction performance for ±5% and ±10% is lower than that of Orell and Rembrand (1986). Considering the pros and cons for each correlation, Nicklin and Davidson (1962) (or Bonneczae et al. (1971)) and Orell and Rembrand (1986) correlations are recommended for prediction of void fraction in slug flow. The performance of these two correlations for the entire data is shown in Figure 6.6.

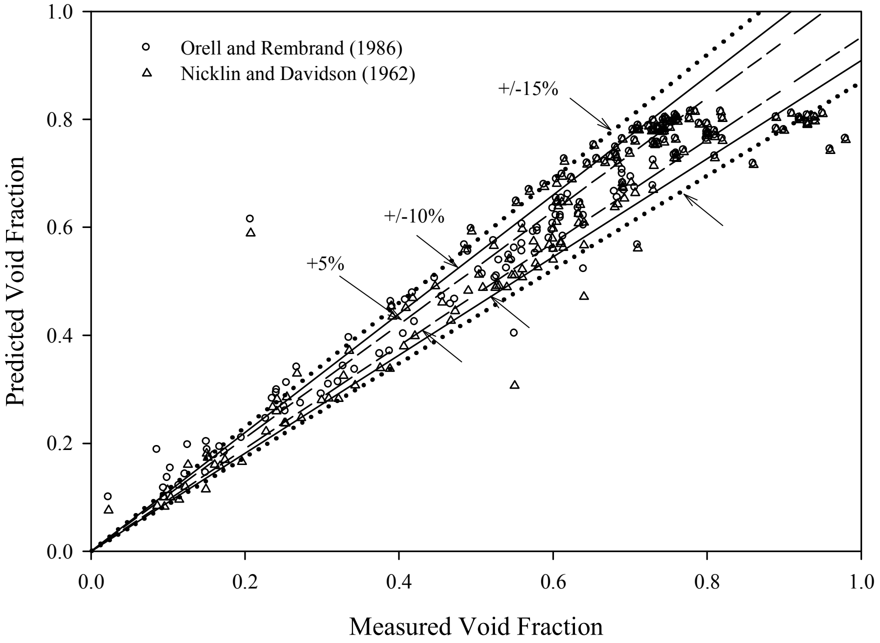


Figure 6.6 – Comparison of Orell and Rembrand (1986) and Nicklin and Davidson (1962) Correlations with All Slug Flow Data

Prediction of Nicklin and Davidson (1962) at lower void fraction values (below 0.3) is better than Orell and Rembrand (1986). Majority of those low void fraction data points are from Oshinowo (1971) data. Between void fraction values of 0.3 to 0.8, performance of Orell and Rembrand (1986) is better than Nicklin and Davidson (1962). Most of the values above 0.9 are from Mukherjee (1979) data and both of the correlations do not perform well for those data points. But, void fraction values above 0.9 for slug flow is also questionable.

Apart from the correlations considered in Table 6.6, correlations by Felizola and Shoham (1995), Abdul-Majeed and Al-Mashat (2000) were modeled numerically in Engineering Equation Solver. But, the convergence of these correlations was not achieved by the software. The criteria specified by Felizola and shoham (1995) for achieving convergence were followed, but still the prediction of void fraction was not achieved. Other numerically simple correlations predict void fraction with sufficient accuracy. Correlation of Guet et al. (2006) was also tried in Engineering Equation Solver, but it is very complicated and it requires Sauter mean diameter of entrained gas in liquid slug for entrainment rate due to pressure drop. Sauter mean diameter is not easily calculable. The need for such complicated models is questionable considering the good performance of simple models.

6.2.3 Comparison of Annular Flow Correlations with Experimental Data

A total of 139 data points were included for comparison of annular flow correlations with experimental data, as shown in Table 6.8.

As mentioned earlier in this chapter, void fraction in annular flow is higher than other flow patterns and therefore, the data is expected to be predicted within ±15%. In fact, the accuracy of prediction should be better than 15% (more data points are predicted within

5% and 10%). Table 6.9 shows the prediction performance of correlations for individual data sets. In Table 6.10, performance of correlations for all the annular flow data points is presented.

Table 6.8 – Sources of Data for Annular Flow

Source of Data	Number of Data Points
Present study	36
Sujumnong (1997)	38
Fernandes (1981)	19
Mukherjee (1979)	12
Oshinowo (1971)	34

Fauske (1961), Yao and Sylvetser (1987), Kabir and Hasan (1990) and Gomez et al. (2000) do not perform well. Prediction of these correlations within ±15% error band is of the order of 65% of the data points, which is not satisfactory for annular flow. Yao and Sylvester (1987) model appears to perform well for the data of present study, Mukherjee (1972) and Oshinowo (1971), but in reality it predicts results outside the logical values of void fraction (0 to 1). Chen (1986), Tandon et al. (1985), Zivi (1964), Lockhart and Martinelli (1949) and Smith (1969) models predict more than 85% of the data points within ±15%. Smith (1969) is the best performing correlation with 100% of the data points predicted within ±15% and 95.6% within ±10%. It is consistent in prediction of void fraction, predicting accurate void fraction values for all the data sets. But, Lockhart and Marinelli (1949), Tandon et al. (1985) and Chen (1986) correlations perform better than Smith (1969) correlation in ±5% error band. Lockhart and Martinelli (1949) correlation is the best correlation for error band of ±5%, predicting as high as 74.1% of the data points within ±5%. Performance of Lockhart and Martinelli (1949) and Smith (1969) is shown in Figure 6.7. Lockhart-Martinelli (1949) shows excellent performance at void fraction values above 0.9. All the data points are predicted within ±5%. But, below 0.9, its prediction is not consistent and it under-predicts some data points. The error values for some of the data points are high (up to 26%). Smith (1969) correlation over-predicts most of the data points.

Other than these models, Alves et al. (1991) correlation was studied. But, the equation used for calculating liquid film thickness is complicated and requires pressure drop relations for liquid and gas, which are not easy to calculate with the equations given in their work. Implicit equations are used for liquid film thickness and liquid superficial velocity. A logical order in which the model can be implemented is missing in their work.

Table 6.9 - Prediction Performance of Correlations with Individual Data Sets for Annular Flow

Correlation	Data Source and Percentage of Data Points Predicted Correctly														
	Present Study			Sujumnong (1997)			Fernandes (1981)			Mukherjee (1979)			Oshinowo (1971)		
	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Chen (1986)	69.4	94.4	100	52.6	73.6	78.9	55	70	75	83.3	91.6	100	91.1	100	100
Kabir and Hasan (1990)	0	0	13.8	36.8	55.2	68.4	10	30	80	50	83.3	100	8.8	58.8	91.1
Tandon et al. (1985)	38.8	72.2	88.8	47.3	76.3	76.3	55	70	75	66.6	91.6	100	97	100	100
Zivi (1964)*	30.5	77.7	88.8	63.1	76.3	76.3	60	65	80	75	91.6	100	29.4	91.1	100
Gomez et al. (2000)	0	0	13.8	36.8	55.2	68.4	10	30	80	50	83.3	100	8.8	58.8	91.1
Fauske (1961)	16.6	27.7	33.3	42.1	57.8	63.1	30	40	55	50	91.6	91.6	67.6	97	100
Lockhart and Martinelli (1949)**	86.1	100	100	73.6	78.9	86.8	60	75	85	75	100	100	70.5	100	100
Smith (1969)	30.5	97.2	100	73.6	97.3	100	75	95	100	75	91.6	100	32.3	94.1	100
Yao and Sylvetser (1987)	69.4	94.4	100	34.2	52.6	68.4	10	30	75	41.6	83.3	100	8.8	58.8	91.1

* From Tandon et al. (1985), **From Woldesemayat (2006)

Table 6.10 - Prediction Performance of Correlations with All Data for Slug Flow

Correlation	**Percentage of All Data Predicted Correctly**		
	±5%	±10%	±15%
Chen (1986)	69	86.3	90.6
Kabir and Hasan (1990)	17.2	40.2	64
Tandon et al. (1985)	59.7	81.2	87
Zivi (1964)*	46.7	79.8	87.7
Gomez et al. (2000)	17.2	40.2	64
Fauske (1961)	40.2	59.7	65.4
Lockhart and Martinelli (1949)**	74.1	90.6	94.2
Smith (1969)	52.5	95.6	100
Yao and Sylvetser (1987)	15.8	39.5	63.3

* From Tandon et al. (1985), **From Woldesemayat (2006)

6.2.4 Comparison of Churn Flow Correlations with Experimental Data

A total of 46 data points were included for comparison of churn flow correlations as shown in Table 6.11.

Other data sets were available, but they did not contain churn flow data. From the vast literature on two-phase flow, only few correlations are available for churn flow. Only three correlations could be traced for prediction of void fraction in churn flow. Their performance is shown in Tables 6.12 and 6.13.

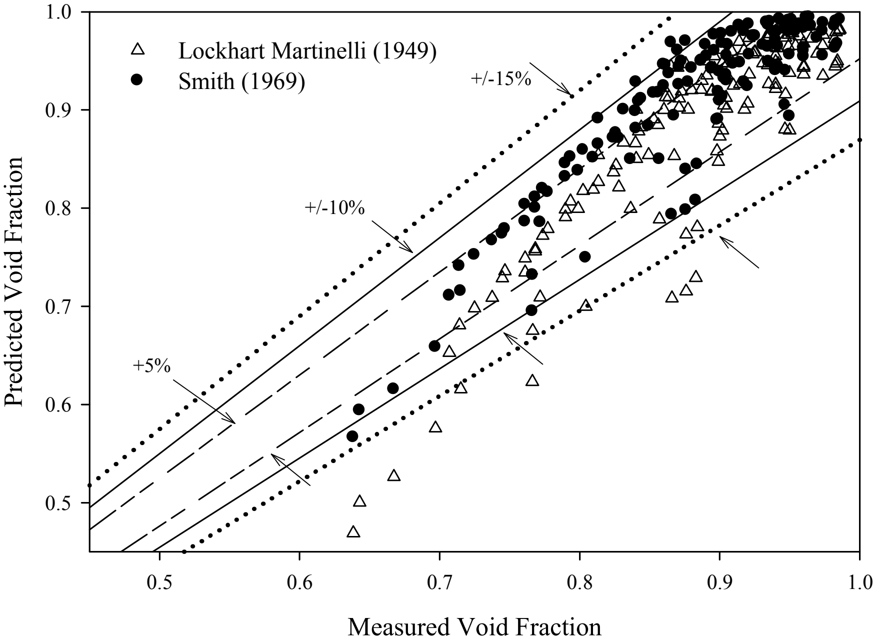


Figure 6.7 – Comparison of Smith (1969) and Lockhart and Martinelli (1949) Correlations with All Annular Flow Data

Table 6.11 – Sources of Data for Churn Flow

Source of Data	Number of Data Points
Present study	24
Sujumnong (1997)	12
Fernandes (1981)	10

Table 6.12 - Prediction Performance of Correlations with Individual Data Sets for Churn Flow

Correlation	Data Source and Percentage of Data Points Predicted Correctly								
	Present Study			Sujumnong (1997)			Fernandes (1981)		
	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Ellis and Jones (1965)[1]	16.6	33.3	54.1	0	0	0	0	0	0
Kabir and Hasan (1990)	41.6	66.6	83.3	75	100	100	50	90	100
Tangesdal et al. (1999)	8.3	16.6	33.3	0	0	0	10	50	70

1 - From Kaminaga (1992)

Table 6.13 - Prediction Performance of Correlations with All Data Sets for Churn Flow

Correlation	Percentage of All Data Predicted Correctly		
	±5%	±10%	±15%
Ellis and Jones (1965)	8.6	17.3	28.2
Kabir and Hasan (1990)	52.1	80.4	91.3
Tangesdal et al. (1999)	6.5	19.5	32.6

From Tables 6.12 and 6.13, it is clear that Kabir and Hasan (1990) model performs the best among the three for prediction of void fraction in churn flow. Prediction of Ellis and Jones (1965) and Tangesdal et al. (1999) is poor for all the data sets.

Comparison of the best performing correlation developed for churn flow (Kabir and Hasan (1990)) and all the data points for churn flow is shown in Figure 6.8.

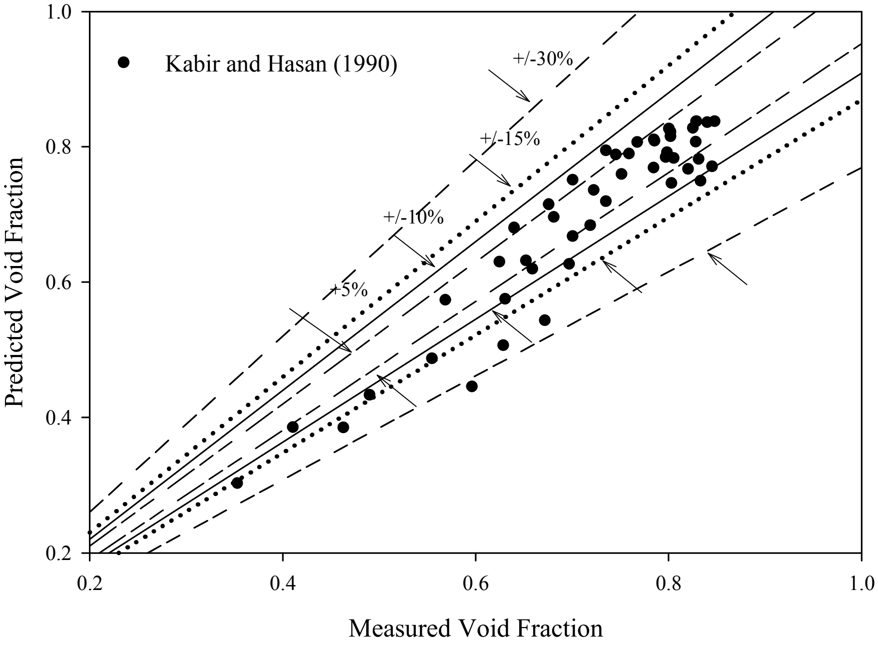


Figure 6.8 – Comparison of Kabir and Hasan (1990) Correlation for Churn Flow with All Churn Flow Data

Some researchers (For example, Mao and Dukler (1993)) have stated that the void fraction in churn flow could be predicted well by slug flow correlations. Therefore, two of the top performing correlations (Nicklin and Davidson (1962) and Orell and Rembrand (1986)) for slug flow were tested against churn flow data. The results are presented in Tables 6.14 and 6.15.

Table 6.14 - Prediction Performance of Top Slug Flow Correlations with Individual Data Sets for Churn Flow

Correlation	**Data Source and Percentage of Data Points Predicted Correctly**								
	Present Study			**Sujumnong (1997)**			**Fernandes (1981)**		
	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Nicklin and David son (1962)	62.5	87.5	91.6	91.6	100	100	30	70	100
Orell and Rembrand (1986)	75	87.5	95.8	91.6	100	100	40	70	100

Table 6.15 - Prediction Performance of Top Slug Flow Correlations with All Data for Churn Flow

Correlation	Percentage of All Data Predicted Correctly		
	±5%	±10%	±15%
Nicklin and Davidson (1962)	63	86.9	95.6
Orell and Rembrand (1986)	71.7	86.9	97.8

From the Tables 6.14 and 6.15, it is evident that slug flow correlations can be used to predict void fraction in churn flow and offer improved prediction in ±5%, ±10% and ±15% error bands compared to churn flow correlations used in the present study. Orell and Rembrand (1986) correlation is recommended for prediction of void fraction in churn flow. Performance of Orell and Rembrand (1986) correlation with all the data points for churn flow is shown in Figure 6.9.

6.2.5 Comparison of Applicable Correlations with Froth Flow Data

A total of 79 froth flow data points were used for comparisons as given in Table 6.16. There are no correlations available in the literature reviewed, which were developed to predict void fraction in froth flow. Froth flow is observed predominantly between churn and annular flow. There are limited correlations for churn flow and correlations of slug flow are found to predict churn flow data very well. Therefore, top performing correlations in slug (Nicklin and Davidson (1962) and Orell and Rembrand (1986)) and annular flow (Lockhart and Martinelli (1949) and Smith (1969)) were tested against the data of froth flow. Their performance is given in Tables 6.17 and 6.18.

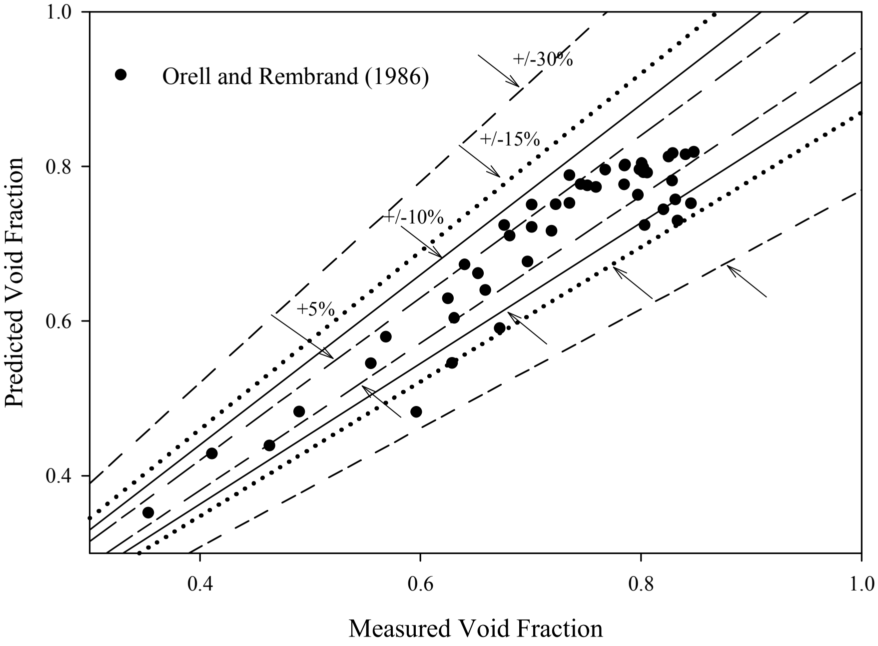


Figure 6.9 - Performance of Orell and Rembrand (1986) Correlation for Churn Flow Data

Table 6.16 – Sources of Data for Froth Flow

Source of Data	Number of Data Points
Present study	43
Sujumnong (1997)	11
Oshinowo (1971)	25

Table 6.17 - Prediction Performance of Top Slug and Annular Flow Correlations with Individual Data Sets for Froth Flow

Correlation	**Data Source and Percentage of Data Points Predicted Correctly**								
	Present Study			**Sujumnong (1997)**			**Oshinowo (1971)**		
	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Lockhart and Martinelli (1949)	27.9	46.5	51.1	0	0	0	72	80	92
Smith (1969)	34.8	74.4	86	0	0	72.7	64	80	96
Nicklin and Davidson (1962)	53.4	74.4	90.6	9	63.6	100	80	100	100
Orell and Rembrand (1986)	58.1	86	90.6	27.2	100	100	80	100	100

Table 6.18 - Prediction Performance of Top Slug and Annular Flow Correlations with All Data for Froth Flow

Correlation	Percentage of All Data Predicted Correctly		
	±5%	±10%	±15%
Lockhart and Martinelli (1949)	37.9	50.6	56.9
Smith (1969)	39.2	65.8	87.3
Nicklin and Davidson (1962)	55.6	81	94.9
Orell and Rembrand (1986)	60.7	92.4	94.9

It is observed that void fraction in froth flow is predicted very accurately by the two slug flow models (Nicklin and Davidson (1962) and Orell and Rembrand (1986)). Smith (1969) correlation for void fraction in annular flow does an acceptable job for prediction of void fraction in froth flow, but Lockhart and Martinelli (1949) correlation fails to predict void fraction accurately. Both Nicklin and Davidson (1962) and Orell and Rembrand (1986) predict void fraction better than Smith (1969) for ±5%, ±10% and ±15% error bands. Orell and Rembrand (1986) correlation gives the best prediction among the correlations considered for froth flow. Performance of Orell and Rembrand (1986) correlation with all the data points for froth flow is shown in Figure 6.10.

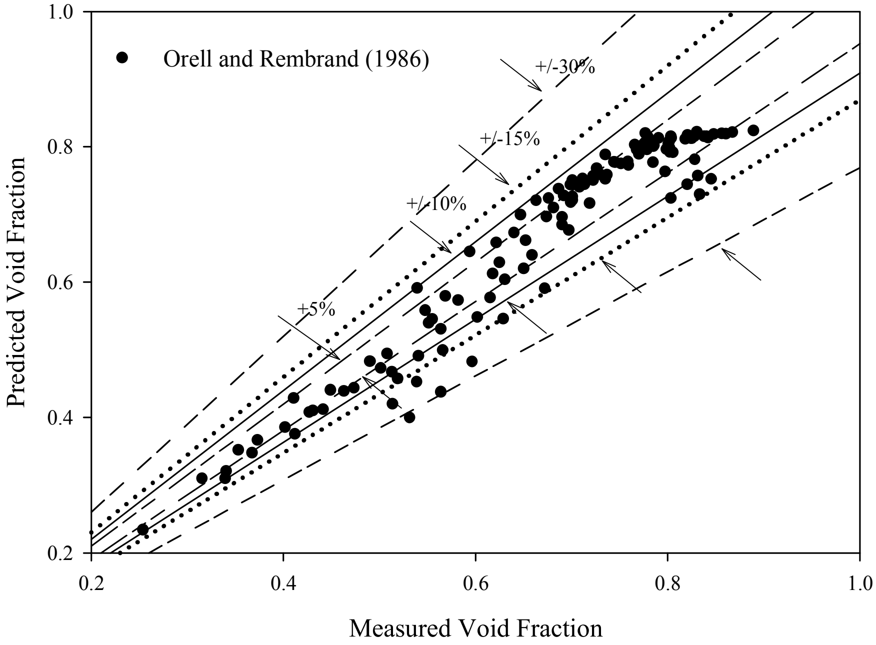


Figure 6.10 - Comparison of Orell and Rembrand (1986) Correlation with all Data of Froth Flow

CHAPTER VII

COMPARISON OF FLOW PATTERN INDEPENDENT VOID FRACTION CORRELATIONS

In this chapter, comparison of void fraction correlations for vertical upward two-phase flow is done against the data collected during present study and data gathered from the literature. The correlations considered in this chapter are not developed for a particular flow pattern. They can predict void fraction in any flow pattern if the properties of flow (Such as liquid and gas mass flow rates, temperature, pressure, liquid and gas viscosities) are known. Most of the correlations are developed for vertical upward flow. Others are either recommended or used by other researchers for prediction of void fraction in upward vertical flow. All the correlations are discussed in Chapter 2. There are 52 flow pattern independent void fraction correlations considered in this study for prediction of upward vertical two-phase flow.

As discussed in Chapter 6, percentage error was used for deciding the accuracy of the correlations. Three error bands (±5%, ±10% and ±15%) were used to check the prediction performance of correlations for individual data sets. Other error bands were introduced for the four void fraction ranges, discussed later. There is no fixed criterion used for deciding the accuracy of a correlation. Each data set and void fraction range is reviewed with respect to performance of all the correlations because uncertainty or inaccuracy related to each data could be different and its value is generally not stated in the literature. The flow parameters for each data set are also different.

