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CHARACTERIZATION OF GAS-LIQUID FLOWS IN ANNULI

Energy & Power
School of Water, Energy & Environment

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Academic Year: 2016 - 2019

Supervisors: Dr Liyun Lao
Prof Gioia Falcone

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ABSTRACT

Gas–liquid two–phase flow in annulus is encountered during certain operations in the nuclear, chemical and petroleum industries. In the Oil and Gas industry, the knowledge of gas liquid two-phase flow in annuli is important during underbalanced drilling of wells and hole clean operations. This technique offers several advantages over the conventional drilling method including reducing formation damage, preventing fluid losses and enhancing the safety and efficiency of operation. Proper design of underbalanced drilling operations hinges on the accurate prediction and monitoring of gas-liquid two-phase flow parameters such as flow regimes, liquid holdup and pressure drop; however the complexities associated with two-phase flows coupled with complex geometry makes this difficult. Limited studies exist in literature for gas-liquid flow hydraulics in horizontal annuli and no studies have been undertaken on the effects of annulus eccentricity on two-phase flow parameters including flow regimes, liquid holdup and pressure drop.

In order to provide an improved fundamental understanding of gas-liquid two-phase flow in horizontal annulus and give insight necessary for accurate model development, detailed systematic experimental studies are conducted at atmospheric conditions in horizontal concentric and fully eccentric annulus formed using a 3 inch outer and 2 inch inner pipes. Flow parameters including flow regimes, liquid holdup and pressure drop are investigated using high speed camera, conductance probes and pressure transducers, with air and water as testing fluids.

Results show that annulus eccentricity affects the flow regimes, liquid holdup and pressure drop. Predictive models are compared with experimental data and new models are proposed for flow regime identification and liquid holdup prediction, while a new real-time objective flow regime identification tool is developed using Support Vector Machine (SVM). The data generated from this study can be used for developing models which would be incorporated into commercial software for study of flow through annulus.

Keywords:

Concentric, Eccentricity, Flow regimes, Liquid holdup, Pressure drop

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NOMENCLATURE

Symbol	Description	Unit
A	Cross sectional area of a conduit	m^2
A_C	Cross-sectional flow area of gas core	m^2
A_F	Cross-sectional flow area of liquid film	m^2
$A_L; A_G$	Cross sectional area of the liquid and gas phases respectively	m^2
Bo	Bond number	-
C_0	Distribution parameter	-
D	Pipe diameter	m
D_H	Hydraulic diameter definition	m
D_e	Equivalent (slot) diameter	m
Di	Outer diameter of inner pipe	m
Do	Inner diameter of outer pipe	m
D_r	Omurlu representative diameter	m
$dP_L; dP_G$	Frictional pressure drop of the liquid and gas phase respectively	Pa/m
$\frac{dP}{dx}$	Pressure drop	Pa/m
$\left(\frac{dp}{dL}\right)_{frSL}$	Frictional pressure drop of slug unit	Pa/m
FE	Entrainment fraction	-
Fr	Froude number	-
f_G	Friction factor for the gas phase	-
f_i	Interfacial friction factor	-
f_L	Friction factor for the liquid phase	-
f_m	Friction factor for computing elongated bubble drift velocity	-
f_{mL}	Petalas & Aziz (2000) Friction factor based on mixture Reynolds number	-
f	Friction factor	-
g	Acceleration gravity	m/s^2
h_l	Liquid height	m

Symbol	Description	Unit
H_{LS}	Liquid fraction in slug body	-
L_F	Length of liquid film part in a slug unit	m
L_S	Slug body length	m
$\dot{m}$	Total mass flow rate through channel	(kg/s)
$\dot{m}_G$	Mass flow rate of gas phase	(kg/s)
$\dot{m}_L$	Mass flow rate of liquid phase	(kg/s)
Q	Volumetric flow rate	(m ³ /s)
Q_G	Gas phase volumetric flow rate	(m ³ /s)
Q_L	Liquid phase volumetric flow rate	(m ³ /s)
Re	Reynolds number	-
Re_M	Reynolds number based on mixture velocities	-
Re_{ML}	Modified Reynolds number based on mixture velocities	-
Re_S	Slug Reynolds number	-
$Re_{SL}; Re_{SG}$	Superficial liquid and gas Reynolds number respectively	-
Re_{∞}	Reynolds number based on Drift velocity of elongated bubble	-
S	Slip ratio	-
S_F	Contact perimeter of the conduit wall and liquid film	m
S_G	Contact perimeter between the conduit wall and gas phase	m
S_L	Contact perimeter between the conduit walls and liquid phase	m
V_b	Dispersed bubble rise velocity	m/s
V_D, V_d	Drift velocity	m/s
V_{db}	Velocity of dispersed bubble	m/s
$V_{d\infty}$	Drift velocity for elongated bubble	m/s
$V_{dh\infty}$	Drift velocity for elongated bubble in horizontal system	m/s
$V_L; V_G$	Actual velocity of the liquid and gas phases respectively	m/s
V_M	Mixture velocity	m/s