For numerical modeling of correlations, Engineering Equation Solver was used. It employs a Newton-Raphson solver. It was helpful in solving complex iterative correlations. For some correlations, certain conditions were applied to achieve convergence or to obtain logical void fraction values. For example, Nishino and Yamazaki (1963) correlation (equation (2.87)) contains terms: α *and* $(1-\alpha)$ in the numerator and denominator, respectively. Hence, upper and lower limits for void fraction (α) were set as 0.000001 and 0.999999 respectively. Limits of void fraction for Ohkawa and Lahey (1980) correlation (equations (2.141) and (2.142)) were set between 0 and 1. Otherwise, the void fraction values predicted were out of the logical boundaries of 0 and 1. But, this strategy could not work for some of the correlations like Kutucuglu (equation (2.129)). Convergence was not achieved for many data points if limits of 0 and 1 were applied. Attempt was made to achieve convergence and logical prediction of void fraction for all correlations, but it was not always possible because of limitations of correlations.

Comparison of correlations with data and observations based on the results are now presented. It should be noted that the observations are based on the data available in the present study and care should be taken before extending them to other diameters and fluid combinations. Comparison for each data set is presented first, followed by comparison with all the data points.

A total of 1208 data points were used for the comparison. Different gas-fluid combinations and a wide range of diameters were used. The database used is presented in brief in Table 7.1. Details of the database are provided in Appendix A. Significant amount of data is available from different researchers, which ensures that one data set does not influence the final results.

Table 7.1 - Database Used for Upward Vertical Void Fraction Comparison (1208 Data Points)

Data Source	Diameter (m)	Fluid Combination	Number of Data Points
Present Study	0.0127	air-water	153
Schmidt et al. (2008)	0.0545	nitrogen-water	20
Sujumnong (1997)	0.0127	air-water	104
Sujumnong (1997)	0.0127	air-glycerin	77
Chokshi (1994)	0.076	air-water	103
Fernandes (1981)	0.05074	air-water	88
Mukherjee (1979)	0.0381	air-kerosene	65
Spedding and Nguyen (1976)	0.0455	air-water	224
Beggs (1972)	0.0254 and 0.0381	air-water	27
Oshinowo (1971)	0.0254	air-water	153
Oshinowo (1971)	0.0254	air-glycerin	172
Isbin et al. (1957)	0.02215	steam-water	22

Table 7.2 - Comparison of Prediction of Correlations with Air-Water Data of Present study

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	3.3	10.5	25.5
Armand and Masina[1]	52.9	84.3	93.5
Kowalczewski[2]	21.6	43.1	49
Kutucuglu[2]	11.1	28.1	35.3
Moussali[2]	11.8	24.2	37.9
Sterman (1956)	3.9	5.2	6.5
Filimonov et al. (1957)	10.5	24.8	47.1
Dimentiev et al. (1959)	10.5	21.6	28.1
Bankoff (1960)	4.6	23.5	58.2
Wilson et al. (1961)	5.9	15.7	19.6
Nicklin et al. (1962)	49.7	75.8	90.2
Hughmark (1962)	11.1	47.1	73.2
Nishino and Yamazaki (1963)	42.5	79.1	88.2
Thom (1964)	11.8	28.1	43.8
Neal and Bankoff (1965)	8.5	20.3	32.7
Baroczy (1966)	17.0	40.5	47.1
Guzhov et al. (1967)	60.1	86.9	93.5
Rouhani and Axelsson – I (1970)	49	59.5	80.4
Rouhani and Axelsson – II (1970)	26.8	65.4	85.6
Bonnecaze et al. (1971)	49.7	75.8	90.2
Premoli et al. (1971)	41.8	46.4	48.4
Dix (1971)	52.3	69.9	75.8
Chisholm (1973a)	43.1	82.4	92.2
Mattar and Gregory (1974)	0	9.8	39.2
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	28.1	40.5	57.5
Yamazaki and Yamaguchi (1976)	42.5	79.1	88.2
Lahey and Moody (1977)	3.9	9.8	28.1
Ishii (1977b)	30.7	48.4	56.9
Mukherjee (1979)	21.6	45.1	51.6
Sun et al. (1980)	37.3	54.9	65.4
Gardner – I (1980)	8.5	19	40.5
Gardner – II (1980)	7.8	17.6	30.7
Yeh and Hochreiter (1980)	2	7.8	13.7
Ohkawa and Lahey (1980)	43.1	47.1	52.9
Chisholm (1983)	46.4	83.7	92.2
Jowitt et al. (1984)	20.3	43.1	45.1
Spedding and Chen (1984)	22.9	47.1	55.6
Bestion (1985)	17.6	41.2	51
El-Boher et al. (1988)	19	60.8	79.1
Kokal and Stanislav (1989)	51.0	75.8	90.8
Sonneburgh (1989)	39.9	59.5	72.5
Morooka et al. (1989)	15.7	47.1	64.1
Spedding et al. (1990)	22.2	36.6	40.5
Chexal et al. (1992)	27.5	73.2	81
Takeuchi et al. (1992)	9.8	30.1	81
Huq and Loth (1992)	38.6	77.8	87.6
Inoue et al. (1993)	8.5	34.6	51
Shvarts et al. (1993)	3.9	19.6	49.7
Czop et al. (1994)	43.1	56.2	58.8
Maier and Coddington (1996)	9.8	43.8	46.4
Woldesemayat and Ghajar (2007)	30.7	73.9	81.7

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

7.1 Comparison of Correlations with Individual Experimental Data Sets

Table 7.2 presents comparison of 153 data points in present study with 52 correlations considered for comparison. Guzhov et al. (1967) correlation, which takes into consideration the effect of superficial velocities and diameter of pipe, gives the best performance in all the error bands (±5%, ±10% and ±15%) for the data collected in the present study. It predicts 93.5% of the data points within ±15% error. Correlations by Chisholm (1973a), Chisholm (1983), Nishino and Yamazaki (1963), Nishino and Yamazaki (1976) and Huq and Loth (1992) perform well for ±10% and ±15% error, but their performance for ±5% is not up to the mark. Other correlations which give good performance in all error bands are Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989) and Armand and Masina. It is interesting to note that none of the better performing correlations are complicated and iterative.

Comparison of nitrogen-water void fraction data of Schmidt et al. (2008) with prediction of correlations is presented in Table 7.3. A large diameter pipe (0.0545m) was used for this data. There were only 20 data points for this data set and therefore prediction performance of most of the correlations for ±15% error band is below 85%.

The correlations which give a satisfactory performance for nitrogen-water data of Schmidt et al. (2008) are Kokal and Stanislav (1989), Ishii (1977b) and Rouhani and Axelsson – I (1970). All the four are drift-velocity correlations. Each of them predicts 85% of the data points within ±15%. Dimentiev et al. (1975), Morooka et al. (1989) and El-Boher et al. (1988) achieve good prediction for ±10% error band. Morooka et al. (1989) gives the best performance within ±5% error, predicting 65% of the data points.

Table 7.3 – Comparison of Prediction of Correlations with Nitrogen-Water Data of Schmidt et al. (2008)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	10	50	70
Armand and Masina[1]	20	70	75
Kowalczewski[2]	15	40	40
Kutucuglu[2]	10	10	20
Moussali[2]	15	40	65
Sterman (1956)	0	10	10
Filimonov et al. (1957)	35	70	80
Dimentiev et al. (1959)	25	75	80
Bankoff (1960)	10	10	20
Wilson et al. (1961)	5	15	15
Nicklin et al. (1962)	15	40	80
Hughmark (1962)	55	70	80
Nishino and Yamazaki (1963)	15	50	75
Thom (1964)	15	30	40
Neal and Bankoff (1965)	0	5	5
Baroczy (1966)	20	25	40
Guzhov et al. (1967)	15	40	75
Rouhani and Axelsson – I (1970)	25	55	85
Rouhani and Axelsson – II (1970)	35	55	65
Bonnecaze et al. (1971)	15	40	80
Premoli et al. (1971)	50	55	75
Dix (1971)	20	60	80
Chisholm (1973a)	25	65	80
Mattar and Gregory (1974)	0	0	0
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	20	20	35
Yamazaki and Yamaguchi (1976)	15	50	75
Lahey and Moody (1977)	35	65	75
Ishii (1977b)	15	60	85
Mukherjee (1979)	30	50	55
Sun et al. (1980)	5	45	75
Gardner – I (1980)	15	20	40
Gardner – II (1980)	15	25	30
Yeh and Hochreiter (1980)	15	25	35
Ohkawa and Lahey (1980)	0	55	75
Chisholm (1983)	25	65	80
Jowitt et al. (1984)	0	25	60
Spedding and Chen (1984)	20	25	45
Bestion (1985)	15	20	65
El-Boher et al. (1988)	55	75	80
Kokal and Stanislav (1989)	15	40	85
Sonneburgh (1989)	0	5	10
Morooka et al. (1989)	65	75	80
Spedding et al. (1990)	15	20	30
Chexal et al. (1992)	60	70	80
Takeuchi et al. (1992)	15	20	20
Huq and Loth (1992)	15	50	75
Inoue et al. (1993)	55	60	65
Shvarts et al. (1993)	40	70	70
Czop et al. (1994)	20	30	45
Maier and Coddington (1996)	35	45	60
Woldesemayat and Ghajar (2007)	20	55	75

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

In Table 7.4, the comparison of correlations with the 104 air-water data points of Sujumnong (1997) is shown. Characteristic of this data set is high gas velocities.

Correlation of Ishii (1977b) gives the best performance in ±15% and ±10%, predicting as high as 94.2% and 86.5% of data, respectively. Woldesemayat and Ghajar (2007) correlation predicts the highest number of data points within ±5% error. Other correlations worth mentioning for this data set are – Takeuchi et al. (1992), Filimonov et al. (1957), Chisholm (1973a), Chisholm (1983), Morooka et al. (1989) and Ohkawa and Lahey (1980). All these correlations predict more than 85% of the data within ±15% and more than 75% data within ±10%.

Prediction performance of the 52 correlations for the 77 air-59% glycerin data points of Sujumnong (1997) is presented in Table 7.5. Important point about this data set is the viscosity of glycerin solution, which is higher than that of water.

A note about Premoli et al. (1971) correlation (equation (2.92)) should be mentioned here. As discussed in Chapter 2, this correlation does not converge if value of the term *y*F2* in the correlation becomes greater than a critical value. This is particularly observed for high viscosity fluids. Therefore, convergence for all data points was not achieved in this data set for Premoli et al. (1971) correlation. Those data points were assigned a predicted value of 0 and performance was evaluated. Same procedure was also followed for data of Mukherjee (1979), discussed later.

Excellent performance of Ishii (1977b) for high gas velocity data of Sujumnong (1997) continues for air-glycerin data. It gives the best prediction performance for ±10% and ±15% error band, predicting 85.7% and 92.2% of data points, respectively. It also exhibits high accuracy by predicting 53.2% of the data within ±5%. Other correlations

Table 7.4 - Comparison of Prediction of Correlations with Air-Water Data of Sujumnong (1997)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	24	44.2	59.6
Armand and Masina[1]	39.4	67.3	76
Kowalczewski[2]	37.5	47.1	49
Kutucuglu[2]	25	31.7	39.4
Moussali[2]	25	40.4	52.9
Sterman (1956)	0	1	1
Filimonov et al. (1957)	36.5	67.3	86.5
Dimentiev et al. (1959)	3.8	8.7	11.5
Bankoff (1960)	1.9	5.8	25
Wilson et al. (1961)	2.9	6.7	6.7
Nicklin et al. (1962)	31.7	57.7	81.7
Hughmark (1962)	49	67.3	76
Nishino and Yamazaki (1963)	41.3	58.7	77.9
Thom (1964)	19.2	38.5	45.2
Neal and Bankoff (1965)	5.8	10.6	19.2
Baroczy (1966)	35.6	44.2	45.2
Guzhov et al. (1967)	23.1	40.4	61.5
Rouhani and Axelsson – I (1970)	26.9	60.6	76
Rouhani and Axelsson – II (1970)	28.4	60.2	78.4
Bonnecaze et al. (1971)	31.7	57.7	81.7
Premoli et al. (1971)	46.2	57.7	68.3
Dix (1971)	55.8	63.5	71.2
Chisholm (1973a)	47.1	76	90.4
Mattar and Gregory (1974)	0	1	18.3
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	29.8	60.6	79.8
Yamazaki and Yamaguchi (1976)	0	0	0
Lahey and Moody (1977)	36.5	62.5	79.8
Ishii (1977b)	37.5	86.5	94.2
Mukherjee (1979)	37.5	60.6	70.2
Sun et al. (1980)	19.2	48.1	72.1
Gardner – I (1980)	20.2	33.7	36.5
Gardner – II (1980)	20.2	31.7	39.4
Yeh and Hochreiter (1980)	21.2	30.8	41.3
Ohkawa and Lahey (1980)	50	77.9	87.5
Chisholm (1983)	47.1	76	90.4
Jowitt et al. (1984)	8.7	28.8	58.7
Spedding and Chen (1984)	42.3	51.9	59.6
Bestion (1985)	40.4	54.8	82.7
El-Boher et al. (1988)	34.6	48.1	57.7
Kokal and Stanislav (1989)	31.7	57.7	81.7
Sonneburgh (1989)	10.6	31.7	45.2
Morooka et al. (1989)	46.2	85.6	93.3
Spedding et al. (1990)	31.7	41.3	44.2
Chexal et al. (1992)	45.2	64.4	72.1
Takeuchi et al. (1992)	36.5	67.3	93.3
Huq and Loth (1992)	38.5	58.7	76.9
Inoue et al. (1993)	49	74	82.7
Shvarts et al. (1993)	38.5	59.6	81.7
Czop et al. (1994)	13.5	23.1	39.4
Maier and Coddington (1996)	31.7	48.1	51
Woldesemayat and Ghajar (2007)	57.7	61.5	69.2

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

which predict more than 85% of the data for ±15% error band are: Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Lahey and Moody (1977) and Rouhani and Axelsson – I (1970). Performance of Ohkawa and Lahey (1980) is not excellent for ±15% error, but it predicts the highest percentage (57.1%) of the data points within ±5% and as high as 76.6% of the data points within ±10%.

The next data set compared with the correlations is by Chokshi (1994). The data was taken in a 0.076 m pipe, which is the highest diameter studied. Air and water were used as gas and liquid phases and 103 data points were collected. Prediction performance of correlations is demonstrated in Table 7.6. No correlation is capable of predicting the data above 80% for ±15% error band. This is an indication of incapability of correlations to handle large diameter data because many correlations give a satisfactory prediction for the same fluid combination in smaller diameter pipes.

Sun et al. (1980) correlation offers the best prediction performance for ±15% error criterion. It predicts 79.6% of the data points within ±15%. For ±10% and ±5% error band, Ohkawa and Lahey (1980) correlation gives the best performance. Percentage of the data points predicted by Ohkawa and Lahey (1980) is 66% for ±10% error and 46.6% for ±5% error. Other correlations which give a satisfactory performance for this large diameter data are: Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Maier and Coddington (1996), Inoue et al. (1993), Bestion (1985), Takeuchi et al. (1992), Lahey and Moody (1977), Ishii (1977b) Rouhani and Axelsson – I and II (1970) and Dix (1971).

Table7.5 - Comparison of Prediction of Correlations with Air-Glycerin Data of Sujumnong (1997)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	7.8	19.5	28.6
Armand and Masina[1]	37.7	55.8	77.9
Kowalczewski[2]	16.9	31.2	39
Kutucuglu[2]	9.1	14.3	18.2
Moussali[2]	10.4	24.7	37.7
Sterman (1956)	1.3	1.3	3.9
Filimonov et al. (1957)	20.8	35.1	49.4
Dimentiev et al. (1959)	3.9	7.8	14.3
Bankoff (1960)	15.6	32.5	48.1
Wilson et al. (1961)	5.2	11.7	14.3
Nicklin et al. (1962)	39	75.3	88.3
Hughmark (1962)	44.2	62.3	71.4
Nishino and Yamazaki (1963)	36.4	67.5	80.5
Thom (1964)	11.7	20.8	27.3
Neal and Bankoff (1965)	2.6	6.5	6.5
Baroczy (1966)	10.4	19.5	29.9
Guzhov et al. (1967)	28.6	59.7	80.5
Rouhani and Axelsson – I (1970)	45.5	72.7	88.3
Rouhani and Axelsson – II (1970)	32.5	54.5	76.6
Bonnecaze et al. (1971)	39	75.3	88.3
Premoli et al. (1971)	27.3	37.7	41.6
Dix (1971)	33.8	55.8	66.2
Chisholm (1973a)	40.3	68.8	79.2
Mattar and Gregory (1974)	2.6	22.1	46.8
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	16.9	28.6	44.2
Yamazaki and Yamaguchi (1976)	36.4	67.5	80.5
Lahey and Moody (1977)	19.5	48.1	66.2
Ishii (1977b)	53.2	85.7	92.2
Mukherjee (1979)	27.3	44.2	63.6
Sun et al. (1980)	40.3	71.4	85.7
Gardner – I (1980)	5.2	9.1	15.6
Gardner – II (1980)	3.9	7.8	13
Yeh and Hochreiter (1980)	9.1	14.3	27.3
Ohkawa and Lahey (1980)	57.1	76.6	84.4
Chisholm (1983)	37.7	68.8	79.2
Jowitt et al. (1984)	29.9	48.1	64.9
Spedding and Chen (1984)	16.9	41.6	59.7
Bestion (1985)	22.1	41.6	75.3
El-Boher et al. (1988)	33.8	48.1	61
Kokal and Stanislav (1989)	39	75.3	88.3
Sonneburgh (1989)	19.5	41.6	50.6
Morooka et al. (1989)	28.6	63.6	81.8
Spedding et al. (1990)	13	28.6	33.8
Chexal et al. (1992)	44.2	64.9	76.6
Takeuchi et al. (1992)	33.8	51.9	76.6
Huq and Loth (1992)	37.7	68.8	80.5
Inoue et al. (1993)	22.1	53.2	75.3
Shvarts et al. (1993)	27.3	37.7	64.9
Czop et al. (1994)	16.9	41.6	50.6
Maier and Coddington (1996)	14.3	33.8	46.8
Woldesemayat and Ghajar (2007)	36.4	51.9	66.2

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

The 88 data points of Fernandes (1981) were also collected in a large diameter (0.05074 m) pipe. This data set again brings forward the limitation of prediction of void fraction in large diameter pipes. Performance of correlations for this data set is shown in Table 7.7. Only three correlations are capable of predicting greater than 80% of data within ±15%. The best performance is provided by Ishii (1977b) correlation. Its prediction for ±10% and ±15% error bands is 61.4% and 81.8%, respectively. Best prediction for ±5% error band is given by Rouhani and Axelsson – I (1970). It predicts 34.1% of data within ±5%. Other than these, Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Takeuchi et al. (1992) and Guzhov et al. (1967) provide reasonable prediction of data within ±15%. Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Premoli et al. (1971), Takeuchi et al. (1992), Chisholm (1973a), Chisholm (1983), Rouhani and Axelsson – I (1970) and Huq and Loth (1992) give an acceptable performance for ±10% error criterion. For ±5% error band, Premoli et al. (1971), Inoue et al. (1993), Takeuchi et al. (1992) and Morooka et al. (1989) predict more than 30% of the data points.

In Table 7.8, air-kerosene data (65 data points) of Mukherjee (1979) is compared with the prediction of correlations. It is important to note that viscosity of kerosene is higher than water and surface tension is lower than water.

None of the correlations offer a satisfactory prediction for data set of Mukherjee (1979). Filimonov et al. (1957) correlation gives the best prediction performance, with 75.4% prediction of the data points within ±15%. Greskovich and Cooper (1975) and Shvarts et al. (1993) give the best performance in ±10% and ±5% error band, respectively.

Table 7.6 - Comparison of Prediction of Correlations with Air-Water Data of Chokshi (1994)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	0	17.5	31.1
Armand and Masina[1]	32	46.6	54.4
Kowalczewski[2]	27.2	50.5	58.3
Kutucuglu[2]	0	0	0
Moussali[2]	2.9	20.4	32
Sterman (1956)	1	1	1
Filimonov et al. (1957)	31.1	50.5	68.9
Dimentiev et al. (1959)	5.8	10.7	18.4
Bankoff (1960)	27.2	36.9	51.5
Wilson et al. (1961)	2.9	4.9	5.8
Nicklin et al. (1962)	24.3	52.4	78.6
Hughmark (1962)	29.1	49.5	69.9
Nishino and Yamazaki (1963)	27.2	65	74.8
Thom (1964)	33	52.4	65
Neal and Bankoff (1965)	10.7	26.2	40.8
Baroczy (1966)	35.9	59.2	69.9
Guzhov et al. (1967)	14.6	39.8	72.8
Rouhani and Axelsson – I (1970)	29.1	58.3	76.7
Rouhani and Axelsson – II (1970)	27.2	56.3	75.7
Bonnecaze et al. (1971)	24.3	53.4	78.6
Premoli et al. (1971)	28.2	39.8	50.5
Dix (1971)	33	58.3	76.7
Chisholm (1973a)	31.1	46.6	68.9
Mattar and Gregory (1974)	7.8	20.4	48.5
Madsen (1975)	0	0	1
Greskovich and Cooper (1975)	30.1	47.6	68
Yamazaki and Yamaguchi (1976)	27.2	65	74.8
Lahey and Moody (1977)	19.4	51.5	75.7
Ishii (1977b)	32	58.3	77.7
Mukherjee (1979)	20.4	47.6	68
Sun et al. (1980)	16.5	49.5	79.6
Gardner – I (1980)	8.7	18.4	35
Gardner – II (1980)	2.9	11.7	22.3
Yeh and Hochreiter (1980)	1.9	11.7	24.3
Ohkawa and Lahey (1980)	46.6	66	74.8
Chisholm (1983)	27.2	47.6	72.8
Jowitt et al. (1984)	4.9	17.5	32
Spedding and Chen (1984)	25.2	47.6	70.9
Bestion (1985)	34	55.3	75.7
El-Boher et al. (1988)	35.9	59.2	71.8
Kokal and Stanislav (1989)	24.3	54.4	78.6
Sonneburgh (1989)	2.9	7.8	21.4
Morooka et al. (1989)	31.1	61.2	73.8
Spedding et al. (1990)	21.4	30.1	41.7
Chexal et al. (1992)	18.4	38.8	43.7
Takeuchi et al. (1992)	30.1	56.3	78.6
Huq and Loth (1992)	28.2	48.5	72.8
Inoue et al. (1993)	38.8	63.1	75.7
Shvarts et al. (1993)	30.1	50.5	68.9
Czop et al. (1994)	21.4	38.8	65
Maier and Coddington (1996)	46.6	60.2	75.7
Woldesemayat and Ghajar (2007)	32	46.6	59.2

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.7 - Comparison of Prediction of Correlations with Air-Water Data of Fernandes (1981)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	6.8	28.4	37.5
Armand and Masina[1]	14.8	44.3	59.1
Kowalczewski[2]	20.5	30.7	42
Kutucuglu[2]	17	20.5	30.7
Moussali[2]	5.7	31.8	39.8
Sterman (1956)	0	8	17
Filimonov et al. (1957)	18.2	46.6	56.8
Dimentiev et al. (1959)	1.1	10.2	21.6
Bankoff (1960)	11.4	25	31.8
Wilson et al. (1961)	4.5	8	10.2
Nicklin et al. (1962)	22.7	56.8	76.1
Hughmark (1962)	40.9	58	68.2
Nishino and Yamazaki (1963)	28.4	48.9	68.2
Thom (1964)	17	34.1	42
Neal and Bankoff (1965)	11.4	13.6	19.3
Baroczy (1966)	17	33	40.9
Guzhov et al. (1967)	23.9	46.6	80.7
Rouhani and Axelsson – I (1970)	34.1	60.2	73.9
Rouhani and Axelsson – II (1970)	31.8	46.6	62.5
Bonnecaze et al. (1971)	22.7	55.7	76.1
Premoli et al. (1971)	33	50	65.9
Dix (1971)	20.5	35.2	51.1
Chisholm (1973a)	33	53.4	61.4
Mattar and Gregory (1974)	3.4	4.5	9.1
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	25	48.9	71.6
Yamazaki and Yamaguchi (1976)	28.4	48.9	68.2
Lahey and Moody (1977)	13.6	34.1	44.3
Ishii (1977b)	23.9	61.4	81.8
Mukherjee (1979)	22.7	38.6	45.5
Sun et al. (1980)	21.6	43.2	72.7
Gardner – I (1980)	15.9	43.2	51.1
Gardner – II (1980)	15.9	47.7	56.8
Yeh and Hochreiter (1980)	4.5	14.8	26.1
Ohkawa and Lahey (1980)	14.8	33	51.1
Chisholm (1983)	33	53.4	61.4
Jowitt et al. (1984)	0	22.7	30.7
Spedding and Chen (1984)	22.7	40.9	52.3
Bestion (1985)	0	8	39.8
El-Boher et al. (1988)	29.5	37.5	52.3
Kokal and Stanislav (1989)	23.9	55.7	76.1
Sonneburgh (1989)	1.1	9.1	25
Morooka et al. (1989)	31.8	46.6	62.5
Spedding et al. (1990)	21.6	31.8	44.3
Chexal et al. (1992)	29.5	52.3	63.6
Takeuchi et al. (1992)	33	60.2	76.1
Huq and Loth (1992)	28.4	51.1	68.2
Inoue et al. (1993)	30.7	35.2	39.8
Shvarts et al. (1993)	22.7	43.2	52.3
Czop et al. (1994)	11.4	22.7	48.9
Maier and Coddington (1996)	23.9	31.8	38.6
Woldesemayat and Ghajar (2007)	21.6	33	42

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Greskovich and Cooper (1975) correlation predicts 67.7% of data points within ±10% and Shvarts et al. (1993) predicts 53.8% of the data points within ±5%. Other than Shvarts et al. (1993), only Greskovich and Cooper (1975) and Filimonov et al. (1957) correlations give a reasonable prediction in ±5% band, predicting 46.2% and 50.8% of the data points respectively. For ±15% error band, Chexal et al. (1992), Chisholm (1973a), Chisholm (1983), Armand and Masina, Greskovich and Cooper (1975), Morooka et al. (1989), Woldesemayat and Ghajar (2007) and Shvarts et al. (1993) predict more than 70% of the data points within ±15% error band. Correlations by Filimonov et al. (1957), Chisholm (1973a), Chisholm (1983), Armand and Masina, Morooka et al. (1989), Dix (1971), Woldesemayat and Ghajar (2007) and Shvarts et al. (1993) predict more than 60% of the data points within ±10%.