Symbol	Description	Unit
$V_{SG}; V_{sg}$	Gas superficial velocity	m/s
$V_{SL}; V_{sl}$	Liquid superficial velocity	m/s
V_T	Translational velocity	m/s
x	Gas mass fraction	-
X^2	Martinelli parameter	-
X_L	Liquid volume fraction	-

Greek Letters

Symbol	Description	Unit
λ_L	No-slip holdup	-
$\mu_L; \mu_G$	Liquid and gas phase viscosities, respectively	cP
μ_M	Mixture viscosity	cP
$\rho_L; \rho_G$	Liquid and gas densities, respectively	kg/m ³
ρ_M	Mixture density	kg/m ³
$\tau_{WL}; \tau_{WG}$	Shear stresses exerted by liquid and gas phases, respectively	Pa.s
ϵ_L	Liquid holdup in slug unit	-
ϵ_{LS}	Liquid fraction in slug body	-
α	Gas void fraction	-
μ	Viscosity	cP
ρ	Density	kg/m ³
τ	Shear stress	Pa.s
ν	Slug frequency	Hz
ϵ	Eccentricity	-
$\Phi_L^2; \Phi_G^2$	Two-phase friction multipliers for liquid and gas phases	-
$\bar{\delta}$	Dimensionless liquid film thickness	-

LIST OF ABBREVIATIONS

Acronym	Description
AF	Annular Flow
CF	Churn Flow
DBC	Distance Between Centres
DBF	Dispersed Bubble Flow
DFM	Drift Flux Model
EB	Elongated Bubble Flow
ERM	Empirical Risk Minimization
PDF	Probability Density Function
SRM	Structural Risk Minimization
St	Strouhal number
STF	Stratified Flow
SVM	Support Vector Machine
WAF	Wavy Annular Flow
WSF	Wavy Slug Flow
UBD	Underbalanced Drilling

1 INTRODUCTION

1.1 Background

The simultaneous two-phase flow of gas and liquid is encountered in many chemical, nuclear and petroleum industrial applications. As a result, it has been studied extensively during the past decades. Typical applications that involves two-phase flows ranged from large scale processes in nuclear power generation and chemical industrial reactors, to small scale applications like electronic cooling. Majority of the research in two-phase gas-liquid flows is concentrated in circular geometry channels. However, two-phase flows also widely exist in channels with more complex geometries like annulus which is also present in chemical, nuclear and oil & gas industrial applications.

The double pipe heat exchanger employed for evaporation and condensation, consisting of two concentrically arranged pipes has an annular geometry. One fluid flows in the inner pipe while the second fluid flows in-between both pipes. Depending on the design of the heat exchanger, the fluids may be flowing in similar or opposite directions. If water is the working fluid, operation within the wet steam region would indicate the presence of two-phase gas (steam) and liquid (water) flows.

In the nuclear industry, annular geometries are encountered when subcooled liquid coolants may develop two-phase flow during off-normal boiling (Ekberg *et al.*, 1999).

Several different scenarios exist in the petroleum industry where gas-liquid flow in annuli is observed. For example, during high rates of gas and oil production, some fluids are flowed vertically through the annulus configuration between well tubing and casing. Also, during the influx of gas into the wellbore of an oil well, “gas kicks” which is an important phenomenon occurs. During such situations, gas-liquid flow in annulus could cause blowout, which could damage the entire production system. Gas-liquid flow in annular geometries in petroleum industry is also found in association with gravitational gas separators applied with

submersible centrifugal pump (SCP) technologies for production of oil and gas in directional wells (Mendes *et al.*, 2011).

Another application of two-phase flows in annuli is in the drilling processes in the Oil & Gas industry. The need to recover hydrocarbons in an effective and efficient manner has led to continuous improvements in drilling technology. Several drilling methods have been studied and employed for drilling of oil and gas wells. A typical example is the underbalanced drilling technique (UBD), where the hydrostatic pressure of the drilling fluid is designed to be lower than those of the formation being drilled. This offers several advantages including making drilling safe, efficient and economical.

During underbalanced drilling operations, the annulus eccentricity can be changing between the concentric and fully eccentric configurations. UBD conditions are achieved by injecting a gas-liquid two-phase mixture simultaneously. However, poor design of this operation can result in severe damage to the reservoir and huge loss of resources.

The simultaneous flow of gas-liquid mixture in annulus results in different topological arrangements known as flow regimes. These include stratified, bubble, slug, plug and annular flow regimes. The accurate prediction and monitoring of these flow regimes are fundamental for control and process optimisation purposes especially for obtaining adequate pressure drop model in an annulus (Na *et al.*, 2015). The economical design of many industrial processes depend on the accurate estimation of process variables such as pressure drop, flow rates of gas and liquid phases in the associated channel. Again taking the UBD operations as an example, to ensure the optimized design of the operation, the hydraulics of aerated drilling fluids in annuli must be better understood. Indeed the complexities associated with gas-liquid flows coupled with complex geometry, implies that accurate determination of UBD design parameters depend on proper two-phase gas-liquid flow modelling although this is rather difficult for the same reasons.

1.2 Motivation

Information available for understanding the phenomenology of gas-liquid flows in annuli is scarce, which is in contrast to the wide application of the gas-liquid flow in annular channels. This situation provides a good justification for conducting experimental and theoretical studies of gas liquid flows in annuli.

1.3 Research Aim

The aim of this study is to improve the understanding of the behaviours of two-phase gas-liquid flows in horizontal annuli by undertaking systematic experimental and modelling studies.

1.4 Research Objectives

To achieve the outlined aim, the following objectives have been developed:

- Investigate gas-liquid flow in horizontal concentric annulus
- Study the effect of annulus eccentricity in horizontal annulus on gas-liquid flow regimes
- Study the effect of annulus eccentricity in horizontal annulus on gas- liquid holdup
- Study the effect of annulus eccentricity in horizontal annulus on gas-liquid pressure drop

1.5 Thesis Structure

This thesis is structured into 8 chapters, whose content are described in the following beginning with chapter 2.

Chapter 2: Gives a comprehensive review of related literature beginning with fundamental concepts in multiphase flow, two-phase flow in annuli focusing mainly on horizontal and inclined flows. Particular attention is paid to flow regimes and different modelling techniques which have been adopted for two-phase flow in annuli. In addition, various empirical and theoretical models which describe the pressure drop, liquid holdup and flow regimes are discussed together with how they are applied to horizontal annuli.

Chapter 3: Describes the experimental facility employed in conducting experiments together with the installed instrumentation (Conductance probes, pressure transducers etc.) and their operating procedures, calibration and error margins.

Chapter 4: This chapter presents the gas-liquid two-phase flow regimes and their development in horizontal concentric and fully eccentric annuli. The first part of the chapter presents subjective means of flow regime identification combined with more characterization of the flow features using instrumentation; the second part develops an objective flow regime identification technique in horizontal annulus.

Chapter 5: Slug flow characterization in horizontal annulus is presented. Properties including slug frequency, slug translational velocity, slug body holdup and slug length are measured using conductance probes. The effect of annulus eccentricity on these properties are also reported and comparison of experimental results with predictive models/correlations are also made.

Chapter 6: In this chapter, the focus is on liquid holdup determination in horizontal annulus. The mean liquid holdup measured using conductance probes in horizontal concentric and fully eccentric annulus are presented. The effect of annulus eccentricity on the mean liquid holdup is investigated and performance evaluation of some existing models and correlations developed for flow in circular pipes and adapted to the annulus geometries based on different diameter concepts are presented. A new liquid holdup correlation is developed based on dimensionless parameters using an integration of data points from experiments and literature.

Chapter 7: This chapter is centred on pressure drop determination in horizontal annuli. It begins with an overview which provides information about some of the models and predictions compared against experimental data, followed by single phase water test results and then two-phase air-water results in both the horizontal and fully eccentric annulus channels. The effect of annulus eccentricity on the measured pressure drop is also highlighted and different diameter concepts are used to test the performance of the modelling approaches utilized.

Chapter 8: A summary of the key findings are presented together with the potential impact to the design of equipment and processes that have annular geometries. Recommendations for future work is also enumerated.