For the 224 air-water data points of Spedding and Nguyen (1976), as shown in Table 7.9, Takeuchi et al. (1992) correlation predicts the highest percentage of the data points within ±15%. It predicts 93.8% of the data points within ±15% error band. Other correlations which offer a comparable prediction within ±15% error band are – Greskovich and Cooper (1975) and Morooka et al. (1989). These correlations predict greater than 85% of the data points within ±15%. Morooka et al. (1989) correlation predicts the highest percentage (83%) of the data points within ±10%. Correlations by Chexal et al. (1992), Takeuchi et al. (1992), Rouhani and Axelsson – I (1970) and Dix (1971) predict greater than 75% of data within ±10%. Dix (1971) correlation gives the best prediction (62.9%) for error band of ±5%. Other than Dix (1971), Premoli et al. (1971), Sonnenburgh (1989), El-Boher et al. (1988) and Woldesemayat and Ghajar (2007) perform well for ±5% error band.

Table 7.8 - Comparison of Prediction of Correlations with Air-Kerosene Data of Mukherjee (1979)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	26.2	53.8	63.1
Armand and Masina[1]	38.5	61.5	72.3
Kowalczewski[2]	33.8	49.2	55.4
Kutucuglu[2]	29.2	41.5	50.8
Moussali[2]	24.6	46.2	63.1
Sterman (1956)	1.5	1.5	1.5
Filimonov et al. (1957)	50.8	66.2	75.4
Dimentiev et al. (1959)	10.8	26.2	33.8
Bankoff (1960)	0	0	18.5
Wilson et al. (1961)	1.5	4.6	6.2
Nicklin et al. (1962)	13.8	27.7	61.5
Hughmark (1962)	44.6	61.5	69.2
Nishino and Yamazaki (1963)	35.4	53.8	66.2
Thom (1964)	29.2	44.6	53.8
Neal and Bankoff (1965)	9.2	15.4	16.9
Baroczy (1966)	36.9	47.7	55.4
Guzhov et al. (1967)	18.5	26.2	49.2
Rouhani and Axelsson – I (1970)	26.2	55.4	66.2
Rouhani and Axelsson – II (1970)	6.1	23.1	53.8
Bonnecaze et al. (1971)	13.8	27.7	61.5
Premoli et al. (1971)	44.6	61.5	63.1
Dix (1971)	40	63.1	66.2
Chisholm (1973a)	36.9	63.1	72.3
Mattar and Gregory (1974)	0	0	3.1
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	46.2	67.7	72.3
Yamazaki and Yamaguchi (1976)	35.4	53.8	66.2
Lahey and Moody (1977)	30.8	52.3	64.6
Ishii (1977b)	32.3	55.4	67.7
Mukherjee (1979)	24.6	40	49.2
Sun et al. (1980)	12.3	26.2	49.2
Gardner – I (1980)	23.1	43.1	56.9
Gardner – II (1980)	20	41.5	52.3
Yeh and Hochreiter (1980)	10.8	36.9	49.2
Ohkawa and Lahey (1980)	20	52.3	64.6
Chisholm (1983)	36.9	60	70.8
Jowitt et al. (1984)	1.5	1.5	4.6
Spedding and Chen (1984)	35.4	43.1	50.8
Bestion (1985)	13.8	43.1	67.7
El-Boher et al. (1988)	12.3	41.5	66.2
Kokal and Stanislav (1989)	13.8	27.7	61.5
Sonneburgh (1989)	3.1	9.2	12.3
Morooka et al. (1989)	29.2	66.2	70.8
Spedding et al. (1990)	38.5	52.3	58.5
Chexal et al. (1992)	38.5	56.9	70.8
Takeuchi et al. (1992)	41.5	53.8	67.7
Huq and Loth (1992)	30.8	55.4	66.2
Inoue et al. (1993)	40	56.9	67.7
Shvarts et al. (1993)	53.8	66.2	72.3
Czop et al. (1994)	13.8	20	47.7
Maier and Coddington (1996)	40	53.8	60
Woldesemayat and Ghajar (2007)	38.5	61.5	70.8

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.9 - Comparison of Prediction of Correlations with Air-Water Data of Spedding and Nguyen (1976)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	15.2	24.6	35.3
Armand and Masina[1]	31.3	58.5	65.6
Kowalczewski[2]	43.3	52.7	61.2
Kutucuglu[2]	35.3	44.2	52.7
Moussali[2]	15.6	25	35.7
Sterman (1956)	3.1	6.7	11.2
Filimonov et al. (1957)	34.4	60.3	80.4
Dimentiev et al. (1959)	11.6	25.4	37.9
Bankoff (1960)	14.3	24.1	36.2
Wilson et al. (1961)	5.4	12.1	19.6
Nicklin et al. (1962)	40.2	62.5	80.8
Hughmark (1962)	45.1	71.4	77.2
Nishino and Yamazaki (1963)	52.2	63.8	70.5
Thom (1964)	27.7	49.1	56.7
Neal and Bankoff (1965)	10.7	20.1	29.9
Baroczy (1966)	42.9	55.8	67
Guzhov et al. (1967)	22.3	48.2	71
Rouhani and Axelsson – I (1970)	47.8	80.8	84.4
Rouhani and Axelsson – II (1970)	19.2	41.1	57.6
Bonnecaze et al. (1971)	40.2	62.5	80.8
Premoli et al. (1971)	58.5	73.2	79
Dix (1971)	62.9	75	83.9
Chisholm (1973a)	45.1	56.3	65.2
Mattar and Gregory (1974)	0	1.3	19.2
Madsen (1975)	0	1.8	2.2
Greskovich and Cooper (1975)	34.4	60.3	86.2
Yamazaki and Yamaguchi (1976)	52.2	63.8	70.5
Lahey and Moody (1977)	32.1	52.2	76.3
Ishii (1977b)	37.5	58.9	75
Mukherjee (1979)	48.2	60.7	71
Sun et al. (1980)	37.5	58.9	75
Gardner – I (1980)	27.7	48.2	65.6
Gardner – II (1980)	27.7	48.2	65.6
Yeh and Hochreiter (1980)	19.2	31.7	41.1
Ohkawa and Lahey (1980)	13.4	37.9	39.7
Chisholm (1983)	46.9	56.7	65.2
Jowitt et al. (1984)	13.4	33.5	59.8
Spedding and Chen (1984)	45.1	55.8	71
Bestion (1985)	12.9	29	63.4
El-Boher et al. (1988)	62.5	74.1	83.5
Kokal and Stanislav (1989)	39.7	62.1	79.9
Sonneburgh (1989)	58.5	73.2	79
Morooka et al. (1989)	46.9	83	89.7
Spedding et al. (1990)	40.6	48.7	59.4
Chexal et al. (1992)	45.5	75.9	83.9
Takeuchi et al. (1992)	47.3	79	93.8
Huq and Loth (1992)	50	62.1	70.1
Inoue et al. (1993)	42.4	58.9	63.4
Shvarts et al. (1993)	32.1	57.1	71.4
Czop et al. (1994)	17.4	37.5	54.5
Maier and Coddington (1996)	40.2	55.8	59.8
Woldesemayat and Ghajar (2007)	62.5	74.1	82.1

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.10 demonstrates comparison of the 27 air-water data points of Beggs (1972) and the prediction of correlations. Number of data points in this data set is small, but many correlations perform superbly. Chisholm (1973a), Chisholm (1983) and Dix (1971) give the best performance for ±15% error criterion, predicting 96.3% data. Chisholm (1973a) and Woldesemayat and Ghajar (2007) give the top prediction for ±10% and ±5%, respectively. Correlations which predict more than 90% of data within ±15%, more than 85% of data within ±10% and more than 60% of data within ±5% are: Chexal et al. (1992), Hughmark (1962), Chisholm (1973a), Armand and Masina, Dix (1971) and Woldesemayat and Ghajar (2007).

In Table 7.11, comparison of the 153 air-water data points of Oshinowo (1971) for void fraction predictd by correlations is presented. Premoli et al. (1971), Ishii (1977b) and Ohkawa and Lahey (1980) provide the best performance (98%) for ±15% error band. This percentage is really high for the large amount of data present in this data set (153 data points). For ±10% error band, Ohkawa and Lahey (1980) correlation performs the best, calculating 93.5% of data. Performance of all the correlations for the highest accuracy level (±5%) is not as good as for ±10% and ±15% error bands. Ohkawa and Lahey (1980) correlation tops the performance for ±5%, predicting 58.8% of the data points. Premoli et al. (1971) correlation also does a very good job in all the three error bands. Other correlations, which perform well are: Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Sun et al. (1980), Ishii (1977b), Nishino and Yamazaki (1963), Spedding and Chen (1984), Nishino and Yamazaki (1976) and Rouhani and Axelsson – I (1970).

Table 7.10 - Comparison of Prediction of Correlations with Air-Water Data of Beggs (1972)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	18.5	33.3	51.9
Armand and Masina[1]	63	88.9	92.6
Kowalczewski[2]	37	51.9	55.6
Kutucuglu[2]	22.2	44.4	55.6
Moussali[2]	22.2	40.7	66.7
Sterman (1956)	0	0	0
Filimonov et al. (1957)	70.4	88.9	88.9
Dimentiev et al. (1959)	11.1	18.5	29.6
Bankoff (1960)	0	7.4	18.5
Wilson et al. (1961)	0	7.4	14.8
Nicklin et al. (1962)	11.1	51.9	85.2
Hughmark (1962)	74.1	85.2	92.6
Nishino and Yamazaki (1963)	48.1	66.7	88.9
Thom (1964)	33.3	48.1	59.3
Neal and Bankoff (1965)	11.1	18.5	22.2
Baroczy (1966)	33.3	51.9	55.6
Guzhov et al. (1967)	29.6	63	77.8
Rouhani and Axelsson – I (1970)	48.1	81.5	92.6
Rouhani and Axelsson – II (1970)	33.3	51.9	77.8
Bonnecaze et al. (1971)	11.1	51.9	85.2
Premoli et al. (1971)	55.6	81.5	88.9
Dix (1971)	63	88.9	96.3
Chisholm (1973a)	63	92.6	96.3
Mattar and Gregory (1974)	0	0	0
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	55.6	85.2	92.6
Yamazaki and Yamaguchi (1976)	48.1	66.7	88.9
Lahey and Moody (1977)	37	70.4	88.9
Ishii (1977b)	55.6	77.8	92.6
Mukherjee (1979)	33.3	37	55.6
Sun et al. (1980)	7.4	48.1	70.4
Gardner – I (1980)	29.6	44.4	51.9
Gardner – II (1980)	29.6	40.7	55.6
Yeh and Hochreiter (1980)	29.6	48.1	59.3
Ohkawa and Lahey (1980)	0	44.4	77.8
Chisholm (1983)	59.3	88.9	96.3
Jowitt et al. (1984)	0	0	0
Spedding and Chen (1984)	29.6	44.4	55.6
Bestion (1985)	22.2	37	85.2
El-Boher et al. (1988)	33.3	74.1	85.2
Kokal and Stanislav (1989)	11.1	51.9	85.2
Sonneburgh (1989)	7.4	33.3	37
Morooka et al. (1989)	44.4	88.9	88.9
Spedding et al. (1990)	29.6	44.4	55.6
Chexal et al. (1992)	66.7	85.2	92.6
Takeuchi et al. (1992)	51.9	81.5	88.9
Huq and Loth (1992)	44.4	63	92.6
Inoue et al. (1993)	33.3	63	85.2
Shvarts et al. (1993)	51.9	85.2	85.2
Czop et al. (1994)	11.1	29.6	51.9
Maier and Coddington (1996)	25.9	48.1	55.6
Woldesemayat and Ghajar (2007)	81.5	88.9	92.6

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.11 - Comparison of Prediction of Correlations with Air-Water Data of Oshinowo (1971)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	2	8.5	13.1
Armand and Masina[1]	31.4	52.3	79.7
Kowalczewski[2]	19.6	49	60.1
Kutucuglu[2]	26.1	36.6	45.8
Moussali[2]	4.6	13.1	18.3
Sterman (1956)	0	0	0
Filimonov et al. (1957)	10.5	23.5	39.9
Dimentiev et al. (1959)	9.2	17.6	27.5
Bankoff (1960)	34.6	59.5	75.2
Wilson et al. (1961)	3.9	6.5	9.8
Nicklin et al. (1962)	35.3	68	94.1
Hughmark (1962)	15	40.5	78.4
Nishino and Yamazaki (1963)	37.9	73.2	89.5
Thom (1964)	7.8	24.8	51.6
Neal and Bankoff (1965)	5.9	13.1	19
Baroczy (1966)	32.7	47.7	57.5
Guzhov et al. (1967)	30.7	61.4	87.6
Rouhani and Axelsson – I (1970)	40.5	73.9	94.8
Rouhani and Axelsson – II (1970)	32.7	51	71.9
Bonnecaze et al. (1971)	35.3	68	94.1
Premoli et al. (1971)	53.6	90.2	98
Dix (1971)	24.8	64.1	74.5
Chisholm (1973a)	14.4	48.4	75.8
Mattar and Gregory (1974)	15.7	46.4	69.3
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	6.5	17	29.4
Yamazaki and Yamaguchi (1976)	37.9	73.2	89.5
Lahey and Moody (1977)	11.1	28.8	52.3
Ishii (1977b)	41.8	79.1	98
Mukherjee (1979)	28.1	69.3	79.1
Sun et al. (1980)	41.8	78.4	94.1
Gardner – I (1980)	8.5	16.3	25.5
Gardner – II (1980)	5.9	11.8	19.6
Yeh and Hochreiter (1980)	10.5	23.5	32
Ohkawa and Lahey (1980)	58.8	93.5	98
Chisholm (1983)	16.3	50.3	76.5
Jowitt et al. (1984)	51	69.9	81.7
Spedding and Chen (1984)	42.5	66	94.1
Bestion (1985)	30.1	54.2	75.2
El-Boher et al. (1988)	20.9	51	68
Kokal and Stanislav (1989)	34	67.3	94.8
Sonneburgh (1989)	11.8	20.3	29.4
Morooka et al. (1989)	21.6	41.8	73.2
Spedding et al. (1990)	33.3	45.1	52.9
Chexal et al. (1992)	11.8	31.4	68
Takeuchi et al. (1992)	8.5	35.3	71.2
Huq and Loth (1992)	28.8	70.6	88.2
Inoue et al. (1993)	20.9	46.4	75.2
Shvarts et al. (1993)	13.7	29.4	55.6
Czop et al. (1994)	43.8	67.3	74.5
Maier and Coddington (1996)	19	37.9	66
Woldesemayat and Ghajar (2007)	17.6	52.3	69.9

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

For the 172 air-glycerin data points of Oshinowo (1971), as shown in Table 7.12, Premoli et al. (1971) correlation predicts the highest percentage of data points for all the three error bands. For ±5%, ±10% and ±15% error bands, it predicts 54.1%, 81.4% and 93.6% of the data points, respectively. Correlations of Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Hughmark (1962), Sun et al. (1980), Rouhani and Axelsson – I (1970) and Morooka et al. (1989) also offer significant performance for error band of ±15%. Performance of Ishii (1977b) and Rouhani and Axelsson – I (1970) is comparable with Premoli et al. (1971) for ±5% and ±10%.

Steam-water data of Isbin et al. (1957) is the only boiling two-phase flow data studied in the present work. Performance of correlations for the 22 data points in this experimental data set is shown in Table 7.13. Most of the correlations perform superbly for this data set. But, the number of data points in this data is low (22) and hence this performance does not have much significance in the overall comparison. Premoli et al. (1971) is the best performing correlation along with Kowalczewski, Dix (1971) and Woldesemayat and Ghajar (2007) for ±15% and ±10%. Premoli et al. (1971) correlation tops the ±5% error band with prediction of 72.7% of the data points.

Apart from the data presented in Table 7.1, one more experimental data set was available. It was nitrogen-Luviskol® of Schmidt et al. (2008). Unique characteristic of this data is very high dynamic viscosity of Luviskol® (1 to 7 Pas). In Table 7.14, nitrogen-Luviskol® data and prediction of correlations is compared. High viscosity of liquid phase could be the reason behind poor performance of all the correlations for this data set. The highest percentage of the data points predicted for ±15% error range is 31.3 by Mattar and

Gregory (1974), which proves that no correlation is developed to handle such high dynamic viscosity.

In the next part, all the correlations are compared with combined experimental data. Nitrogen-Luviskol® data of Schmidt et al. (2008) is not considered in this overall comparison because high viscosity liquid is a special case and incapability of correlations developed for general gas-liquid combinations (liquids with moderate viscosities) is understandable. If it is necessary to calculate void fraction in a gas-liquid system involving high viscosity liquid, work of researchers such as Schmidt et al. (2008) and Spisak and Troniewski (1991) could be referred to.

Table 7.12 - Comparison of Prediction of Correlations with Air-Glycerin Data of Oshinowo (1971)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	2.9	14	20.9
Armand and Masina[1]	34.9	54.7	73.3
Kowalczewski[2]	16.9	37.2	48.8
Kutucuglu[2]	14	32.6	39
Moussali[2]	8.7	21.5	33.7
Sterman (1956)	0	0	1.2
Filimonov et al. (1957)	15.7	38.4	61
Dimentiev et al. (1959)	11	20.3	29.1
Bankoff (1960)	22.1	55.2	68.6
Wilson et al. (1961)	5.2	8.7	15.1
Nicklin et al. (1962)	30.8	66.9	90.1
Hughmark (1962)	33.1	62.2	90.7
Nishino and Yamazaki (1963)	25	49.4	65.7
Thom (1964)	8.1	23.8	42.4
Neal and Bankoff (1965)	4.1	10.5	14.5
Baroczy (1966)	23.3	41.9	50.6
Guzhov et al. (1967)	23.3	57.6	81.4
Rouhani and Axelsson – I (1970)	44.8	74.4	90.1
Rouhani and Axelsson – II (1970)	23.8	42.4	68
Bonnecaze et al. (1971)	30.8	66.9	90.1
Premoli et al. (1971)	54.1	81.4	93.6
Dix (1971)	32	54.7	69.8
Chisholm (1973a)	15.1	37.2	54.7
Mattar and Gregory (1974)	4.7	24.4	50
Madsen (1975)	0	0	1.7
Greskovich and Cooper (1975)	15.7	31.4	43
Yamazaki and Yamaguchi (1976)	25	49.4	65.7
Lahey and Moody (1977)	14.5	38.4	56.4
Ishii (1977b)	45.9	71.5	80.8
Mukherjee (1979)	16.3	47.7	65.1
Sun et al. (1980)	39.5	69.2	91.3
Gardner – I (1980)	7.6	19.8	32
Gardner – II (1980)	5.8	17.4	25.6
Yeh and Hochreiter (1980)	11	25.6	37.8
Ohkawa and Lahey (1980)	35.5	65.1	77.3
Chisholm (1983)	18.6	38.4	55.2
Jowitt et al. (1984)	28.5	52.9	71.5
Spedding and Chen (1984)	27.9	52.3	66.9
Bestion (1985)	27.9	41.3	76.7
El-Boher et al. (1988)	44.8	60.5	69.8
Kokal and Stanislav (1989)	30.2	66.3	89.5
Sonneburgh (1989)	24.4	37.2	50
Morooka et al. (1989)	32	56.4	87.2
Spedding et al. (1990)	21.5	41.3	48.8
Chexal et al. (1992)	14	40.1	63.4
Takeuchi et al. (1992)	16.9	41.3	62.8
Huq and Loth (1992)	15.7	45.3	64
Inoue et al. (1993)	33.7	56.4	76.7
Shvarts et al. (1993)	23.8	45.9	72.1
Czop et al. (1994)	24.4	47.7	68.6
Maier and Coddington (1996)	22.7	45.3	62.8
Woldesemayat and Ghajar (2007)	22.7	49.4	62.2

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.13 - Comparison of Prediction of Correlations with Steam-Water Data of Isbin et al. (1957)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	0	4.5	18.2
Armand and Masina[1]	40.9	72.7	86.4
Kowalczewski[2]	72.7	100	100
Kutucuglu[2]	13.6	50	63.6
Moussali[2]	0	4.5	18.2
Sterman (1956)	0	0	0
Filimonov et al. (1957)	0	9.1	27.3
Dimentiev et al. (1959)	27.3	50	59.1
Bankoff (1960)	18.2	45.5	72.7
Wilson et al. (1961)	4.5	9.1	13.6
Nicklin et al. (1962)	45.5	77.3	95.5
Hughmark (1962)	4.5	31.8	63.6
Nishino and Yamazaki (1963)	72.7	81.8	100
Thom (1964)	40.9	86.4	100
Neal and Bankoff (1965)	0	0	0
Baroczy (1966)	63.6	86.4	95.5
Guzhov et al. (1967)	50	81.8	95.5
Rouhani and Axelsson – I (1970)	45.5	77.3	95.5
Rouhani and Axelsson – II (1970)	45.5	72.7	86.4
Bonnecaze et al. (1971)	45.5	77.3	95.5
Premoli et al. (1971)	72.7	100	100
Dix (1971)	68.2	100	100
Chisholm (1973a)	45.5	81.8	95.5
Mattar and Gregory (1974)	18.2	54.5	86.4
Madsen (1975)	0	0	0
Greskovich and Cooper (1975)	0	4.5	18.2
Yamazaki and Yamaguchi (1976)	72.7	81.8	100
Lahey and Moody (1977)	0	13.6	40.9
Ishii (1977b)	50	77.3	95.5
Mukherjee (1979)	59.1	90.9	100
Sun et al. (1980)	59.1	81.8	100
Gardner – I (1980)	9.1	22.7	45.5
Gardner – II (1980)	13.6	45.5	72.7
Yeh and Hochreiter (1980)	9.1	36.4	45.5
Ohkawa and Lahey (1980)	68.2	95.5	100
Chisholm (1983)	50	81.8	95.5
Jowitt et al. (1984)	68.2	90.9	100
Spedding and Chen (1984)	68.2	95.5	100
Bestion (1985)	45.5	59.1	77.3
El-Boher et al. (1988)	4.5	31.8	63.6
Kokal and Stanislav (1989)	45.5	77.3	95.5
Sonneburgh (1989)	40.9	77.3	90.9
Morooka et al. (1989)	18.2	45.5	77.3
Spedding et al. (1990)	31.8	36.4	36.4
Chexal et al. (1992)	18.2	63.6	86.4
Takeuchi et al. (1992)	9.1	36.4	72.7
Huq and Loth (1992)	72.7	81.8	100
Inoue et al. (1993)	9.1	50	77.3
Shvarts et al. (1993)	4.5	18.2	54.5
Czop et al. (1994)	63.6	90.9	100
Maier and Coddington (1996)	27.3	72.7	90.9
Woldesemayat and Ghajar (2007)	68.2	100	100

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.14 - Comparison of Prediction of Correlations with Nitrogen-Luviskol® Data of Schmidt et al. (2008)

Correlation	Percentage of The Data Points Predicted Correctly		
	±5%	±10%	±15%
Homogeneous[1]	1.5	1.5	1.5
Armand and Masina[1]	0	0	1.5
Kowalczewski[2]	1.5	3	3
Kutucuglu[2]	3	3	4.5
Moussali[2]	0	0	1.5
Sterman (1956)	1.5	3	7.5
Filimonov et al. (1957)	6	9	11.9
Dimentiev et al. (1959)	6	20.9	25.4
Bankoff (1960)	4.5	13.4	17.9
Wilson et al. (1961)	7.5	11.9	13.4
Nicklin et al. (1962)	3	7.5	16.4
Hughmark (1962)	6	10.4	17.9
Nishino and Yamazaki (1963)	1.5	1.5	1.5
Thom (1964)	4.5	6	11.9
Neal and Bankoff (1965)	6	16.4	20.9
Baroczy (1966)	7.5	14.9	20.9
Guzhov et al. (1967)	3	9	11.9
Rouhani and Axelsson – I (1970)	0	1.5	1.5
Rouhani and Axelsson – II (1970)	6	22.4	25.4
Bonnecaze et al. (1971)	3	7.5	16.4
Premoli et al. (1971)	0	0	0
Dix (1971)	0	3	7.5
Chisholm (1973a)	1.5	1.5	1.5
Mattar and Gregory (1974)	11.9	13.4	31.3
Madsen (1975)	1.5	4.5	6
Greskovich and Cooper (1975)	1.5	4.5	7.5
Yamazaki and Yamaguchi (1976)	1.5	1.5	1.5
Lahey and Moody (1977)	1.5	3	9
Ishii (1977b)	1.5	4.5	6
Mukherjee (1979)	0	0	0
Sun et al. (1980)	1.5	6	9
Gardner – I (1980)	0	0	0
Gardner – II (1980)	0	0	0
Yeh and Hochreiter (1980)	0	6	13.4
Ohkawa and Lahey (1980)	0	0	4.5
Chisholm (1983)	1.5	1.5	1.5
Jowitt et al. (1984)	6	10.4	23.9
Spedding and Chen (1984)	0	0	3
Bestion (1985)	4.5	13.4	10.4
El-Boher et al. (1988)	0	0	3
Kokal and Stanislav (1989)	1.5	9	16.4
Sonneburgh (1989)	11.9	13.4	20.9
Morooka et al. (1989)	1.5	3	9
Spedding et al. (1990)	0	0	0
Chexal et al. (1992)	4.5	7.5	7.5
Takeuchi et al. (1992)	6	7.5	10.4
Huq and Loth (1992)	1.5	1.5	1.5
Inoue et al. (1993)	3	6	10.4
Shvarts et al. (1993)	4.5	7.5	10.4
Czop et al. (1994)	0	3	4.5
Maier and Coddington (1996)	1.5	9	17.9
Woldesemayat and Ghajar (2007)	0	1.5	7.5

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

7.2 Comparison of Correlations with Overall Data and Selection of Better Performing Correlations

Table 7.15 displays comparison between combined data and prediction of correlations. One more error band of ±20% is introduced to have additional aspect to gauge the performance of correlations. Nicklin et al. (1962) predicts the highest number of the data points in ±20% and ±15% error band. Other than Nicklin et al. (1962), Bonnecaze et al. (1971) and Kokal and Stanislav (1989) correlations perform the best in ±15% error band. For ±10% error in prediction, Rouhani and Axelsson – I (1970) correlation predicts the highest number of data points. Premoli et al. (1971) correlation predicts the highest percentage of the data points in ±5% error band. Other than the best performing correlations in the four error bands, quite a few correlations perform well in all the four error criteria.

It can be observed that the correlations do not predict much percentage of the data points in ±10% and ±5% error bands. Therefore, these two error bands are not considered for choosing the better performing correlations. A list of correlations is made which predict more than 85% and 75% of the data points in ±20% and ±15% error bands, respectively. These are selected as the probable candidates for the best correlation for prediction of void fraction in vertical upward two-phase flow.

1) Nicklin et al. (1962)
2) Hughmark (1962)
3) Nishino and Yamazaki (1963)
4) Guzhov et al. (1967)
5) Rouhani and Axelsson – I (1970)
6) Bonnecaze et al. (1971)

Table 7.15 - Comparison of Prediction of Correlations with All Data (1208 Data Points)

Correlation	Percentage of The Data Points Predicted Correctly			
	±5%	±10%	±15%	±20%
Homogeneous[1]	8.9	22.1	32.8	44.6
Armand and Masina[1]	35.2	60	73.8	83.4
Kowalczewski[2]	27.9	45.4	53.6	57.8
Kutucuglu[2]	19.6	30.3	37.8	42.5
Moussali[2]	11.8	25.7	37.4	49.9
Sterman (1956)	1.5	3.1	5	6.8
Filimonov et al. (1957)	24.6	45.2	63.1	81.4
Dimentiev et al. (1959)	9	19.3	28.1	36.8
Bankoff (1960)	15.6	31.4	48.3	65.8
Wilson et al. (1961)	4.3	9.4	13.4	18.8
Nicklin et al. (1962)	33.1	62.1	84.4	91.7
Hughmark (1962)	33.9	58.2	76.7	86.1
Nishino and Yamazaki (1963)	43.2	66.6	78.6	84.7
Thom (1964)	18.5	36.2	49.6	56.5
Neal and Bankoff (1965)	7.5	15.3	22.6	30
Baroczy (1966)	29.7	45.4	54.2	61.3
Guzhov et al. (1967)	28.1	54.6	77.6	88.7
Rouhani and Axelsson – I (1970)	39.9	68.5	83.5	89.3
Rouhani and Axelsson – II (1970)	24.6	48.5	70	83.4
Bonnecaze et al. (1971)	33.1	62.1	84.4	91.7
Premoli et al. (1971)	46.4	64.4	72.6	80.6
Dix (1971)	42.1	63.1	74	78.4
Chisholm (1973a)	34.1	58.9	73.4	80.7
Mattar and Gregory (1974)	4.1	15.4	35.5	54.6
Madsen (1975)	0.3	0.6	0.7	1.7
Greskovich and Cooper (1975)	25.1	43.5	60.7	74.4
Yamazaki and Yamaguchi (1976)	38.2	63.1	76.7	83.9
Lahey and Moody (1977)	20	41	60.6	77.6
Ishii (1977b)	37.9	66.6	80.5	87.3
Mukherjee (1979)	29.3	52.6	64.8	73.6
Sun et al. (1980)	31.3	58.1	78.1	91.1
Gardner – I (1980)	14.6	28.3	41.6	51.4
Gardner – II (1980)	13.2	27.1	38.3	47.4
Yeh and Hochreiter (1980)	11.2	23.2	33.4	42.1
Ohkawa and Lahey (1980)	35.2	59.9	68.8	74.9
Chisholm (1983)	35.1	59.4	73.8	81.1
Jowitt et al. (1984)	19.5	38.7	54.6	63.7
Spedding and Chen (1984)	33	51.4	67	75.2
Bestion (1985)	22	40.3	50.7	57.0
El-Boher et al. (1988)	35.6	56.9	70.8	77.6
Kokal and Stanislav (1989)	33	61.9	84.4	91.6
Sonneburgh (1989)	24.2	38.2	48.8	58.8
Morooka et al. (1989)	32.5	62.1	79.1	87.9
Spedding et al. (1990)	10.3	21.4	32.6	44.5
Chexal et al. (1992)	30.6	56.8	71.7	78.1
Takeuchi et al. (1992)	27.6	52.7	78.1	88.6
Huq and Loth (1992)	34.4	60.6	76	83.3
Inoue et al. (1993)	31.5	53	68	75.3
Shvarts et al. (1993)	45.1	45.1	65.6	77.7
Czop et al. (1994)	24.7	42.5	58.8	68.2
Maier and Coddington (1996)	27.5	46.6	58	62.7
Woldesemayat and Ghajar (2007)	37.8	59.4	70.5	77.3

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

7) Ishii (1977b)
8) Sun et al. (1980)
9) Kokal and Stanislav (1989)
10) Morooka et al. (1989)
11) Takeuchi et al. (1992)

7.3 Comparison of Correlations in Four Void Fraction Ranges

The correlations are short-listed on the basis of overall performance of correlations. But, it is also important that a correlation performs well for the entire range of void fraction (0 to 1). Therefore, performance of each correlation is analyzed in the ranges: 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75 and 0.75 to 1. The comparisons are shown in Tables 7.17 to 7.20. All the correlations are compared with data points in the ranges specified so that the reader can select the best correlations for prediction in respective ranges. But, performance of only selected (11) correlations is discussed in detail. The number of data points in each range is specified in Table 7.16.

Table 7.16 – Number of Data Points in Void Fraction Ranges

Range	Number of Data points
0 To 0.25	199
0.25 To 0.5	190
0.5 To 0.75	351
0.75 To 1	468

From Table 7.17 for the void fraction range 0 to 0.25, it can be observed that the correlations do not perform satisfactorily in ±5%, ±10% and ±15% error bands. Due to lower values of void fraction, the percentage error in prediction with respect to measured data is expected to be high. Even for error band of ±20%, only few correlations can predict more than 70% of the data points. Therefore ±25% and ±30% error bands were also used. The criteria were set as prediction of 70% and 80% of the data points within ±25% and ±30% error, respectively.

Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989) and Takeuchi et al. (1992) give the best performance for error band of ±30%. Sun et al. (1980) and Morooka et al. (1989) correlations give a satisfactory performance by predicting more than 80% of data within ±30%. Ishii (1977b), Guzhov et al. (1967), Rouhani and Axelsson – I (1970) predict close to 80% of the data points within ±30%. But, performances of Nishino and Yamazaki (1963) and Hughmark (1962) correlations are not adequate in ±30% error criterion. All the selected correlations, except for Nishino and Yamazaki (1963) meet the criterion of more than 70% of the data points within ±25%.

Takeuchi (1992) correlation gives the best prediction performance in ±20% and ±25% error criteria. Rouhani and Axelsson – II (1970) correlation predicts the highest number of the data points in ±15%. It predicts 62.8% of the data points within ±15%. Greskovich and Cooper (1975) correlation tops the error band of ±10% by calculating 45.2% of the data points. Rouhani and Axelsson – II (1970) and Nishino and Yamazaki (1963) give the best performance in ±5% error band by predicting 24.1% of the data points.

For the range of 0 to 0.25, other than the selected 11 correlations, correlation by Greskovich and Cooper (1975) gives the expected performance. It predicts 77.4% and 80.9% of the data points in ±25% and ±30% error bands, respectively.

Performances of two of the best performing correlations: Nicklin et al. (1962) and Takeuchi et al. (1992) for the range 0 to 0.25 are shown in Figure 7.1 and Figure 7.2.

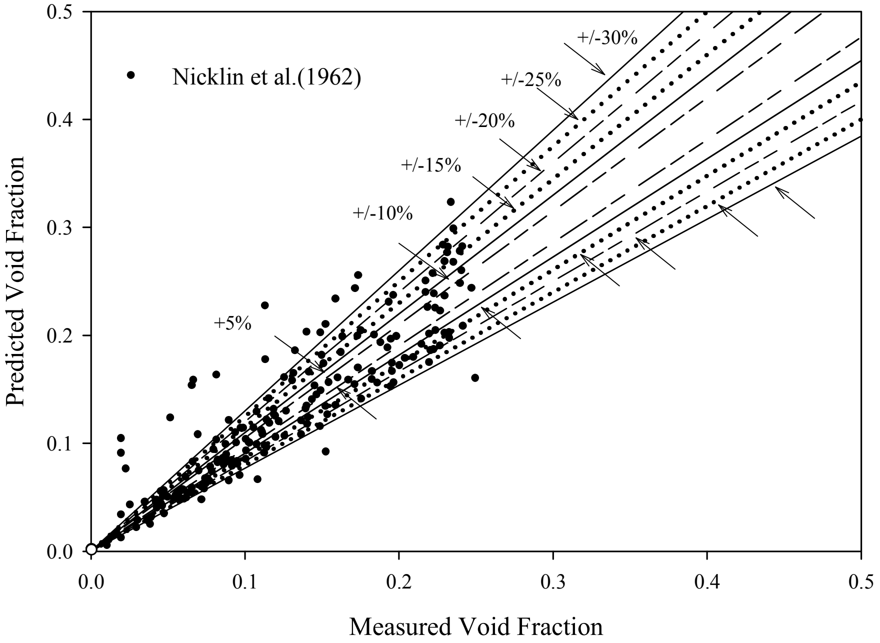


Figure 7.1 – Performance of Nicklin et al. (1962) Correlation for Void Fraction Data in 0 to 0.25 Range

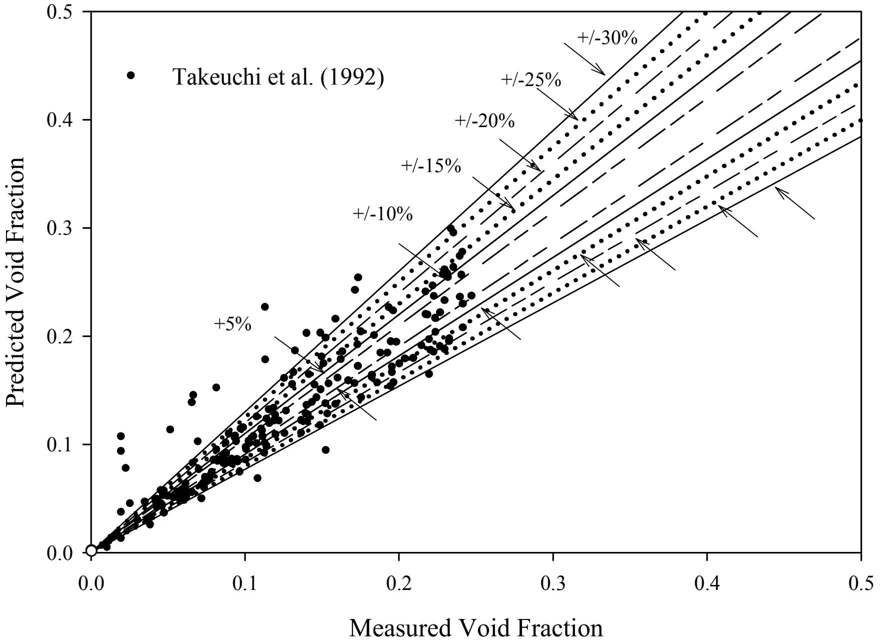


Figure 7.2 - Performance of Takeuchi et al.(1992) Correlation for Void Fraction Data in 0 to 0.25 Range

For void fraction range of 0.25 to 0.5, as demonstrated in Table 7.18, due to higher values of void fraction (than 0 to 0.25 range), criteria are set as: prediction of more than 80% data points within ±20% and more than 70% data points within ±15%.

Sun et al. (1980) correlation predicts the highest percentage of the data points within ±20% error band. Kokal and Stanislav (1989) and Takeuchi et al. (1992) correlations top the ±15% error band, predicting 81.6% of the data points. Nishino and Yamazaki (1963) correlation gives the best prediction for ±10% error criterion. All the 11 selected correlations, except for Hughmark (1962), Nishino and Yamazaki (1963), Ishii (1977b) and Morooka et al. (1989) predict 80% or more of the data points within ±20% error. Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Takeuchi et al. (1992), Nishino and Yamazaki (1963), Sun et al. (1980) and Rouhani and Axelsson – I (1970) provide the expected performance for ±15% error band. Each of them predicts 70% or more data points within ±15%. But, correlations of Hughmark (1962), Ishii (1977b), Guzhov et al. (1967) and Morooka et al. (1989) do not perform up to the mark. Their prediction in the error band of ±15% is below 70%.

For this range of void fraction, no correlation (other than selected correlations) gives the performance as per the selected criteria.

The performances of two of the top performing correlations by Sun et al. (1980) and Kokal and Stanislav (1989) for this range are shown in Figure 7.3 and Figure 7.4, respectively.

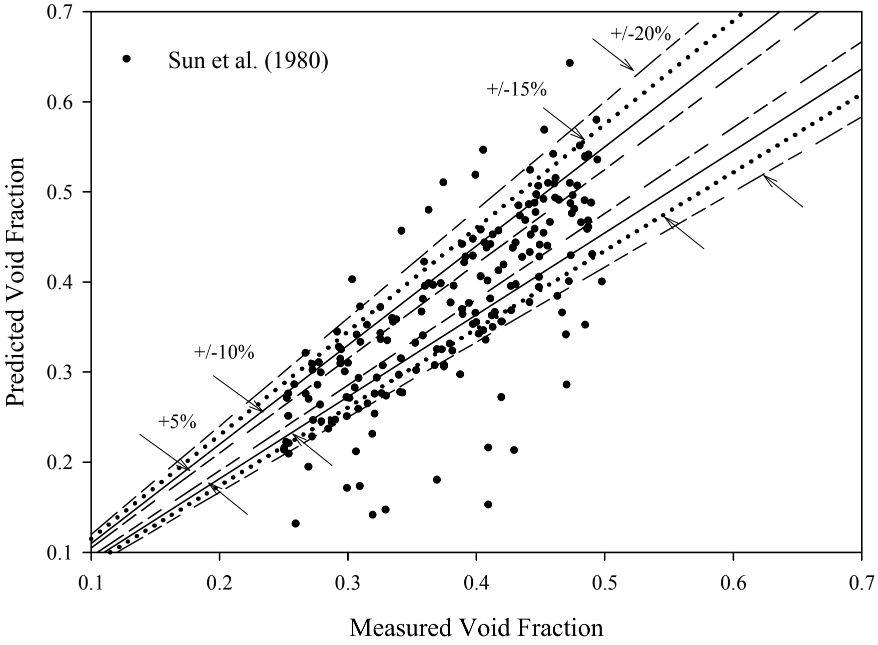


Figure 7.3 - Performance of Sun et al. (1980) Correlation for Void Fraction Data in 0.25 to 0.5 Range

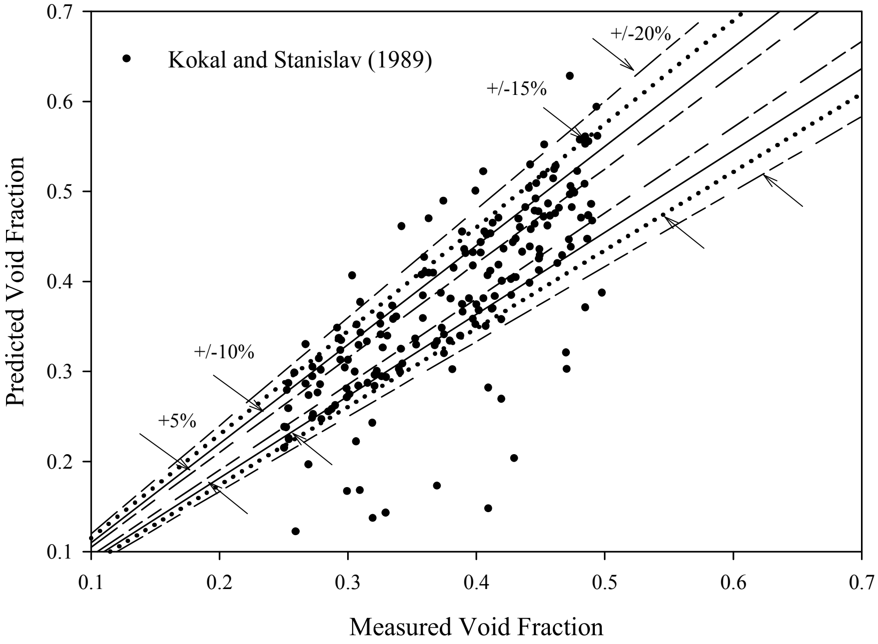


Figure 7.4 - Performance of Kokal and Stanislav (1989) Correlation for Void Fraction Data in 0.25 to 0.5 Range

As the void fraction value increases, accuracy of the correlations also increases. Therefore criteria for the void fraction range of 0.5 to 0.75 are set as – prediction of more than 80% and 90% of the data points within ±15% and ±20%, respectively.

All the selected correlations, except for Takeuchi et al. (1992) perform superbly in the error band of ±20%, predicting more than 90% of the data points. Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989) predict the highest percentage of data points (96.6%) in ±20% error band. For ±15% error criterion, Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Sun et al. (1980), Ishii (1977b), Guzhov et al. (1967) and Rouhani and Axelsson – I (1970) predict more than 90% of the data points. Hughmark (1962) and Nishino and Yamazaki (1963) predict close to 80% of the data points within ±15%. Morooka et al. (1989) does not perform as per the criterion for ±15% error band. Sun et al. (1980) correlation offers the best performance in ±10% and ±5% error band. It predicts 81.2% and 48.1% of the data points, respectively.

Other than the 11 selected correlations, Bankoff (1960), Dix (1971), Chexal et al. (1992) and Woldesemayat and Ghajar (2007) correlations perform close to the set criteria.

Performances of correlations by Rouhani and Axelsson – I (1970), Sun et al. (1980) and Nicklin et al. (1962), which predict more than 95% of the data points within ±20% error band in this range of 0.5 to 0.75 is shown in Figure 7.5 to Figure 7.7.