1.6 List of Publications and Presentations

- Eyo, E.N., Lao, L., Gas-liquid flow regimes in horizontal annulus, Journal of Petroleum Science and Engineering (2019), doi: <https://doi.org/10.1016/j.petrol.2018.12.056>
- Eyo, Edem N., Pilario, Karl E., Lao, L., Falcone, Gioia. Development of a Real-time Objective Gas-Liquid Flow Regime Identifier using Kernel Methods. IEEE Transactions on Cybernetics (201X) (Accepted)
- Eyo, Edem N., Lao, L., Slug Flow Characterisation in Horizontal Annulus. AIChE Journal (201x) (In Review)
- Edem Nsefik Eyo., Characterisation of Air-Water Flows in Horizontal Annuli. TMF Consortium meeting, 19th September, 2018
- Edem Nsefik Eyo., Experimental Study of Gas-Liquid Flows in Annuli. TMF Consortium meeting, 19th & 20th April, 2017

2 LITERATURE REVIEW

In this chapter, a brief overview of the fundamental concepts of two-phase flow is presented together with review of the state of the art in gas-liquid two-phase flow in horizontal annuli. The objective is to present a review of the two-phase gas-liquid studies undertaken particularly in horizontal annuli and highlight the need for further studies by showing the existing gaps. Emphasis have been concentrated on studies looking at flow regime identification, liquid holdup and pressure drop prediction.

The chapter begins with an introduction of the fundamental definitions in two-phase flows and thereafter reviews previous experimental and modelling studies of gas-liquid flows in annuli.

2.1 Two-Phase Flow Overview

Two-phase flow refers to the interactive motion of two different types of media or matter, i.e. the motion of matter dispersed in a fluid which acts as the carrier. The difference between the media or matter could be multi chemical components and or its thermodynamic state referred to as the phase (e.g., solid, liquid, or gas)(Kleinstreuer, 2003). There has been interest in two-phase flow research since the 1950's due to its occurrence in major fields of industry. Examples include, chemical, space, nuclear, petroleum and geothermal industries, where two-phase flow is encountered in a range of engineering applications.

In the chemical and process industry, two-phase flow occurs in distillation plants, boilers, reactors, condensers and evaporators. The space industry experiences a unique type of two-phase flow occurring in space known as the zero-gravity flow, where two-phase flow occurs in power generation, life support systems and energy storage. Two-phase flow in the geothermal industry occurs as steam-water flow in gathering systems and vertical risers, while the nuclear and petroleum industries consider two-phase flow for safety purposes and during the transportation of oil and gas respectively (Shoham, 2006).

The presence of fluids with two phases with changeable and deformable interfacial structures brings about great challenges in quantifying the nature of the flow when compared to single phase flow conditions. Because of lack of detailed information of the local individual phase velocities, it is almost impossible to give a true picture of the velocity distribution, which presents a great challenge in understanding the flow behaviours.

Two-phase flow phenomena are generally characterised by a turbulent nature or instabilities induced by the phase interactions. These instabilities may be as a result of particle-fluid or particle-particle interactions, relatively high velocities, critical or excessive flow rates, microscale fluctuations which are amplified, irregular behaviour at wall or phase boundaries and imbalance between surface tension and gravitational forces.

2.1.1 Variables Used in Two-Phase Flow

Due to the complexities associated with simultaneous gas-liquid flows through a conduit, it is usually more complicated physically than single-phase flow. Apart from the inertia, viscous and pressure forces, two-phase flows are also influenced by momentum exchange between the flowing phases, liquid wetting characteristics on the pipe wall, and interfacial tension forces. Also, variation of flow conditions throughout the pipe with time makes two-phase flow a three dimensional transient problem and as a result, researchers have derived simplified descriptions of the problem for analysis but at the same time maintained the key flow features. Variables utilized in this work are based on one-dimensional flow i.e. flow conditions of each phase only varying with distance along the pipe. This is the commonly used approach in literature for analysing two-phase pressure drop.

Mass Flow Rate, $\dot{m}$ (kg/s): The total mass flow rate through the channel is the sum of the mass flow rate of both phases as presented in Eqn. (2-1).

$$\dot{m} = \dot{m}_L + \dot{m}_G \quad (2-1)$$

Where $\dot{m}_L$ and $\dot{m}_G$ are mass flow rates of liquid and gas respectively.