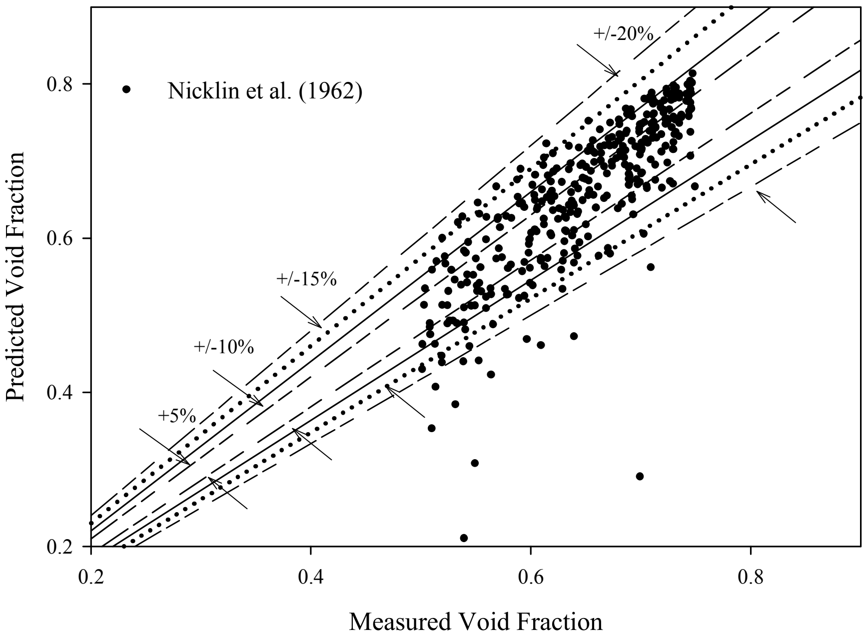


Figure 7.5 - Performance of Nicklin et al. (1962) Correlation for Void Fraction Data in 0.5 to 0.75 Range

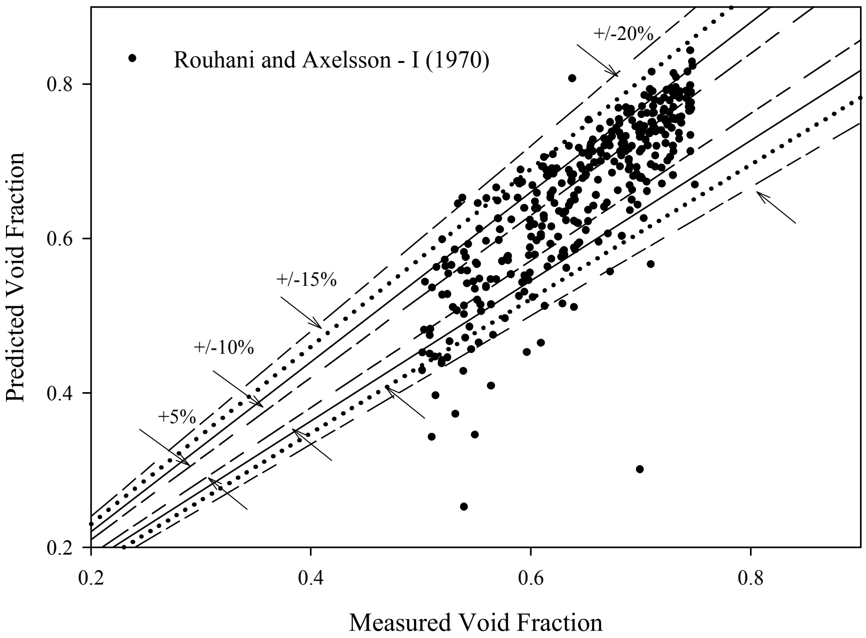


Figure 7.6 - Performance of Rouhan I and Axelsson – I (1970) Correlation for Void Fraction Data in 0.5 to 0.75 Range

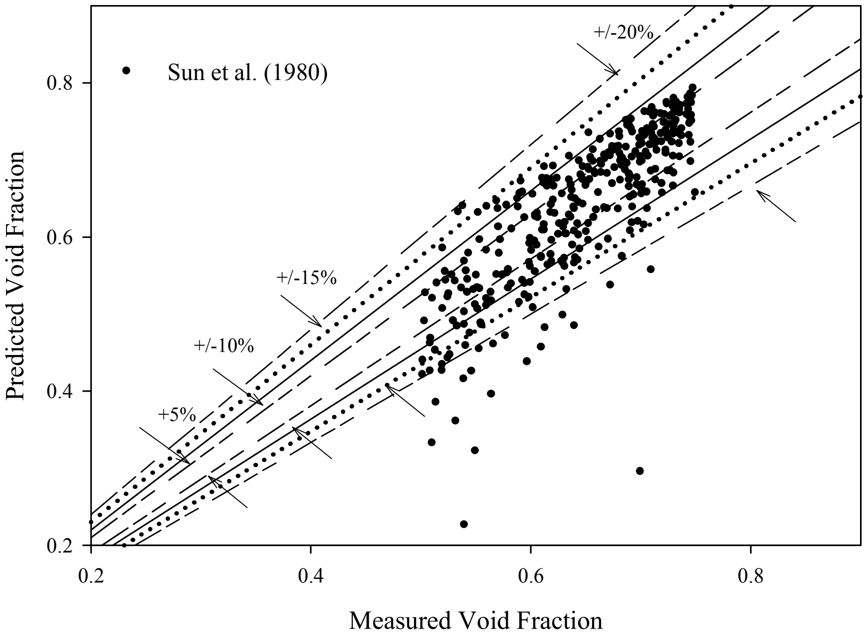


Figure 7.7 - Performance of Sun et al. (1980) Correlation for Void Fraction Data in 0.5 to 0.75 Range

For the highest range of void fraction (0.75 to 1), the accuracy of prediction is expected to be high and therefore ±10% error band is also used to analyze the performance of the correlations. The criteria used for this range are – more than 75%, 85% and 95% of the data points within ±10%, ±15% and ±20%, respectively.

All the 11 correlations perform according to the criteria for ±15% and ±20% error bands. But, for ±10% error band, correlations of Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989), Sun et al. (1980) and Takeuchi et al. (1992) do not predict the adequate number of data points.

Hughmark (1962), Armand and Masina, Morooka et al. (1989) and Woldesemayat and Ghajar (2007) correlations predict 100% of the data points within ±20%. Rouhani and Axelsson – I (1970) and Morooka et al. (1989) predict 99.4% of the data points within

±15%. Except for Takeuchi et al. (1992), Sun et al. (1980) and Guzhov et al. (1967), all the selected correlations predict more than 90% of data within ±15%. Armand and Masina correlation gives the best performance in ±10% error band, predicting 94.7% of the data points. From the 11 selected correlations, only Rouhani and Axelsson – I (1970) and Morooka et al. (1989) correlations predict more than 90% of the data points within ±10% error criterion. Dix (1971) correlation predicts the highest number of data points (73.3%) within ±5%.

Other than selected 11 correlations, many other correlations give the performance according to set criteria. They are listed below:

1) Armand and Masina
2) Kowalczewski
3) Dix (1971)
4) Chisholm (1973a)
5) Yamazaki and Yamaguchi (1976)
6) Mukherjee (1979)
7) Chisholm (1983)
8) El-Boher et al. (1988)
9) Chexal et al. (1992)
10) Huq and Loth (1992)
11) Inoue et al. (1993)
12) Maier and Coddington (1996)
13) Woldesemayat and Ghajar (2007)

There are many correlations which give a remarkable performance in this range. Performances of Hughmark (1962), Rouhani and Axelsson – I (1970), Morooka et al. (1989) and Woldesemayat and Ghajar (2007) correlations, which give an excellent prediction in this range, are shown in Figure 7.8 to Figure 7.11.

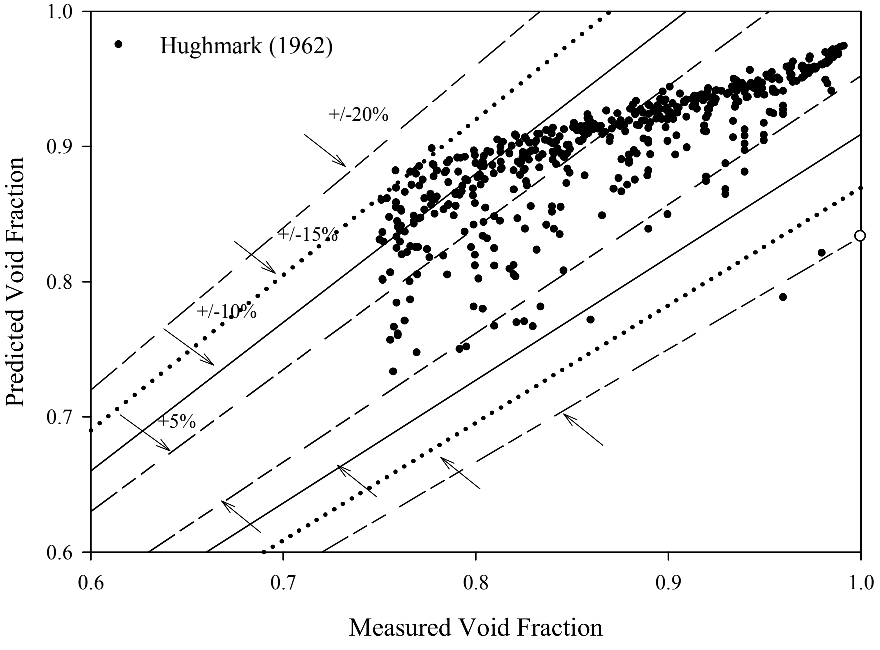


Figure 7.8 - Performance of Hughmark (1962) Correlation for Void Fraction Data in 0.75 to 1 Range

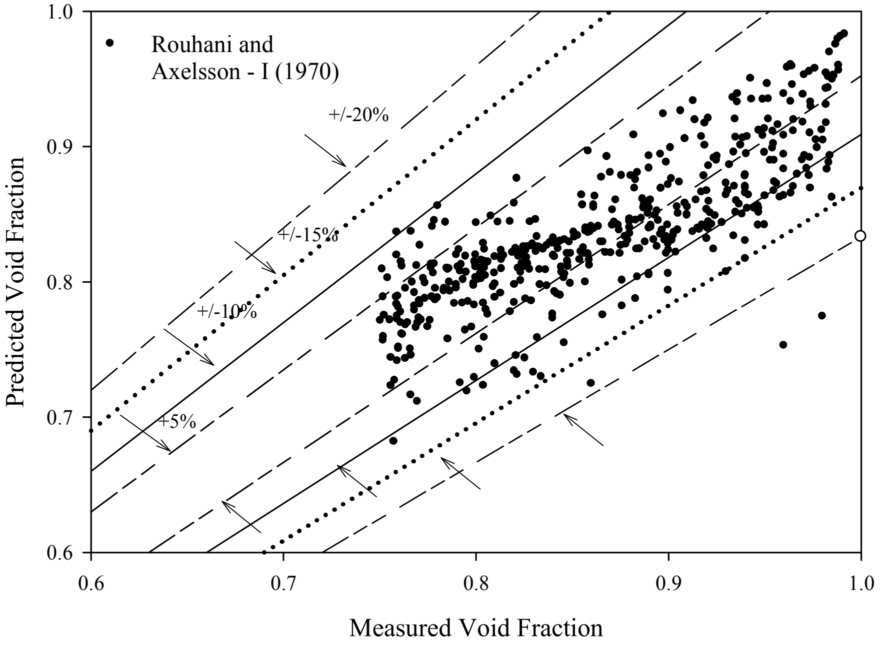


Figure 7.9 - Performance of Rouhani and Axelsson (1970) Correlation for Void Fraction Data in 0.75 to 1 Range

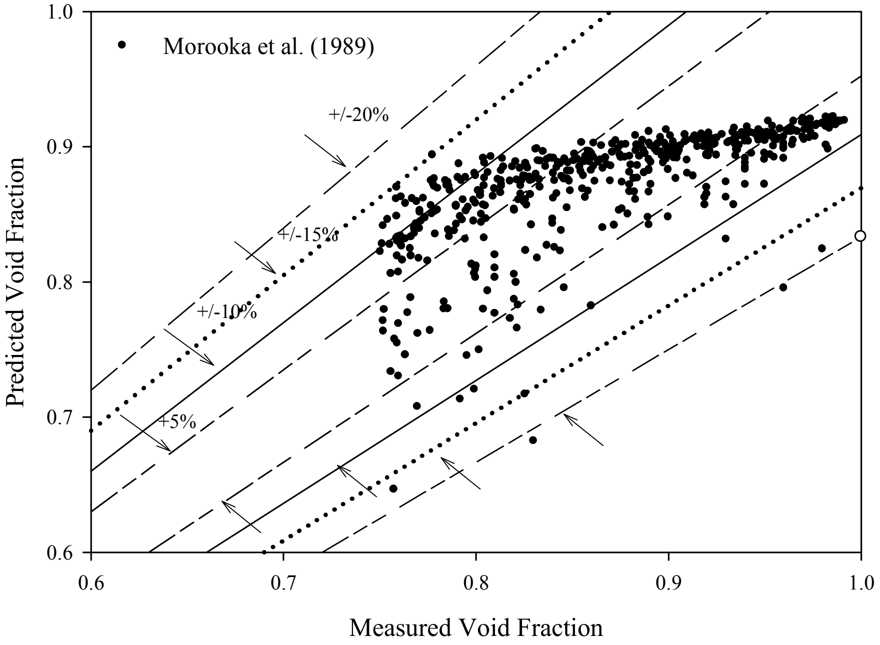


Figure 7.10 - Performance of Morooka et al. (1989) Correlation for Void Fraction Data in 0.75 to 1 Range

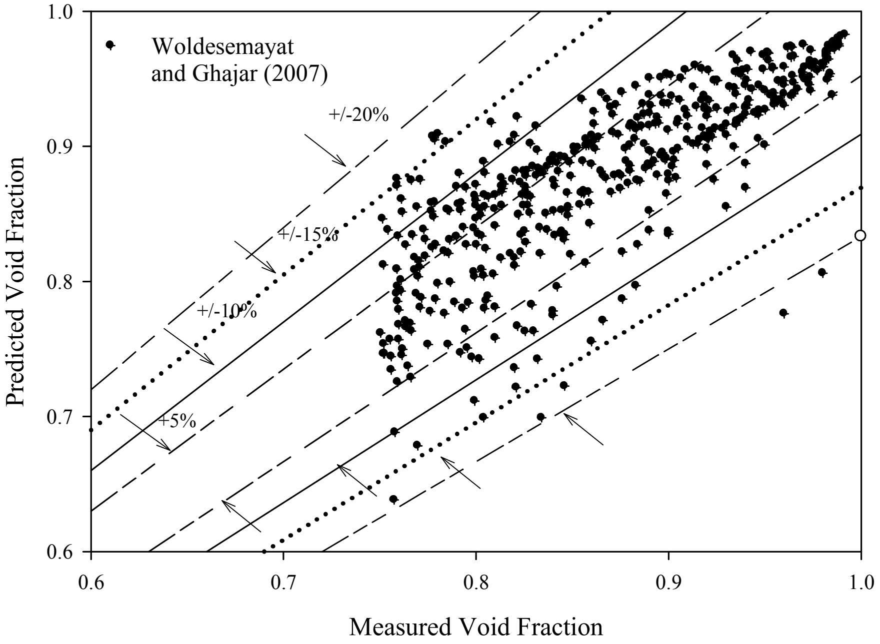


Figure 7.11 - Performance of Woldesemayat and Ghajar (2007) Correlation for Void Fraction Data in 0.75 to 1 Range

Table 7.17 - Comparison of Prediction of Correlations with Void Fraction Data in the Void Fraction Range 0 To 0.25

Correlation	Percentage of The Data Points Predicted Correctly					
	±5%	±10%	±15%	±20%	±25%	±30%
Homogeneous[1]	9	21.6	27.1	36.2	39.2	45.7
Armand and Masina[1]	12.1	26.1	39.7	51.3	58.3	62.3
Kowalczewski[2]	0	0.5	0.5	0.5	0.5	0.5
Kutucuglu[2]	0.5	0.5	0.5	1	1.5	2
Moussali[2]	15.1	27.1	37.7	48.2	54.8	58.3
Sterman (1956)	2	5	8.5	10.6	12.1	14.6
Filimonov et al. (1957)	20.6	37.7	53.3	66.8	74.9	78.9
Dimentiev et al. (1959)	2.5	7	10.6	11.6	16.1	17.6
Bankoff (1960)	11.6	24.1	29.1	42.2	53.3	62.3
Wilson et al. (1961)	2.5	5.5	7	10.1	14.1	20.6
Nicklin et al. (1962)	21.6	37.2	52.3	70.9	80.9	84.9
Hughmark (1962)	13.6	22.6	32.7	49.2	69.3	73.4
Nishino and Yamazaki (1963)	24.1	35.2	46.2	53.8	60.3	64.8
Thom (1964)	1.5	4	5.5	7.5	9	10.1
Neal and Bankoff (1965)	5	10.1	14.6	18.6	21.1	26.6
Baroczy (1966)	1.5	9	13.6	19.6	26.6	38.2
Guzhov et al. (1967)	13.6	33.2	51.3	60.8	71.9	77.4
Rouhani and Axelsson – I (1970)	16.1	31.2	43.7	59.3	73.9	78.4
Rouhani and Axelsson – II (1970)	24.1	40.2	62.8	71.9	79.9	82.4
Bonnecaze et al. (1971)	21.6	36.7	52.3	70.9	80.4	84.9
Premoli et al. (1971)	18.1	27.6	37.7	53.3	60.3	64.3
Dix (1971)	5	12.6	17.1	18.6	24.6	31.2
Chisholm (1973a)	16.1	26.6	35.7	40.7	49.2	57.3
Mattar and Gregory (1974)	2.5	6.5	12.1	21.1	34.7	50.3
Madsen (1975)	0	0	0	0	0	0
Greskovich and Cooper (1975)	22.1	45.2	57.8	67.8	77.4	80.9
Yamazaki and Yamaguchi (1976)	14.1	25.6	41.2	50.8	57.8	62.8
Lahey and Moody (1977)	12.6	29.1	45.2	59.8	71.4	81.9
Ishii (1977b)	16.6	37.2	51.8	64.3	70.9	76.4
Mukherjee (1979)	9.5	16.1	21.6	24.1	28.6	32.2
Sun et al. (1980)	16.6	30.7	48.2	68.8	79.9	83.9
Gardner – I (1980)	1.5	5.5	10.6	13.6	16.1	17.6
Gardner – II (1980)	2.5	8	11.1	13.1	15.1	16.1
Yeh and Hochreiter (1980)	5.5	7	9	10.6	12.6	17.1
Ohkawa and Lahey (1980)	20.6	36.2	44.7	57.8	65.3	71.9
Chisholm (1983)	16.1	26.6	35.7	40.7	49.2	57.3
Jowitt et al. (1984)	2	6.5	13.1	28.6	42.2	53.8
Spedding and Chen (1984)	13.6	23.1	36.7	48.2	57.8	62.8
Bestion (1985)	0.5	3.5	29.1	12.6	16.1	57.8
El-Boher et al. (1988)	2.5	5	11.6	16.6	19.6	23.6
Kokal and Stanislav (1989)	20.6	35.7	51.8	70.9	80.4	84.9
Sonneburgh (1989)	2.5	4.5	6.5	7.5	10.6	14.1
Morooka et al. (1989)	19.1	35.7	55.3	66.8	78.4	83.4
Spedding et al. (1990)	2	3	7	11.1	14.6	19.1
Chexal et al. (1992)	7	12.1	16.6	20.1	26.6	30.7
Takeuchi et al. (1992)	23.1	39.2	61.8	76.9	81.9	84.9
Huq and Loth (1992)	14.1	25.6	41.2	50.3	57.8	62.8
Inoue et al. (1993)	6	16.6	29.1	35.2	45.7	57.8
Shvarts et al. (1993)	15.1	26.1	39.2	50.3	61.8	72.4
Czop et al. (1994)	0.5	0.5	0.5	2.5	3	5
Maier and Coddington (1996)	3	5	6	7.5	7.5	7.5
Woldesemayat and Ghajar (2007)	3	8.5	12.6	17.1	23.1	25.6

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.18 - Comparison of Prediction of Correlations with Void Fraction Data in the Void Fraction Range 0.25 To 0.5

Correlation	Percentage of The Data Points Predicted Correctly			
	±5%	±10%	±15%	±20%
Homogeneous[1]	3.7	13.7	22.6	31.1
Armand and Masina[1]	18.4	35.3	47.9	65.3
Kowalczewski[2]	1.1	3.2	5.3	7.4
Kutucuglu[2]	0.5	1.6	2.6	3.2
Moussali[2]	12.6	23.7	32.6	41.1
Sterman (1956)	4.7	6.3	7.9	12.6
Filimonov et al. (1957)	17.4	37.4	53.2	66.8
Dimentiev et al. (1959)	8.9	18.9	22.6	31.1
Bankoff (1960)	25.8	38.4	50.5	67.9
Wilson et al. (1961)	5.8	11.6	14.7	23.2
Nicklin et al. (1962)	22.1	53.2	80.5	85.3
Hughmark (1962)	18.4	34.7	60	77.9
Nishino and Yamazaki (1963)	24.7	53.7	69.5	75.3
Thom (1964)	2.1	5.3	7.9	11.6
Neal and Bankoff (1965)	14.2	24.2	33.2	44.7
Baroczy (1966)	4.7	10	14.2	18.9
Guzhov et al. (1967)	22.6	42.1	66.8	78.9
Rouhani and Axelsson – I (1970)	15.8	33.7	71.1	83.7
Rouhani and Axelsson – II (1970)	21.6	48.9	63.2	80
Bonnecaze et al. (1971)	22.1	53.2	80.5	85.3
Premoli et al. (1971)	22.1	33.2	40	47.4
Dix (1971)	19.5	38.4	56.8	69.5
Chisholm (1973a)	23.7	38.4	53.2	69.5
Mattar and Gregory (1974)	5.3	16.8	28.9	40.5
Madsen (1975)	0	0	0	0
Greskovich and Cooper (1975)	31.1	46.8	57.9	65.8
Yamazaki and Yamaguchi (1976)	16.8	47.4	66.3	75.3
Lahey and Moody (1977)	21.6	44.7	58.9	71.1
Ishii (1977b)	21.1	42.1	63.7	70
Mukherjee (1979)	22.1	42.1	58.9	74.2
Sun et al. (1980)	18.9	46.8	68.9	85.8
Gardner – I (1980)	4.2	9.5	18.4	24.2
Gardner – II (1980)	6.3	10.5	15.8	19.5
Yeh and Hochreiter (1980)	4.7	9.5	15.3	22.1
Ohkawa and Lahey (1980)	23.7	39.5	48.4	55.3
Chisholm (1983)	23.7	38.4	54.2	68.9
Jowitt et al. (1984)	14.2	26.8	37.9	45.8
Spedding and Chen (1984)	7.9	17.9	40	50
Bestion (1985)	7.9	15.8	26.8	53.7
El-Boher et al. (1988)	17.4	32.6	50	65.3
Kokal and Stanislav (1989)	23.2	53.2	81.6	84.7
Sonneburgh (1989)	10	20	25.8	32.6
Morooka et al. (1989)	20	38.9	58.4	74.7
Spedding et al. (1990)	7.4	13.7	17.4	23.7
Chexal et al. (1992)	16.3	34.7	50.5	64.7
Takeuchi et al. (1992)	24.2	52.6	81.6	84.2
Huq and Loth (1992)	15.3	45.8	65.8	75.8
Inoue et al. (1993)	20.5	34.7	45.3	53.7
Shvarts et al. (1993)	17.4	33.2	43.7	59.5
Czop et al. (1994)	5.3	14.2	22.1	28.4
Maier and Coddington (1996)	1.1	5.8	12.6	20
Woldesemayat and Ghajar (2007)	15.8	32.6	47.9	60.5

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.19 - Comparison of Prediction of Correlations with Void Fraction Data in the Void Fraction Range 0.5 To 0.75

Correlation	Percentage of The Data Points Predicted Correctly			
	±5%	±10%	±15%	±20%
Homogeneous[1]	1.7	5.1	9.4	16.2
Armand and Masina[1]	19.1	47.3	72.9	89.5
Kowalczewski[2]	21.7	40.2	54.7	63.5
Kutucuglu[2]	9.4	15.7	23.4	29.9
Moussali[2]	3.1	7.7	12.3	20.8
Sterman (1956)	0.9	4	8	10.3
Filimonov et al. (1957)	14.8	32.5	49.3	75.5
Dimentiev et al. (1959)	10.5	19.7	28.5	38.7
Bankoff (1960)	33	68.4	84.6	93.2
Wilson et al. (1961)	8	17.1	22.8	31.6
Nicklin et al. (1962)	41.3	80.3	93.4	96.6
Hughmark (1962)	25.4	54.1	81.2	93.2
Nishino and Yamazaki (1963)	39.3	64.4	79.2	88.6
Thom (1964)	17.9	34.2	46.4	56.7
Neal and Bankoff (1965)	7.1	15.4	23.9	31.1
Baroczy (1966)	20.5	35.3	49.9	60.7
Guzhov et al. (1967)	33.6	71.5	89.5	95.2
Rouhani and Axelsson – I (1970)	37.6	75.5	91.7	95.7
Rouhani and Axelsson – II (1970)	30.5	57.3	74.9	87.2
Bonnecaze et al. (1971)	41.3	80.3	93.4	96.6
Premoli et al. (1971)	35.6	58.7	69.8	81.2
Dix (1971)	34.8	65.2	82.6	88.6
Chisholm (1973a)	23.4	51.9	76.4	85.8
Mattar and Gregory (1974)	9.7	29.6	50.4	62.4
Madsen (1975)	0	0	0	0
Greskovich and Cooper (1975)	15.7	27.1	46.2	59.5
Yamazaki and Yamaguchi (1976)	34.5	61.3	77.2	87.7
Lahey and Moody (1977)	20.2	35.3	57.8	74.4
Ishii (1977b)	41	77.2	90.3	93.4
Mukherjee (1979)	16.5	39.3	55.3	69.8
Sun et al. (1980)	48.1	81.2	91.2	95.4
Gardner – I (1980)	8.8	16	25.6	37.9
Gardner – II (1980)	6.6	15.7	23.1	31.6
Yeh and Hochreiter (1980)	9.4	17.9	24.5	29.3
Ohkawa and Lahey (1980)	36.2	61.5	73.2	80.1
Chisholm (1983)	23.9	53	76.9	87.2
Jowitt et al. (1984)	28.2	42.7	55.6	66.1
Spedding and Chen (1984)	21.9	45.6	65	74.6
Bestion (1985)	16.8	31.3	42.2	77.8
El-Boher et al. (1988)	27.6	53	78.3	90
Kokal and Stanislav (1989)	40.7	80.1	93.2	96.6
Sonneburgh (1989)	37.6	54.7	65.5	72.4
Morooka et al. (1989)	22.2	51	76.6	90.9
Spedding et al. (1990)	17.1	29.6	43.3	51.9
Chexal et al. (1992)	40.2	66.1	80.9	89.7
Takeuchi et al. (1992)	23.4	46.2	72.4	86.9
Huq and Loth (1992)	31.3	56.4	76.1	86.9
Inoue et al. (1993)	20.5	42.5	62.7	77.8
Shvarts et al. (1993)	35	35	59.5	74.6
Czop et al. (1994)	42.7	66.7	79.2	86
Maier and Coddington (1996)	24.5	41.9	59.5	68.1
Woldesemayat and Ghajar (2007)	32.2	60.7	78.9	90.3

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

Table 7.20 - Comparison of Prediction of Correlations with Void Fraction Data in the Void Fraction Range 0.75 To 1

Correlation	Percentage of The Data Points Predicted Correctly			
	±5%	±10%	±15%	±20%
Homogeneous[1]	16.5	38.5	56.8	75
Armand and Masina[1]	65	94.7	99.4	100
Kowalczewski[2]	55.6	86.1	94.9	98.3
Kutucuglu[2]	43.4	66	78.8	85.7
Moussali[2]	16.5	39.3	58.1	76.1
Sterman (1956)	0	0	0	0.2
Filimonov et al. (1957)	36.5	61.5	81.6	97.9
Dimentiev et al. (1959)	10.9	24.8	37.6	48.5
Bankoff (1960)	0	4.3	28.4	54.5
Wilson et al. (1961)	1.9	4.5	8.5	11.1
Nicklin et al. (1962)	37.6	63.5	92.7	99.6
Hughmark (1962)	55.6	86.5	99.1	100
Nishino and Yamazaki (1963)	62	87.6	95.7	98.7
Thom (1964)	32.9	64.3	87.6	95.3
Neal and Bankoff (1965)	6.2	13.9	20.7	28.2
Baroczy (1966)	59	83.5	91	96.6
Guzhov et al. (1967)	33.5	57.1	84.2	99.6
Rouhani and Axelsson – I (1970)	63	94	99.4	99.6
Rouhani and Axelsson – II (1970)	22	45.9	72.2	87
Bonnecaze et al. (1971)	37.6	63.7	92.7	99.6
Premoli et al. (1971)	67.1	83.1	87.2	87.4
Dix (1971)	73.3	93.8	98.7	99.8
Chisholm (1973a)	54.1	86.8	95.5	98.5
Mattar and Gregory (1974)	0	7.9	37	68.6
Madsen (1975)	0	0.9	1.9	4.3
Greskovich and Cooper (1975)	31	53.8	73.9	91.9
Yamazaki and Yamaguchi (1976)	60	87.4	95.7	98.7
Lahey and Moody (1977)	22.4	48.9	69.9	90.2
Ishii (1977b)	51.5	81.4	92.1	99.4
Mukherjee (1979)	50.9	83.1	92.7	97.2
Sun et al. (1980)	31.2	57.9	84.8	99.6
Gardner – I (1980)	28.8	55.3	76.3	88.7
Gardner – II (1980)	25.9	50.9	70.5	85.3
Yeh and Hochreiter (1980)	17.7	39.7	57.9	73.1
Ohkawa and Lahey (1980)	46.8	77.8	84	86.3
Chisholm (1983)	56.2	87.2	95.7	98.7
Jowitt et al. (1984)	23.7	54.7	78.2	84.2
Spedding and Chen (1984)	60.5	82.3	92.3	97.2
Bestion (1985)	42.1	73.3	84.2	99.4
El-Boher et al. (1988)	63.5	92.5	98.7	99.4
Kokal and Stanislav (1989)	37.8	63.9	92.7	99.6
Sonneburgh (1989)	29.7	48.1	63.5	81
Morooka et al. (1989)	51.5	91.7	99.4	100
Spedding et al. (1990)	9.8	26.3	41.7	61.5
Chexal et al. (1992)	39.5	78.6	96.8	99.6
Takeuchi et al. (1992)	34	63.7	87.8	96.6
Huq and Loth (1992)	53.2	85	94.9	97.6
Inoue et al. (1993)	55.1	84.6	97.6	99.4
Shvarts et al. (1993)	66	66	90.4	99.1
Czop et al. (1994)	30.3	54.7	83.1	98.9
Maier and Coddington (1996)	50.9	85.3	97.4	99.4
Woldesemayat and Ghajar (2007)	66.2	91.9	98.1	100

1 – As reported by Woldesemayat and Ghajar (2007), 2 – As reported by Isbin and Biddle (1979)

7.3 Selection of Best Void Fraction Correlation for Vertical Upward Two-phase Flow

Based on the data in Tables 7.17 to 7.20, comments on the performance of the selected correlations and the criteria for each range mentioned above, Table 7.21 shows the performance of the selected correlations qualitatively.

Referring to Table 7.21, correlation of Rouhani and Axelsson – I (1970) performs satisfactorily in all the four void fraction ranges. But, it should be noted that its performance is just below the set criteria for the void fraction range of 0 to 0.25. Other correlations do not perform satisfactorily in at least one range of void fraction.

Considering the overall performance (Table 7.15), correlations of Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989) and Sun et al. (1980) predict more than 90% of the data points within ±20% error band. All of these correlations do not perform satisafactorily in the range 0.75 to 1 for only ±10% error band. In ±15% and ±20% error bands, they perform satisfactorily.

Therefore, further comparison of only Rouhani and Axelsson – I (1970), Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989) and Sun et al. (1980) is done. As discussed in Chapter 2, correlations of Nicklin et al. (1962), Bonnecaze et al. (1971), Kokal and Stanislav (1989) are essentially the same for vertical upward flow. Therefore, further comparison between only Nicklin et al. (1962), Rouhani and Axelsson – I (1970) and Sun et al. (1980) is done.

Prediction of Nicklin et al. (1962) in the lower range of void fraction (0 to 0.25) is better than that of Rouhani and Axelsson – I (1970). Sun et al. (1980) predicts slightly higher number of data points in this range than Rouhani and Axelsson – I (1970). Nicklin et al. (1962) predicts 6 to 10% more data in each error band than Rouhani and Axelsson – I (1970). Nicklin et al. (1962) predicts 4 to 6% more data points than Sun et al. (1980) for ±5%, ±10% and ±15% error bands. For ±20%, ±25% and ±30% error bands, performance of Nicklin et al. (1962) and Sun et al. (1980) is almost identical.

Table 7.21 - Qualitative Performance of selected Correlations in Four Void Fraction Ranges

Correlation	Void Fraction Range			
	0 to 0.25	0.25 to 0.5	0.5 To 0.75	0.75 To 1
Nicklin et al. (1962)	Satisfactory	Satisfactory	Satisfactory	Not Satisfactory
Hughmark (1962)	Not Satisfactory	Not Satisfactory	Satisfactory	Satisfactory
Nishino and Yamazaki (1963)	Not Satisfactory	Not Satisfactory	Satisfactory	Satisfactory
Guzhov et al. (1967)	Satisfactory	Not Satisfactory	Satisfactory	Satisfactory
Rouhani and Axelsson – I (1970)	Satisfactory	Satisfactory	Satisfactory	Satisfactory
Bonnecaze et al. (1971)	Satisfactory	Satisfactory	Satisfactory	Not Satisfactory
Ishii (1977)	Satisfactory	Not Satisfactory	Satisfactory	Satisfactory
Sun et al. (1980)	Satisfactory	Satisfactory	Satisfactory	Not Satisfactory
Kokal and Stanislav (1989)	Satisfactory	Satisfactory	Satisfactory	Not Satisfactory
Morooka et al. (1989)	Satisfactory	Not Satisfactory	Not Satisfactory	Satisfactory
Takeuchi et al. (1992)	Satisfactory	Satisfactory	Not Satisfactory	Not Satisfactory

Performance of Rouhani and Axelsson – I (1970) is comparable to Nicklin et al. (1962) and Sun et al. (1980) in the error band of ±20% for void fraction data in the range 0.25 to 0.5. For ±5% and ±15% error, prediction of Rouhani and Axelsson – I (1970) lags the prediction of Nicklin et al. (1962) by 6.3% and 9.4%, respectively. This is reasonable but, there is a difference of 19.5% in the prediction of the two correlations for error band of ±10%. Rouhani and Axelsson – I (1970) predicts higher number of data points than Sun et al. (1980) in ±15% error band. But, for ±10% error band, Rouhani and Axelsson – I (1970) predicts 13% less data points than Sun et al. (1980). Prediction of Nicklin et al. (1962) is higher than Sun et al. (1980) for ±5%, ±10% and ±15% error bands.

In the void fraction range of 0.5 to 0.75, all the three correlations perform equally well for ±15% and ±20% error criterion. For ±5% and ±10% error, Rouhani and Axelsson – I (1970) correlation predicts 3.7% and 4.8% less data points than Nicklin et al. (1962). Sun et al. (1980) and Nicklin et al. (1962) predict almost equal number of data points in ±10%, ±15% and ±20% error criteria. In ±5% error band, Sun et al. (1980) predicts 7% and 11% more data than Nicklin et al. (1962) and Rouhani and Axelsson – I (1970), respectively.

In the void fraction range 0.75 to 1, all the three correlations predict 99.6% of the data points within ±20% accuracy. In ±15% error band, Rouhani and Axelsson – I (1970) predicts 6.7% and 14.6% more data points than Nicklin et al. (1962) and Sun et al. (1980), respectively. But, for ±5% and ±10% error bands, Rouhani and Axelsson – I (1970) predicts 25.4% and 30.5% more data than Nicklin et al. (1962) and 34% and 32% more data than Sun et al. (1980), respectively.

Considering performance of the three correlations, prediction of Nicklin et al. (1962) and Sun et al. (1980) is better for error band of 0 to 0.25, but Rouhani and Axelsson – I (1970) gives a comparable performance. For void fraction values from 0.25 to 0.5, Nicklin et al. (1962) and Sun et al. (1980) give a superior performance than Rouhani and Axelsson – I (1970), especially in ±10% error band. Prediction of all the three correlations in ±20% error band is almost equal. In the void fraction range of 0.5 to 0.75, all the correlations perform equally well for ±15% and ±20% error bands. But, Sun et al. (1980) and Nicklin et al. (1962) predict higher number of data points than Rouhani and Axelsson – I (1970) in ±5% and ±10% error criteria.

Highest number of data points is present in the range of 0.75 to 1. It should be noted that data from different researchers is collected in this study and the highest number of data points signifies the importance of this range. For 0.75 to 1 range, Rouhani and Axelsson – I (1970) performs much better than Nicklin et al. (1962) and Sun et al. (1980). A large difference in performance for error bands ±5% and ±10% shows the high accuracy of Rouhani and Axelsson – I (1970) correlation. The lack of performance by Nicklin et al. (1962) correlation in this range is understandable. It is a correlation developed for slug flow, in which void fraction values do not exceed 0.7 to 0.8, as observed in the present study and by Sujumnong (1997) and Fernandes (1981). Inadequate performance of Sun et al. (1980) correlation in this range could be because of the value of critical pressure in the correlation. As mentioned in Chapter 2, this correlation was developed for steam-water system and in the present study, calculations for all the fluid combinations were done with a value of critical pressure equal to 221 bar.

Comparisons of all the data and predictions of Nicklin et al. (1962), Rouhani and Axelsson – I (1970) and Sun et al. (1980) are shown in Figures 7.12 to 7.14.

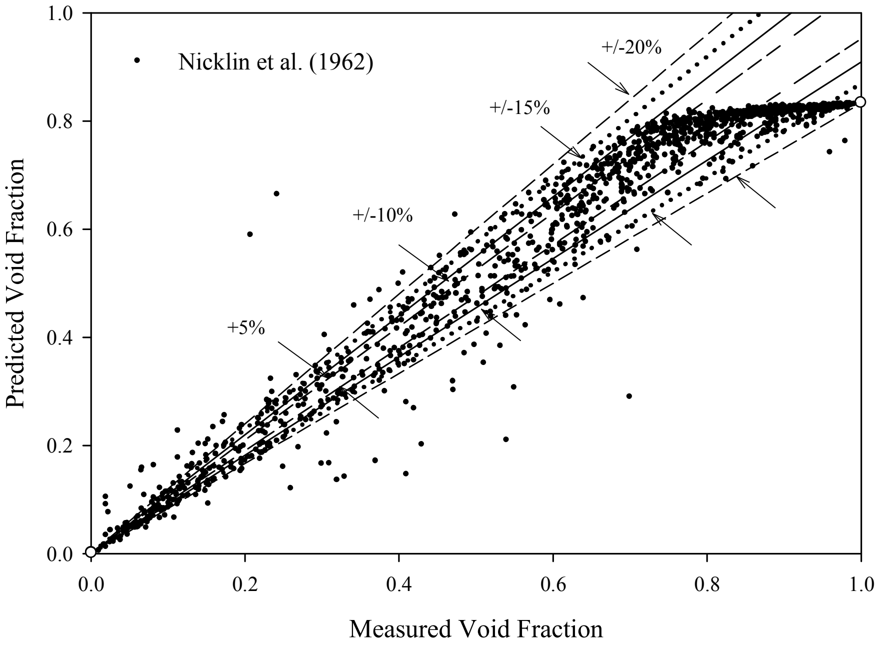


Figure 7.12 - Comparison of Nicklin et al. (1962) Correlation with All Data

Deviation from accuracy of Nicklin et al. (1962) and Sun et al. (1980) correlations in higher void fraction region is clearly observed from Figures 7.12 and 7.14. Spread of for Rouhani and Axelsson – I (1970) correlation is even over the entire void fraction range, though its prediction in lower void fraction range needs improvement. Lower prediction of Rouhani and Axelsson – I (1970) for lower void fraction range could be attributed to diameter effect not considered in the correlation.

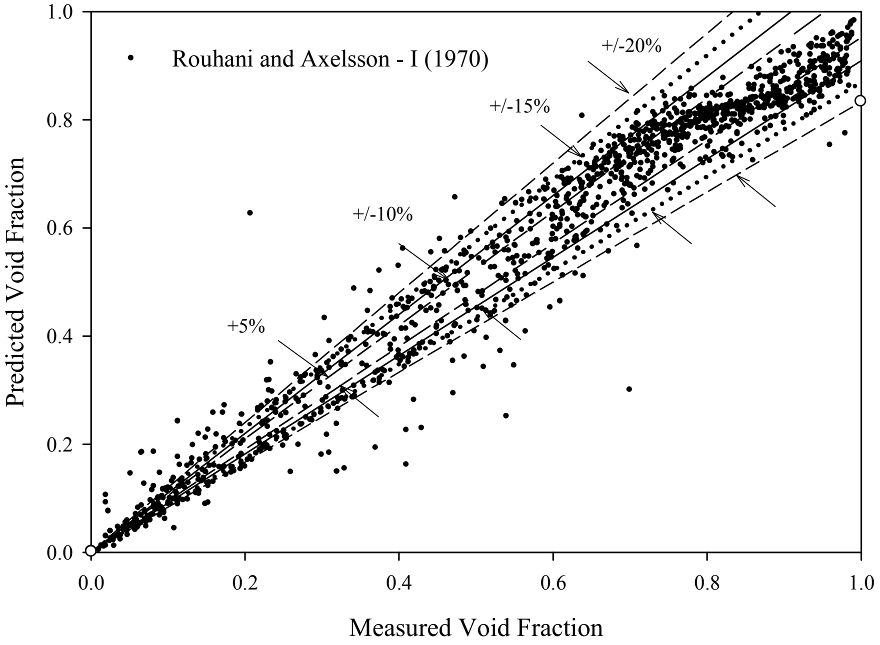


Figure 7.13 - Comparison of Rouhani and Axelsson – I (1970) Correlation with All Data

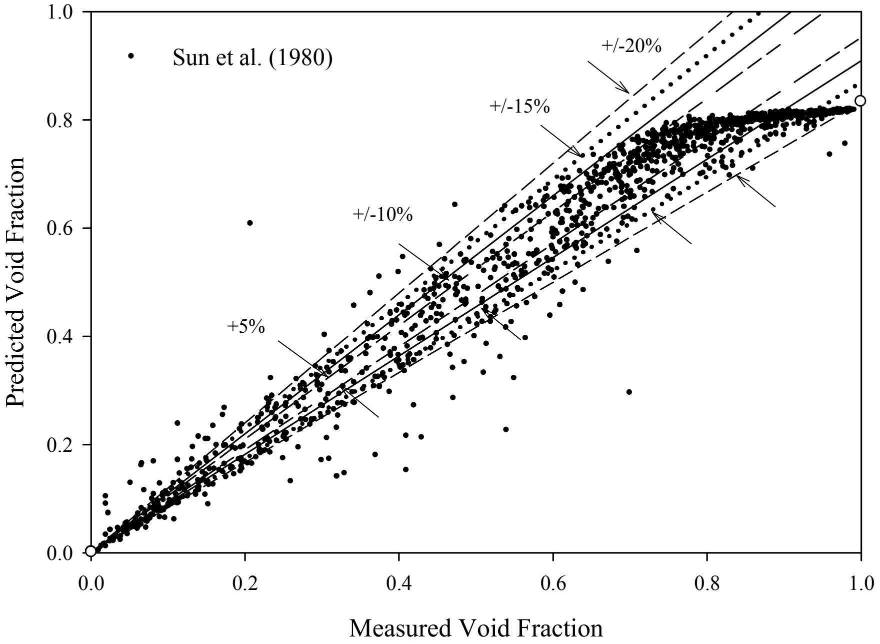


Figure 7.14 - Comparison of Sun et al. (1980) Correlation with All Data

As demonstrated in Table 7.15 for comparison with overall data, Rouhani and Axelsson – I (1970) correlation also does a better job than Nicklin et al. (1962) and Sun et al. (1980) in the error criteria of ±5% and ±10% for overall data. It predicts 6.8% and 6.4% more data points in ±5% and ±10% error band than Nicklin et al. (1962) correlation. Comparison with individual data sets (Tables 7.2 to 7.13) also reveals that prediction of Rouhani and Axelsson – I (1970) for error bands ±5% and ±10% is more than prediction of Nicklin et al. (1962) for 9 out of 12 data sets. Rouhani and Axelsson – I (1970) correlation also predicts higher number of overall data points in ±5% and ±10% error bands than Sun et al. (1980) correlation. For individual data sets, Rouhani and Axelsson – I (1970) predicts more number of data points in ±5% and ±10% error bands than Sun et al. (1980) for 10 out of 12 data sets. This shows the higher accuracy of Rouhani and Axelsson – I (1970) correlation.

The three correlations predict just over 80% and 90% of the data points within ±15% and ±20% of measured void fraction. The correlations need an improvement for a better prediction in ±15% and ±20% as well as ±5% and ±10% error bands. Rouhani and Axelsson – I (1970) and Sun et al. (1980) could be modified to achieve a better performance, as a number of parameters such as quality, surface tension, gas and liquid phase density and total mass flow rate are considered in these two correlations. Nicklin et al. (1962) only considers effect of diameter in the equation of drift velocity. Rouhani and Axelsson – I (1970) is easier to modify than Sun et al. (1980). Sun et al. (1980) correlation contains critical pressure term and critical pressure value for other two-phase fluid systems than steam-water system is not known.

Considering the above points, Rouhani and Axelsson – I (1970), it is chosen as the best correlation for prediction of void fraction data in vertical upward two-phase flow, based on the results in this work. The correlation is given by equation (2.124) in Chapter 2.

Performance of Rouhani and Axelsson – I (1970) correlation for void fraction ranges 0.5 to 0.75 and 0.75 to 1 is shown in Figures 7.7 and 7.9, respectively. Its performance for void fraction ranges of 0 to 0.25 and 0.25 to 0.5 is shown in Figures 7.15 and 7.16, respectively.