Volumetric Flow Rate, Q (m^3/s): The total volumetric flow rate Q is defined as follows in Eqn. (2-2):

$$Q = Q_L + Q_G \quad (2-2)$$

Where Q_L = volumetric flowrate of the liquid phase and Q_G = volumetric flowrate of the gas phase.

Liquid Holdup, H_L & Gas Void Fraction, α (-) : The liquid holdup (H_L) refers to the ratio of the cross-sectional area of the pipe or duct which is occupied by the liquid phase in a two-phase flow system, while the gas void fraction refers to the fraction of the conduit cross-section occupied by the gas phase.

The liquid holdup is given in Eqn. (2-3) as:

$$H_L = \frac{A_L}{A} = 1 - \alpha \quad (2-3)$$

Where the area of the pipe is occupied by the liquid is A_L and A is the cross-sectional area of the conduit.

Similarly, the void fraction is expressed as follows in Eqn. (2-4) as:

$$\alpha = \frac{A_G}{A} = 1 - H_L \quad (2-4)$$

Superficial Velocities of liquid, V_{SL} and gas V_{SG} (m/s): The velocity that a phase would be travelling if it was flowing on its own through the cross-sectional area of the conduit available for flow is the superficial velocity of that phase. The liquid and gas superficial velocities are given as follows:

$$V_{SL} = \frac{Q_L}{A} \quad (2-5)$$

$$V_{SG} = \frac{Q_G}{A} \quad (2-6)$$

Mixture Velocity, V_M (m/s): The total velocity of both phases flowing simultaneously in the conduit is known as the mixture velocity. It is given as:

$$V_M = \frac{Q_L + Q_G}{A} = V_{SL} + V_{SG} \quad (2-7)$$

If the two phases travelling in the conduit are moving at different velocities, the flow is said to be slip flow and on the other hand, when they are travelling at the same velocity, no slip is said to be occurring. The terms no-slip holdup refers to the ratio of the liquid volumetric flowrate to the total volume flowrate. The no-slip holdup(λ_L) is given as

$$\lambda_L = \frac{Q_L}{Q_L + Q_G} = \frac{V_{SL}}{V_M} \quad (2-8)$$

Mass Flux, G (kg/m²s): The total mass flux or mass velocity is a sum of the mass fluxes of both phases given as follows:

$$G = \frac{\dot{m}_L + \dot{m}_G}{A} = G_L + G_G \quad (2-9)$$

Where the liquid mass flux, $G_L = \frac{\dot{m}_L}{A}$ and $G_G = \frac{\dot{m}_G}{A}$ is the gas mass flux

Actual Velocity, V_L and V_G (m/s): The velocity of individual phases also known as the in-situ velocity is the actual velocity of that phase when the two-phase travel together and can be expressed as follows:

$$V_L = \frac{Q_L}{A_L} = \frac{V_{SL}}{H_L}, \quad \text{and} \quad V_G = \frac{Q_G}{A_G} = \frac{V_{SG}}{1-H_L} \quad (2-10)$$

Quality, x (-): The term quality refers to the ratio of the mass flow rate of gas to the total mass flow rate.

$$x = \frac{\dot{m}_G}{\dot{m}_G + \dot{m}_L} \quad (2-11)$$

Average fluid properties: The two-phase density and viscosity relationships are expressed respectively as follows:

$$\rho_M = \rho_L H_L + \rho_G(1 - H_L) \quad (2-12)$$

$$\mu_M = \mu_L H_L + \mu_G(1 - H_L) \quad (2-13)$$

2.1.2 Two-Phase Flow Regimes

Flow regimes refer to a unique geometric distribution of the different phases in a two-phase flow system. These are as a result of the dynamic interfacial structure between the phases and depend on parameters including physical properties of the phases, gas and liquid velocities, conduit size, geometry and orientation (Julia et al., 2011). Different researchers have used several descriptions to explain the configurations which gas and liquid flowing together take up. Most of these are different names for the same flow regime while others are subgroups of major classifications. The subjective way in which the flow regimes are characterised is the reason for this confusion. However, most authors agree to certain basic structures depending on the flow rates and direction, orientation as well as the shape and size of the conduit in defining the observed flow regimes. Issues still remain regarding assigning observed flow to one of the agreed regimes and as a result, attempts have been made by researchers to develop more objective ways of flow regime identification. Methods such as using X-rays to measure time-averaged void fractions in tubes and plotting the probability density function (PDF), analysing pressure fluctuations, use of electrical resistance for determining average void fractions and more complex statistical analysis of time-averaged data have been suggested (Bertola, 2003).