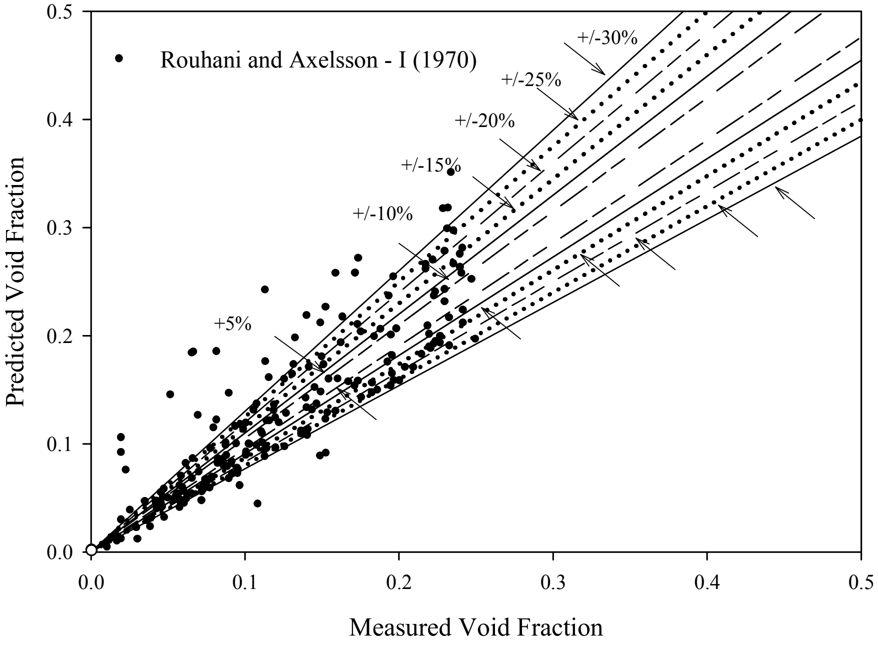


Figure 7.15 - Performance of Rouhani and Axelsson – I (1970) Correlation for Void Fraction Data in 0 to 0.25 Range

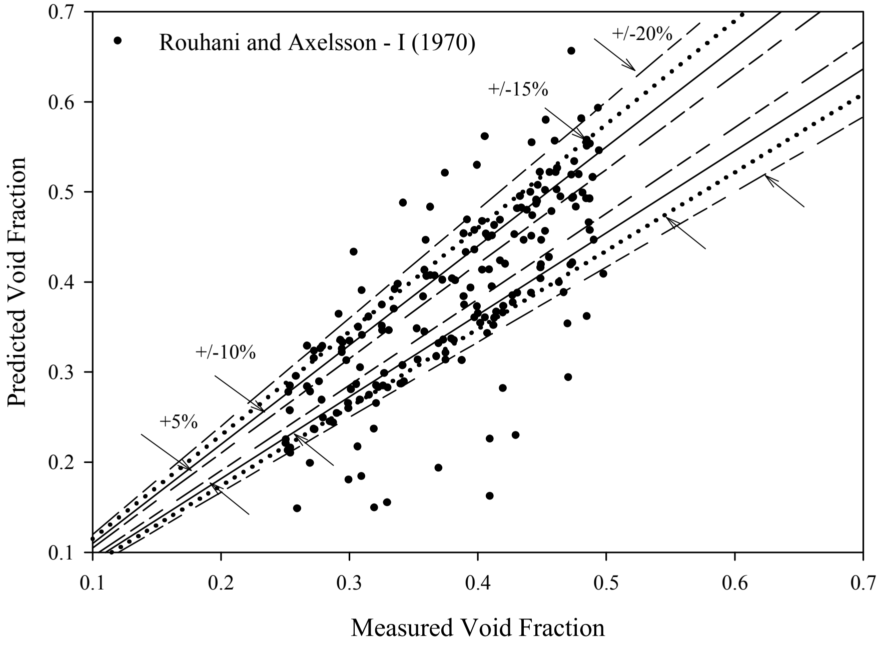


Figure 7.16 - Performance of Rouhani and Axelsson – I (1970) Correlation for Void Fraction Data in 0.25 to 0.5 Range

7.4 Comparison of The Best Flow Pattern Specific and Flow Pattern Independent Correlations

The best correlation from flow independent correlations (Rouhani and Axelsson – I (1970)) is now tested against flow pattern specific void fraction data. Its performance is then compared with the performance of the best flow specific correlation for particular flow pattern. This comparison brings forward some interesting points. The summary of performance is presented in Table 7.22.

The comparison reveals that flow pattern independent correlation predicts data with accuracy level comparable to flow pattern specific correlations. But, flow pattern specific correlations have a higher percentage of data points correctly predicted, especially for bubble flow. Therefore, one could opt for flow specific void fraction correlations. But, there is a high level of inconsistency and disagreement between various researchers on the definition of flow patterns and flow maps. It is not always possible to observe the flow and there is no universal flow map or instrument available for flow pattern recognition. Therefore, improving the accuracy of Rouhani and Axelsson – I (1970) correlation in low void fraction range is a better choice than using five correlations for five flow patterns.

Table 7.22 - Comparison of Flow Pattern Specific and Flow Pattern Independent Correlations for Flow Pattern Specific Data

Flow pattern/No. of Data points	Best Flow Pattern Specific Correlation for the Flow Pattern	Percentage of The Data Points Predicted Correctly by the Best Flow Pattern Specific Correlation			Percentage of The Data Points Predicted Correctly by Rouhani and Axelsson – I (1970) correlation		
		±5%	±10%	±15%	±5%	±10%	±15%
Bubble / 111	Gomez et al. (2000)	13.5	36.0	64.0	13.5	22.5	44.1
Slug / 175	Nicklin and Davidson (1962) and Orell and Rembrand (1986)	30.9	67.4	86.9	26.9	58.9	83.4
Churn / 46	Orell and Rembrand (1986)	71.7	87.0	95.7	60.9	82.6	93.5
Froth / 79	Orell and Rembrand (1986)	60.8	92.4	94.9	54.4	72.1	88.6
Annular / 139	Smith (1969)	52.5	95.7	100	63.3	92.8	100

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

An extensive study of flow patterns and void fraction in vertical upward two-phase flow was done in this work. The work was divided into three areas: flow visualizations and flow pattern transitions, effect of gas phase density and diameter on flow pattern map and study of flow pattern specific and flow pattern independent correlations for prediction of void fraction. An extensive literature related to all the three areas was studied. Experiments were carried out with air and water in a 0.0127 m diameter tube and 153 accurate data points for flow patterns and void fraction were collected.

Significant flow patterns and flow pattern transitions in vertical upward two-phase flow were studied with the help of the experimental setup. Flow pattern map was developed for vertical upward two-phase flow. The experimental data from the present study and from the literature was used to test flow transition theories in the literature. Six theories for slug-churn transition and five theories for churn/froth- annular transition were tested. Prediction of void fraction correlations studied was tested against experimental data of the present study and experimental data from other researchers. Effect of gas phase density and diameter on flow pattern map was analyzed using the data in the present study, data from other researchers and flow pattern transition theories.

Variation of void fraction with respect to liquid and gas mass flow rates and flow patterns was studied. Trend of void fraction for different flow patterns was analyzed. Five bubble flow correlations, ten slug flow correlations, nine annular flow correlations and three churn flow correlations from the literature were tested against flow pattern specific void fraction data. Froth flow correlations were not available in the literature. Therefore, froth flow data was tested against top performing slug and annular flow correlations. Churn flow data was also tested against top performing slug flow correlatiosns. For comparison of flow pattern specific correlations, 111, 175, 139, 46 and 79 void fraction data points of bubble, slug, churn, froth and annular flow were used, respectively.

Fifty Two flow pattern independent correlations were tested against 1208 void fraction data points. The correlations were tested against each data set and four void fraction ranges: 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75 and 0.75 to 1. The best performing void fraction correlation was suggested.

The colncusions and recommendations in the respective areas are given below.

8.1 Conclusions

8.1.1 Conclusions on Flow Patterns and Flow Pattern Transition Theories

Five flow patterns were observed in the present study of vertical upward air-water two-phase flow in 0.0127 m diameter tube. Froth flow emerged as an independent flow pattern along with the dispersed bubble, slug, churn and annular flows observed by other researchers. Based on the readings for flow pattern, flow pattern map was developed, which is shown in Figure 4.3. Flow pattern transitions observed in the present study are marked in the flow pattern map.

For slug-churn and churn/froth-annular transition, McQuillan and Whalley (1985) model gives best results for experimental data in the present study. It also gives a reliable performance for other data sets. This could be because McQuillan and Whalley (1985) have considered effect of both gas density and diameter on flow pattern transition. Other theories do not take into consideration both of these effects and some of them are based on unreasonable assumptions. For example, Brauner and Barnea (1986) have used liquid slug void fraction of 0.52 for slug-churn transition, but other researchers have observed higher values of void fraction in liquid slugs.

The constant *C* in McQuillan and Whalley (1985) theory makes it possible to apply it to variety of data sets. This constant is also present in Jayanti and Hewitt (1992) model and their prediction of slug-churn transition is also very good as shown in Figure 4.5. But, this model, as demonstrated in their work, predicts increasing transition superficial gas velocities after a certain value of superficial liquid velocity. This is contrary to the trend observed in the present study. Jayanti and Hewitt (1992) have not suggested a churn-annular transition model whereas McQuillan and Whalley (1985) have developed models for both slug-churn and churn-annular transitions.

For churn-annular transition, only McQuillan and Whalley (1985) have considered diameter effect. Others have based their theories on *Kutateladze number*, which is independent of diameter.

It should also be noted that McQuillan and Whalley (1985) have compared their theories for transition with a variety of data sets. The prediction of flow patterns by McQuillan and Whalley (1985) is quite satisfactory for all the data sets considered in their study. Other researchers have compared their theory with limited or only one data set.

In experimental studies of flooding mechanism (For example, Hewitt et al. (1965), Wallis (1969), Govan et al. (1991)), at flooding point, value of dimensionless superficial gas velocity (U^*_{SG}) decreases as dimensionless superficial liquid velocity (U^*_{SL}) increases. Same trend is observed in the present study. This further supports the validity of flooding theory of McQuillan and Whalley (1985) for the present data.

Considering above facts, it is fair to conclude that McQuillan and Whalley (1985) model is the best model for predicting slug-churn and churn-annular transition. The equations for the McQuillan and Whalley (1985) models are (2.8) and (2.11), respectively.

There is a definite trend for constant *C* in McQuillan and Whalley (1985) theory, for slug-churn transition. The value of *C* increases with increase in diameter and decreases with increase in density of gas phase. But, this could not be proved for all the data sets.

8.1.2 Conclusions on Pressure and Diameter Effect

The important point coming forward in this study is: diameter and gas phase density have a definite effect on flow pattern map of a two-phase flow system and they should be considered while calculating flow pattern transitions. For constant density, transition velocities could be approximated to vary proportional to square root of diameter of pipe. Many transition theories have used this relation. For a constant pipe diameter, superficial gas velocities are seen to vary inversely to square root of density. But, there is only one evidence to support this conclusion for slug-churn transition. It should be noted that neither diameter nor pressure is constant if a variety of two-phase flow systems are considered and therefore their effect should be considered simultaneously.

8.1.3 Conclusions on Void Fraction Correlations

Changes in void fraction with respect to flow pattern were observed during this study. The slope of void fraction profile is steep in bubble and slug flow patterns. Therefore, there is less margin for error. It was observed that the slope becomes gradual at gas mass flow rate of 0.035 kg/min. This value is observed to be approximately constant for the range of liquid flow rates used. This value is important because the change in void fraction with respect to gas mass flow rate becomes gradual after this value.

For bubble flow, there is a need for more accurate correlations which can predict more bubble flow data within ±15%. But, this task is really difficult considering very low values of void fraction in bubble flow. Gomez et al. (2000), Kabir and Hasan (1990) and Hibiki and Ishii (2002) offer good prediction of void fraction (within ±30%). There are many slug flow correlations (Orell and Rembrand (1986), Kataoka and Ishii (1987), Nicklin and Davidson (1962) and Bonneczae et al. (1971)), which can be used for accurate prediction of void fraction in slug flow. Based on Tables 6.15 and 6.18, it can be concluded that void fraction in churn and froth flow can be predicted satisfactorily by slug flow correlations. Smith (1969) and Lockhart and Martinelli (1949) correlations give the best performance for prediction of void fraction in annular flow. Recommended correlations for prediction of void fraction in flow patterns are given in Table 8.1.

Table 8.1 - Recommended Correlations for Different Flow Patterns

Flow Pattern	Correlation	Equation Number
Bubble	Gomez et al. (2000)	(2.35)
Slug	Nicklin and Davidson (1962) and Orell and Rembrand (1986)	(2.39) and (2.65)
Churn	Orell and Rembrand (1986)	(2.65)
Froth	Orell and Rembrand (1986)	(2.65)
Annular	Smith (1969)	(2.70)

Rouhani and Axelsson – I (1970) correlation (equation (2.124)) performs the best for the flow pattern independent data sets studied in the present study, predicting 89.3%, 83.5%, 68.5% and 39.9% of data within ±20%, ±15%, ±10% and ±5%, respectively. Rouhani and Axelsson – I (1970) also predicts void fraction accurately for all the four void fraction ranges considered. But, it needs improvement in the lower void fraction range (0 to 0.25). Rouhani and Axelsson – I (1970) is closely followed by Nicklin et al. (1962) correlation (equation (2.39)) for prediction of void fraction. But, it needs a lot of improvement in prediction of higher void fraction values (0.75 to 1).

Performance of the correlations for low void fraction (0 to 0.25) values needs much improvement. The low void fraction values have a higher tendency for errors and hence prediction of 90% of data within ±30% and 85% of data within ±25% could be a satisfactory performance in this range. For the range of 0.25 to 0.5, only few can predict more than 80% of data within ±20% error. Many correlations predict more than 90% of data in ±15% and more than 95% of data in ±20% for void fraction range of 0.5 to 0.75, which is excellent. But, more work is needed to improve predictions in ±5% error range. For 0.75 to 1 range, many correlations give superb performance, predicting more than 85% of data within ±10%, more than 90% of data for ±15% and 100% of data within ±20%. But, improved accuracy (more data within ±5%) is desired.

Air-kerosene data of Mukherjee (1979) was also not predicted well by any correlation. Probable cause for this could be low value of surface tension associated with kerosene. But, this could not be verified due to lack of another low surface tension data set.

High viscosity liquid (Luviskol®) and nitrogen system was not predicted satisfactorily by any of the correlations considered in this study. Therefore, a general purpose correlation should not be used for special cases of gas-liquid two-phase flow systems.

Boiling void fraction data of Isbin et al. (1957) was predicted well by many correlations. But, this data set contained only 22 data points. It is difficult to obtain data for boiling systems from literature as most of the data is for steam-water system which is proprietary of some institutions.

Simple correlations give the same level of performance as complex and iterative correlations. For example, complex correlation of Chexal et al. (1992) does not perform as well as simple correlation of Rouhani and Axelsson – I (1970).

It is observed that most of the better performing correlations are based on drift-flux approach. For example, correlations of Rouhani and Axelsson – I (1970) and Nicklin et al. (1962) fall into this group.

Flow pattern independent correlation of Rouhani and Axelsson – I (1970) predicts void fraction in all flow patterns reasonably well when compared to flow pattern specific correlations. But, percentage of the data points correctly predicted by flow pattern specific correlations is generally higher than that of Rouhani and Axelsson – I (1970).

8.2 Recommendations

8.2.1 Recommendations on Flow Patterns and Flow Pattern Transition Theories

1) A limitation of using superficial liquid velocities as flow map parameters is observed during the present study. For nearly all the data sets considered in the present study, gas mass flow rate, for a constant liquid flow rate increases with the

increase in diameter. But, if flow map is plotted using superficial gas velocities, results vary depending upon the increase in density of the gas phase. For example, in Govier and Short (1958) data, volume flow rate and mass flow rate increase with the increase in diameter, but the trend of gas velocities is not consistent. Hence, improved coordinates for flow maps are desired.

2) Further scrutiny of constant *C* using more data is desired. But, there are limited data sets available in open literature which report comprehensive parameters including operating pressure and flow patterns.
3) Bubble-froth and churn-froth transitions cannot be predicted because there are no models for these transitions. There is a need for further study in this area.
4) Comparison of pressure drop and heat transfer data for churn and froth flow is necessary.

8.2.2 Recommendation on Pressure and Diameter Effect

A correlation or a scaling factor incorporating the effects of diameter and gas phase density is not yet developed. Further study in this area will be useful.

8.2.3 Recommendations on Void Fraction Correlations

1) The critical gas mass flow rate, at which slope of void fraction profile changes, could be studied for different pipe diameters.
2) Performance of correlations for large diameter is a challenge, as demonstrated in Tables 7.6 and 7.7 for Chokshi (1994) and Fernandes (1981) data.
3) More accurate correlations are required, especially for prediction of lower values of void fraction.

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APPENDIX A

DETAILS OF EXPERIMENTAL DATA SETS AND FLUID PROPERTIES

Details of experimental data used for comparison with vertical upward void fraction correlations are presented in this appendix. The correlations were divided as flow pattern specific and flow pattern independent correlations. Therefore, data sets are also presented in those groups to maintain the consistency. Ranges of important parameters in data sets are given in this appendix along with method of void fraction measurement, diameter, total number of data points and fluid combination.

Fluid properties were calculated based on the correlations cited in the works of other researchers or from books. The correlations used for calculating fluid properties are also listed in this appendix.

Complete data set is available from:

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FLOW PATTERN INDEPENDENT DATA

Data Source: Present Study (2009)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 153

Fluids used: Air – water

Pressure range: 0.1139 – 0.2601 ***MPa***

Temperature range: 18.5806 – 25.1660 ***ºC***

Range of liquid mass flow rate: 0.5698 – 13.1020 ***kg/min***

Range of gas mass flow rate: 0.0026 – 0.2673 ***kg/min***

Range of void fraction covered: 0.1593 – 0.8962

Data Source: Schmidt et al. (2008)

Method of Measurement: Gamma Ray Densitometer

Diameter of pipe: 0.0545 ***m***

Total data points: 20

Fluids used: Nitrogen - Water

Pressure range: 0.0791 – 0.1513 ***MPa***

Temperature range: Constant (20) ***ºC***

Range of liquid mass flow rate: 13.9494 – 442.5948 ***kg/min***

Range of gas mass flow rate: 0.0165 – 5.4238 ***kg/min***

Range of void fraction covered: 0.0300 – 0.9600

Data Source: Sujumnong (1997)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 104

Fluids used: Air – water

Pressure range: 0.1000 – 0.3400 ***MPa***

Temperature range: 18.9700 – 32.1300 ***ºC***

Range of liquid mass flow rate: 0.3552 – 54.5676 ***kg/min***

Range of gas mass flow rate: 0.0002 – 1.4688 ***kg/min***

Range of void fraction covered: 0.0200 – 0.9900

Data Source: Sujumnong (1997)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 77

Fluids used: Air – 59% Glycerine

Pressure range: 0.1020 – 0.3068 ***MPa***

Temperature range: 18.7000 – 32.4000 ***ºC***

Range of liquid mass flow rate: 0.3480 – 44.8452 ***kg/min***

Range of gas mass flow rate: 0.00038 – 1.0050 ***kg/min***

Range of void fraction covered: 0.0110 – 0.9850

Data Source: Chokshi (1994)

Method of Measurement: Gamma ray densitometer

Diameter of pipe: 0.0760 ***m***

Total data points: 103

Fluids used: Air - Water

Pressure range: 1.2183 – 3.4132 ***MPa***

Temperature range: 22.4286 – 34.2569 ***ºC***

Range of liquid mass flow rate: 10.1823 – 448.6481 ***kg/min***

Range of gas mass flow rate: 0.0726 – 125.0816 ***kg/min***

Range of void fraction covered: 0.1135 – 0.9360

Data Source: Fernandes (1981)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.05074 ***m***

Total data points: 88

Fluids used: Air - Water

Pressure range: Constant (0.101325) ***MPa***

Temperature range for gas: 22.3000 – 24.7000 ***ºC***

Temperature range for liquid: 23.1000 – 31.2000 ***ºC***

Range of liquid mass flow rate: 1.9447 – 350.6051 ***kg/min***

Range of gas mass flow rate: 0.0013 – 3.0966 ***kg/min***

Range of void fraction covered: 0.0370 – 0.9570

Data Source: Mukherjee (1979)

Method of Measurement: Capacitance Probes

Diameter of pipe: 0.0381 ***m***

Total data points: 65

Fluids used: Air - Kerosene

Pressure range: 0.2668 – 0.6095 ***MPa***

Temperature range: 12.2222 – 47.7778 ***ºC***

Range of liquid mass flow rate: 1.5265 – 181.8213 ***kg/min***

Range of gas mass flow rate: 0.0162 – 9.6736 ***kg/min***

Range of void fraction covered: 0.0200 – 0.9800

Data Source: Spedding and Nguyen (1976)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0455 ***m***

Total data points: 224

Fluids used: Air - Water

Pressure range: 0.1066 – 0.1250 ***MPa***

Temperature range: 16.3500 – 23.7300 ***ºC***

Range of liquid mass flow rate: 0.5402 – 101.5995 ***kg/min***

Range of gas mass flow rate: 0.0099 – 7.2716 ***kg/min***

Range of void fraction covered: 0.0355 – 0.9915

Data Source: Beggs (1972)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 13

Fluids used: Air - Water

Pressure range: 0.5268 – 0.6769 ***MPa***

Temperature range: 19.4444 – 30.5556 ***ºC***

Range of liquid mass flow rate: 0.7541 – 76.7092 ***kg/min***

Range of gas mass flow rate: 0.0460 – 3.6263 ***kg/min***

Range of void fraction covered: 0.1530 – 0.9820

Data Source: Beggs (1972)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0381 ***m***

Total data points: 14

Fluids used: Air - Water

Pressure range: 0.5650 – 0.6653 ***MPa***

Temperature range: 22.7778 – 35.5556 ***ºC***

Range of liquid mass flow rate: 1.5430 – 109.4062 ***kg/min***

Range of gas mass flow rate: 0.1770 – 7.1472 ***kg/min***

Range of void fraction covered: 0.1950 – 0.9830

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 153

Fluids used: Air – Water

Pressure range: 0.1344 – 0.2062 ***MPa***

Temperature range: 7.7778 – 26.6667 ***ºC***

Range of liquid mass flow rate: 0.8753 – 62.4153 ***kg/min***

Range of gas mass flow rate: 0.0058 – 1.8828 ***kg/min***

Range of void fraction covered: 0.0607 – 0.9636

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 51

Fluids used: Air – 16% Glycerine

Pressure range: 0.1407 – 0.1944 ***MPa***

Temperature range: 18.3333 – 26.6667 ***ºC***

Range of liquid mass flow rate: 0.3391 – 59.1140 ***kg/min***

Range of gas mass flow rate: 0.0047 – 1.6794 ***kg/min***

Range of void fraction covered: 0.0428 – 0.9642

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 40

Fluids used: Air – 35% Glycerine

Pressure range: 0.1407 – 0.1931 ***MPa***

Temperature range: 22.7778 – 27.7778 ***ºC***

Range of liquid mass flow rate: 0.5044 – 58.7217 ***kg/min***

Range of gas mass flow rate: 0.0061 – 1.5969 ***kg/min***

Range of void fraction covered: 0.0434 – 0.9514

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 44

Fluids used: Air – 56% Glycerine

Pressure range: 0.1462 – 0.1979 ***MPa***

Temperature range: 23.0556 – 26.8333 ***ºC***

Range of liquid mass flow rate: 0.7461 – 53.7582 ***kg/min***

Range of gas mass flow rate: 0.0065 – 1.7460 ***kg/min***

Range of void fraction covered: 0.0474 – 0.9335

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 37

Fluids used: Air – 60% Glycerine

Pressure range: 0.1455 – 0.1986 ***MPa***

Temperature range: 23.3333 – 26.0000 ***ºC***

Range of liquid mass flow rate: 0.5039 – 60.1631 ***kg/min***

Range of gas mass flow rate: 0.0047 – 1.5814 ***kg/min***

Range of void fraction covered: 0.0231 – 0.9491

Data Source: Isbin et al. (1957)

Method of Measurement: Gamma Ray Absorption

Diameter of pipe: 0.02215 ***m***

Total data points: 22

Fluids used: Steam-Water

Pressure range: Constant (0.101325) ***MPa***

Temperature range: Constant (100) ***ºC***

Range of liquid mass flow rate: 9.0426 – 20.3316 ***kg/min***

Range of gas mass flow rate: 0.0386 – 0.4186 ***kg/min***

Range of void fraction covered: 0.5914 - 9236

FLOW PATTERN SPECIFIC DATA

Data sets for Bubble Flow Pattern

Data Source: Present Study

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 25

Fluids used: Air – water

Pressure range: 0.1259 – 0.2239 ***MPa***

Temperature range: 20.3337 – 24.9356 ***ºC***

Range of liquid mass flow rate: 5.5694 – 13.1020 ***kg/min***

Range of gas mass flow rate: 0.0026 – 0.0249 ***kg/min***

Range of void fraction covered: 0.1593 – 0.5106

Data Source: Sujumnong (1997)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 13

Fluids used: Air – water

Pressure range: 0.1103 – 0.1786 ***MPa***

Temperature range: 21.2600 – 22.9300 ***ºC***

Range of liquid mass flow rate: 6.6978 – 54.5676 ***kg/min***

Range of gas mass flow rate: 0.0002 – 0.0149 ***kg/min***

Range of void fraction covered: 0.0174 – 0.1414

Data Source: Mukherjee (1979)

Method of Measurement: Capacitance Probes

Diameter of pipe: 0.0381 ***m***

Total data points: 17

Fluids used: Air - Kerosene

Pressure range: 0.2668 – 0.5633 ***MPa***

Temperature range: 22.2222 – 47.2222 ***ºC***

Range of liquid mass flow rate: 2.1911 – 181.8213 ***kg/min***

Range of gas mass flow rate: 0.0162 – 1.8311 ***kg/min***

Range of void fraction covered: 0.0200 – 0.6100

Data Source: Fernandes (1981)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.05074 ***m***

Total data points: 29

Fluids used: Air - Water

Pressure range: Constant (0.101325) ***MPa***

Temperature range for gas: 22.6000 – 24.2000 ***ºC***

Temperature range for liquid: 23.5000 – 30.6000 ***ºC***

Range of liquid mass flow rate: 1.9447 – 350.6051 ***kg/min***

Range of gas mass flow rate: 0.0023 – 0.1269 ***kg/min***

Range of void fraction covered: 0.0370 – 0.2510

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 12

Fluids used: Air – 16% Glycerine

Pressure range: 0.1634 – 0.1800 ***MPa***

Temperature range: 18.3333 – 23.8889 ***ºC***

Range of liquid mass flow rate: 36.9463 – 59.1140 ***kg/min***

Range of gas mass flow rate: 0.0047 – 0.0262 ***kg/min***

Range of void fraction covered: 0.0428 – 0.1497

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 5

Fluids used: Air – 35% Glycerine

Pressure range: 0.1724 – 0.1882 ***MPa***

Temperature range: 22.7778 – 27.4444 ***ºC***

Range of liquid mass flow rate: 45.1705 – 58.7217 ***kg/min***

Range of gas mass flow rate: 0.0061 – 0.0241 ***kg/min***

Range of void fraction covered: 0.0434 – 0.1191

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 7

Fluids used: Air – 56% Glycerine

Pressure range: 0.1696 – 0.1896 ***MPa***

Temperature range: 23.0556 – 25.0000 ***ºC***

Range of liquid mass flow rate: 44.5425 – 53.7582 ***kg/min***

Range of gas mass flow rate: 0.0065 – 0.0361 ***kg/min***

Range of void fraction covered: 0.0474 – 0.9335

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 3

Fluids used: Air – 60% Glycerine

Pressure range: 0.1765 – 0.1841 ***MPa***

Temperature range: 23.8889 – 25.0000 ***ºC***

Range of liquid mass flow rate: 53.6839 – 60.1631 ***kg/min***

Range of gas mass flow rate: 0.0047 – 0.0128 ***kg/min***

Range of void fraction covered: 0.0393 – 0.0884

Data sets for Slug Flow Pattern

Data Source: Present Study (2009)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 21

Fluids used: Air – water

Pressure range: 0.1153 - 0.1288 ***MPa***

Temperature range: 19.2232 – 25.1660 ***ºC***

Range of liquid mass flow rate: 0.5901 – 5.5966 ***kg/min***

Range of gas mass flow rate: 0.0031 – 0.0078 ***kg/min***

Range of void fraction covered: 0.2512 – 0.6908

Data Source: Sujumnong (1997)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 20

Fluids used: Air – water

Pressure range: 0.1014 – 0.1237 ***MPa***

Temperature range: 21.0100 – 30.0900 ***ºC***

Range of liquid mass flow rate: 0.3552 – 20.3742 ***kg/min***

Range of gas mass flow rate: 0.0013 – 0.0175 ***kg/min***

Range of void fraction covered: 0.0954 – 0.8018

Data Source: Mukherjee (1979)

Method of Measurement: Capacitance Probes

Diameter of pipe: 0.0381 ***m***

Total data points: 32

Fluids used: Air - Kerosene

Pressure range: 0.2910 – 0.6095 ***MPa***

Temperature range: 12.2222 – 47.7778 ***ºC***

Range of liquid mass flow rate: 1.5265 – 169.1449 ***kg/min***

Range of gas mass flow rate: 0.0176 – 6.6608 ***kg/min***

Range of void fraction covered: 0.5400 – 0.9800

Data Source: Fernandes (1981)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.05074 ***m***

Total data points: 16

Fluids used: Air - Water

Pressure range: Constant (0.101325) ***MPa***

Temperature range for gas: 22.9000 – 24.7000 ***ºC***

Temperature range for liquid: 26.1000 – 30.4000 ***ºC***

Range of liquid mass flow rate: 1.9466 – 73.6798 ***kg/min***

Range of gas mass flow rate: 0.0543 – 0.1668 ***kg/min***

Range of void fraction covered: 0.4900 – 0.6900

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 16

Fluids used: Air – 16% Glycerine

Pressure range: 0.1462 – 0.1834 ***MPa***

Temperature range: 20.3333 – 25.5556 ***ºC***

Range of liquid mass flow rate: 0.4926 – 29.5605 ***kg/min***

Range of gas mass flow rate: 0.0075 – 0.3762 ***kg/min***

Range of void fraction covered: 0.0861 – 0.7514

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 19

Fluids used: Air – 35% Glycerine

Pressure range: 0.1427 – 0.1820 ***MPa***

Temperature range: 23.0556 – 27.7778 ***ºC***

Range of liquid mass flow rate: 0.5044 – 33.1243 ***kg/min***

Range of gas mass flow rate: 0.0092 – 0.4131 ***kg/min***

Range of void fraction covered: 0.1035 – 0.8175

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 26

Fluids used: Air – 56% Glycerine

Pressure range: 0.1462 – 0.1979 ***MPa***

Temperature range: 24.1667 – 26.8333 ***ºC***

Range of liquid mass flow rate: 0.7461 – 47.6134 ***kg/min***

Range of gas mass flow rate: 0.0076 – 0.5134 ***kg/min***

Range of void fraction covered: 0.0994 – 0.7844

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 25

Fluids used: Air – 60% Glycerine

Pressure range: 0.1455 – 0.1986 ***MPa***

Temperature range: 23.3333 – 26.0000 ***ºC***

Range of liquid mass flow rate: 0.5038 – 53.6828 ***kg/min***

Range of gas mass flow rate: 0.0059 – 0.4878 ***kg/min***

Range of void fraction covered: 0.0231 – 0.7786

Data sets for Churn Flow Pattern

Data Source: Present Study (2009)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 24

Fluids used: Air – water

Pressure range: 0.1139 - 0.1423 ***MPa***

Temperature range: 19.3858 – 23.5606 ***ºC***

Range of liquid mass flow rate: 0.5931 – 4.5198 ***kg/min***

Range of gas mass flow rate: 0.0051 – 0.0916 ***kg/min***

Range of void fraction covered: 0.3539 – 0.8295

Data Source: Sujumnong (1997)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 12

Fluids used: Air – water

Pressure range: 0.1014 – 0.1117 ***MPa***

Temperature range: 21.8400 – 28.7800 ***ºC***

Range of liquid mass flow rate: 0.3552 – 6.6978 ***kg/min***

Range of gas mass flow rate: 0.0202 – 0.0828 ***kg/min***

Range of void fraction covered: 0.5694 – 0.8487

Range of void fraction covered: 0.5400 – 0.9800

Data Source: Fernandes (1981)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.05074 ***m***

Total data points: 10

Fluids used: Air - Water

Pressure range: Constant (0.101325) ***MPa***

Temperature range for gas: 22.7000 – 23.2000 ***ºC***

Temperature range for liquid: 26.3000 – 27.9000 ***ºC***

Range of liquid mass flow rate: 5.9248 – 122.0744 ***kg/min***

Range of gas mass flow rate: 0.5004 – 1.1574 ***kg/min***

Range of void fraction covered: 0.7600 – 0.8460

Data sets for Froth Flow Pattern

Data Source: Present Study (2009)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 43

Fluids used: Air – water

Pressure range: 0.1232 - 0.2430 ***MPa***

Temperature range: 20.3608 – 24.5916 ***ºC***

Range of liquid mass flow rate: 1.2240 – 8.8306 ***kg/min***

Range of gas mass flow rate: 0.0051 – 0.1281 ***kg/min***

Range of void fraction covered: 0.3160 – 0.8025

Data Source: Sujumnong (1997)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 11

Fluids used: Air – water

Pressure range: 0.2275 – 0.3427 ***MPa***

Temperature range: 21.5100 – 23.5100 ***ºC***

Range of liquid mass flow rate: 40.7784 – 54.4314 ***kg/min***

Range of gas mass flow rate: 0.0535 – 0.4650 ***kg/min***

Range of void fraction covered: 0.2546 – 0.7454

Data Source: Oshinowo (1971)

Diameter of pipe: 0.0254 ***m***

Total data points: 8

Fluids used: Air – 16% Glycerine

Pressure range: 0.1407 – 0.1944 ***MPa***

Temperature range: 23.0556 – 26.6667 ***ºC***

Range of liquid mass flow rate: 0.4827 – 29.5564 ***kg/min***

Range of gas mass flow rate: 0.1988 – 0.9381 ***kg/min***

Range of void fraction covered: 0.6994 – 0.8682

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 9

Fluids used: Air – 35% Glycerine

Pressure range: 0.1434 – 0.1931 ***MPa***

Temperature range: 23.8889 – 25.5556 ***ºC***

Range of liquid mass flow rate: 0.5044 – 30.1131 ***kg/min***

Range of gas mass flow rate: 0.1583 – 1.2320 ***kg/min***

Range of void fraction covered: 0.5399 – 0.8902

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 5

Fluids used: Air – 56% Glycerine

Pressure range: 0.1462 – 0.1917 ***MPa***

Temperature range: 24.6111 – 26.2778 ***ºC***

Range of liquid mass flow rate: 0.7589 – 9.9501 ***kg/min***

Range of gas mass flow rate: 0.3471 – 1.2551 ***kg/min***

Range of void fraction covered: 0.7769 – 0.8318

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 3

Fluids used: Air – 60% Glycerine

Pressure range: 0.1565 – 0.1855 ***MPa***

Temperature range: 24.4444 – 25.0000 ***ºC***

Range of liquid mass flow rate: 4.3115 – 10.0220 ***kg/min***

Range of gas mass flow rate: 0.9641 – 1.1953 ***kg/min***

Range of void fraction covered: 0.7913 – 0.8312

Data sets for Annular Flow Pattern

Data Source: Present Study (2009)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 36

Fluids used: Air – water

Pressure range: 0.1188 - 0.2601 ***MPa***

Temperature range: 18.5806 – 24.6051 ***ºC***

Range of liquid mass flow rate: 0.5697 – 6.5472 ***kg/min***

Range of gas mass flow rate: 0.1012 – 0.2673 ***kg/min***

Range of void fraction covered: 0.7070 – 0.8962

Data Source: Sujumnong (1997)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0127 ***m***

Total data points: 38

Fluids used: Air – water

Pressure range: 0.1014 – 0.2599 ***MPa***

Temperature range: 18.9700 – 32.1300 ***ºC***

Range of liquid mass flow rate: 0.3552 – 20.3742 ***kg/min***

Range of gas mass flow rate: 0.0678 – 1.4658 ***kg/min***

Range of void fraction covered: 0.6385 – 0.9858

Data Source: Mukherjee (1979)

Method of Measurement: Capacitance Probes

Diameter of pipe: 0.0381 ***m***

Total data points: 12

Fluids used: Air - Kerosene

Pressure range: 0.2992 – 0.5819 ***MPa***

Temperature range: 13.3333 – 45.5556 ***ºC***

Range of liquid mass flow rate: 1.5265 – 30.3909 ***kg/min***

Range of gas mass flow rate: 1.7644 – 9.6736 ***kg/min***

Range of void fraction covered: 0.8700 – 0.9600

Data Source: Fernandes (1981)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.05074 ***m***

Total data points: 19

Fluids used: Air - Water

Pressure range: Constant (0.101325) ***MPa***

Temperature range for gas: 22.3000 – 24.6000 ***ºC***

Temperature range for liquid: 25.4000 – 28.6000 ***ºC***

Range of liquid mass flow rate: 1.9469 – 122.0710 ***kg/min***

Range of gas mass flow rate: 1.3456 – 3.0966 ***kg/min***

Range of void fraction covered: 0.0.856 – 0.9570

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 15

Fluids used: Air – 16% Glycerine

Pressure range: 0.1496 – 0.1834 ***MPa***

Temperature range: 20.0000 – 26.6667 ***ºC***

Range of liquid mass flow rate: 0.3391 – 9.5737 ***kg/min***

Range of gas mass flow rate: 0.7651 – 1.6793 ***kg/min***

Range of void fraction covered: 0.8399 – 0.9642

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 7

Fluids used: Air – 35% Glycerine

Pressure range: 0.1407 – 0.1882 ***MPa***

Temperature range: 24.1667 – 27.2222 ***ºC***

Range of liquid mass flow rate: 0.5044 – 4.1803 ***kg/min***

Range of gas mass flow rate: 0.8183 – 1.5969 ***kg/min***

Range of void fraction covered: 0.9017 – 0.9514

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 6

Fluids used: Air – 56% Glycerine

Pressure range: 0.1462 – 0.1903 ***MPa***

Temperature range: 25.5556 – 26.1111 ***ºC***

Range of liquid mass flow rate: 0.7538 – 4.2643 ***kg/min***

Range of gas mass flow rate: 0.8594 – 1.7460 ***kg/min***

Range of void fraction covered: 0.8711 – 0.9335

Data Source: Oshinowo (1971)

Method of Measurement: Quick-closing Valves

Diameter of pipe: 0.0254 ***m***

Total data points: 6

Fluids used: Air – 60% Glycerine

Pressure range: 0.1524 – 0.1875 ***MPa***

Temperature range: 24.3333 – 26.0000 ***ºC***

Range of liquid mass flow rate: 0.5168 – 4.2829 ***kg/min***

Range of gas mass flow rate: 0.8817 – 1.5814 ***kg/min***

Range of void fraction covered: 0.8613 – 0.9491

FLUID PROPERTIES

1) Air properties

Density of air was calculated considering it an ideal gas.

$$\rho_{air} = \frac{P}{T\left(R/M_{air}\right)} \text{ (kg/m}^3\text{)} \qquad ,$$

Where,

T = Temperature in Kelvin

P = Pressure in Pa

M_{air} = Molecular weight of air

R = Universal gas constant (8314.34 J/kmol.K)

Viscosity of air was calculated by the following equation taken from Woldesemayat (2006)

$$\mu_{air} = 1.7211 \times 10^{-5} + 4.8837 \times 10^{-8} T - 2.9967 \times 10^{-11} T^2 \quad \text{(Pas)}$$

Where,

T = Temperature in °C

2) Nitrogen properties

Density of nitrogen was calculated considering it an ideal gas.

$$\rho_{nitrogen} = \frac{P}{T\left(R/M_{nitrogen}\right)} \text{(kg/m}^3\text{)}$$

Where,

T = Temperature in Kelvin

P = Pressure in Pa

M_{air} = Molecular weight of nitrogen

R = Universal gas constant (8314.34 J/kmol.K)

Viscosity Data was provided by Schmidt et al. (2008) which is the only data set where Nitrogen is used as gas phase.

3) Water properties

Density, dynamic viscosity and surface tension of water were calculated by the three equations taken from Woldesemayat (2006).

$$\rho_{water} = 999.96 + 1.7158\times10^{-2}T - 5.8699\times10^{-3}T^2 + 1.5487\times10^{-5}T^3 \text{ (kg/m}^3\text{)}$$

$$\mu_{water} = 1.7888\times10^{-3} - 5.9458\times10^{-5}T + 1.3096\times10^{-6}T^2 - 1.8035\times10^{-8}T^3 + 1.3446\times10^{-10}T^4 - 4.0698\times10^{-13}T^5 \quad \text{(Pas)}$$

$$\sigma_{water} = 0.075652711 - 0.000139369566T - 3.0842103\times10^{-7}T^2 + 2.7588435\times10^{-10}T^3 \quad \text{(N/m)}$$

Where,

T = Temperature in °C

4) Kerosene properties (Mukherjee (1979) data)

Density, dynamic viscosity and surface tension of kerosene were calculated by the three equations reported by Woldesemayat (2006).

$$\rho_{\mathrm{ker}\,o} = 52.8858 - 0.0289T \text{ (lb/ft}^3\text{)}$$

$$\mu_{\mathrm{ker}\,o} = Exp(1.4344 - 0.0115T)\text{(Centipoise)}$$

$$\sigma_{\mathrm{ker}\,o} = 29.198 - 0.05T \text{ (dynes/cm)}$$

T = Temperature in °F

5) 59% Glycerin properties (Sujumnong (1997) data)

Density, dynamic viscosity and surface tension of 59% glycerin were calculated by the three equations reported by Sujumnong (1997).

$$\rho_{59\%Gly} = 73.04095 - 0.0187T \text{ (lb/ft}^3\text{)}$$

$$\mu_{59\%Gly} = 124.086 - 2.549T + 0.01955\mathrm{T}^2 - 5.2466\times10^{-5}T^3 \text{ (lbm/ft - h)}$$

$$\sigma_{59\%Gly} = 0.00492 - 3.9556\times T^{-6} \text{ (lbf/ft)}$$

T = Temperature in °F

6) 16% Glycerin properties (Oshinowo (1971) data)

Dynamic viscosity and surface tension of 16% glycerin were calculated by curve fitting the data given in 'Physical properties of glycerin and its solutions' by Glycerin Producers Association (1963). Density was found out from the mass flow rate and volume flow rate data presented by Oshinowo (1971).

$$\mu_{16\%Gly} = \text{-}0.0001 + 0.0558/\mathrm{T} - 0.5435/\mathrm{T}^2 + 2.1085/\mathrm{T}^3 \text{ (Pas)}$$

$$\sigma_{16\%Gly} = 0.0736 - 0.0001\mathrm{T} + 8.058\times10^{-8}\mathrm{T}^2 - 1.9938\times10^{-9}\mathrm{T}^3 \text{ (N/m)}$$

T = Temperature in °C

7) 35% Glycerin properties (Oshinowo (1971) data)

Dynamic viscosity and surface tension of 35% glycerin were calculated by curve fitting the data given in 'Physical properties of glycerin and its solutions' by Glycerin Producers Association (1963). Density was found out from the mass flow rate and volume flow rate data presented by Oshinowo (1971).

$$\mu_{35\%Gly} = \text{-}0.0004 + 0.1059/\mathrm{T} - 0.8502/\mathrm{T}^2 + 2.7389/\mathrm{T}^3 \text{ (Pas)}$$

$$\sigma_{35\%Gly} == 0.0736 - 0.0001\mathrm{T} + 8.058\times10^{-8}\mathrm{T}^2 - 1.9938\times10^{-9}\mathrm{T}^3 \text{ (N/m)}$$

T = Temperature in °C

8) 56% Glycerin properties (Oshinowo (1971) data)

Dynamic viscosity and surface tension of 56% glycerin were calculated by curve fitting the data given in 'Physical properties of glycerin and its solutions' by Glycerin Producers Association (1963). Density was found out from the mass flow rate and volume flow rate data presented by Oshinowo (1971).

$$\mu_{56\%Gly} = -0.0012 + 0.2283/T - 0.3028/T^2 - 4.5851/T^3 \text{ (Pas)}$$

$$\sigma_{56\%Gly} = 0.0694 - 8.2995\times10^{-5}T - 1.9762\times10^{-7}T^2 - 5.503\times10^{-10}T^3 \text{ (N/m)}$$

T = Temperature in °C

9) 60% Glycerin properties (Oshinowo (1971) data)

Dynamic viscosity and surface tension of 60% glycerin were calculated by curve fitting the data given in 'Physical properties of glycerin and its solutions' by Glycerin Producers Association (1963). Density was found out from the mass flow rate and volume flow rate data presented by Oshinowo (1971).

$$\mu_{60\%Gly} = -0.0014 + 0.264/T + 0.0105/T^2 - 7.6761/T^3 \text{ (Pas)}$$

$$\sigma_{60\%Gly} = 0.0694 - 8.2995\times10^{-5}T - 1.9762\times10^{-7}T^2 - 5.503\times10^{-10}T^3 \text{ (N/m)}$$

T = Temperature in °C

10) Luviskol® Data

Density and dynamic of Luviskol® were provided by Schmidt et al. (2008). For surface tension, a constant value of 0.036 N/m was used for surface tension because it was mentioned in Schmidt et al. (2008) and correlation for Luviskol® was not found in the literature.

11) Steam Data

Data for steam was calculated from steam tables given in McQuiston et al. (2005).

VITA

Pranav Vinayak Godbole

Candidate for the Degree of

Master of Science

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

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Pune (India) on October 6, 1982.

Education: Received Bachelor of Engineering degree in Mechanical Engineering from University of Pune, India in July 2004. Completed the requirements for the Master of Science in Mechanical Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2009.

Professional Experience:

2004-2007, Assistant Manager, Burckhardt Compression India Private Limited

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Name: Pranav Vinayak Godbole Date of Degree: December, 2009

Institution: Oklahoma State University Location: Stillwater, Oklahoma

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

Pages in Study: 280 Candidate for the Degree of Master of Science

Major Field: Mechanical Engineering

Scope and Method of Study: An extensive literature search on flow patterns, void fraction and experimental data for vertical upward two-phase flow was done. Experiments were carried out for flow visualization and void fraction data. Flow patterns and flow pattern transitions were studied. Flow pattern transition theories from literature were modeled and tested against experimental data. Effect of diameter and gas phase density on flow pattern map was studied. Variation of void fraction in flow patterns was studied. Flow pattern specific and flow pattern independent correlations from literature were tested against experimental data.

Findings and Conclusions: Five distinct flow patterns were observed in the present study. Flow pattern map was developed based on the data of flow patterns. The details of experimental flow pattern transitions were discussed elaborately. The best flow transition theory was recommended for slug-churn and churn-annular flow pattern transition. Effect of diameter and gas phase density on flow pattern transition was analyzed and recommendations were given. The trend of void fraction in different flow patterns was reported based on the experimental data. The best correlations for prediction of void fraction were recommended for each flow pattern. The best flow pattern independent correlation for prediction of the entire range of void fraction data was recommended.

ADVISER'S APPROVAL: Dr. Afshin J. Ghajar