Depending on the orientation of the pipe where flow is occurring (vertical or horizontal), different flow regimes are encountered. However, the horizontal flow regimes will be the focus of this study. Flow regimes in horizontal flow channels are broadly classified into four major groups namely; Stratified (ST), Intermittent

(I), Annular (A) and Dispersed Bubble (DB) flows. An illustration of the flow regimes (with their subsets) is shown in Figure 2-1 below.

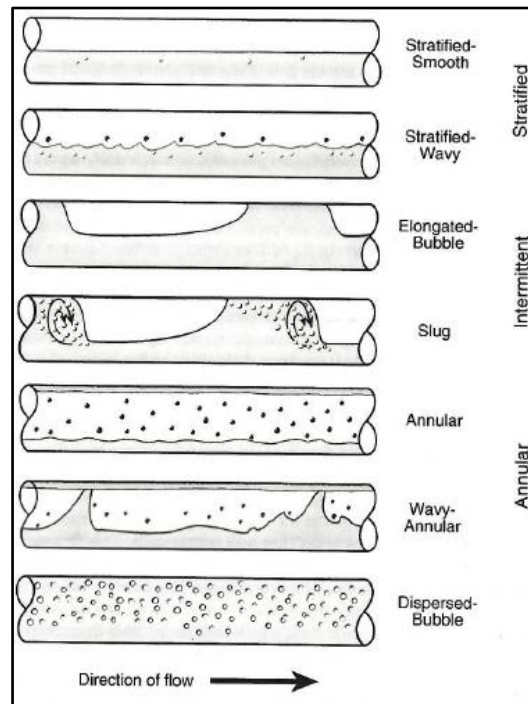


Figure 2-1: Gas-liquid flow regimes in horizontal and near horizontal pipes
(Shoham, 2006)

Stratified Flow (ST): Occurring at relatively low gas- and liquid-flow rates, the phases flow separately due to gravity effects with the denser phase flowing at the bottom of the conduit, while the less dense phase flows closer to the top of the conduit. This flow regime is subdivided into Stratified-Smooth (SS) which has a smooth gas-liquid interface and the Stratified-Wavy (SW), which occurs at higher gas flow rates with a wavy interface.

Intermittent Flow (I): These flow regimes are characterised by alternating liquid slugs and gas pockets. The liquid slugs tend to fill the entire cross-sectional area of the conduit and are then separated by gas pockets which have a stratified liquid layer flowing at the bottom of the conduit. The flow mechanism involves fast moving liquid slugs which override a slower moving liquid film ahead of it. The intermittent flow pattern is subdivided into Slug (SF) and Elongated-Bubble (EB) regimes. Elongated-Bubble is termed as the limiting case of Slug flow with the

main difference being the entrainment of gas bubbles in the elongated liquid body in during Slug flow.

Annular Flow (AF): Characterised by the flow of the gas phase in a core of high velocity, with some entrainment of liquid droplets, the Annular flow regime occurs at very high gas flow rates. The liquid phase on the other hand flows as a thin film around the wall of the conduit. A highly wavy interface results in high interfacial shear stresses. Depending on the magnitude of the flow rates of the gas and liquid phases, a thicker film is observed at the bottom of the conduit than at the top. This flow regime is subdivided into Wavy-Annular (WAF) characterised by frothy waves which are not accelerated by the gas-phase but move slower.

Dispersed Bubble Flow (DBF): This flow regime is encountered at very high liquid flow rates. It is characterised by a continuous liquid-phase and discrete gas bubbles dispersed in the continuous liquid phase mostly near the top of conduit initially, but increase in liquid flow rate results in uniform distribution of the gas bubbles throughout the conduit. Considered as homogeneous no-slip flow because both phases move at uniform velocities due to the high liquid flow rates.

2.1.3 Flow Regime Maps

Flow regime maps are two-dimensional plots based on different coordinate systems which are used to present flow regimes and their transition boundaries in conduits mainly identified using visual observation. Most of the coordinates used in the past to map the two-phase flow regimes had no physical basis and as such, the empirical maps are reliable only in the range of conditions similar to those under which the data were acquired.

Baker (1954) was a pioneer in this area and his flow regime map used a mixture of dimensionless/dimensional coordinates of the mass fluxes of the gas and liquid phases and correction factors for fluid properties in field units. The flow regime map of Baker is shown in Figure 2-2.

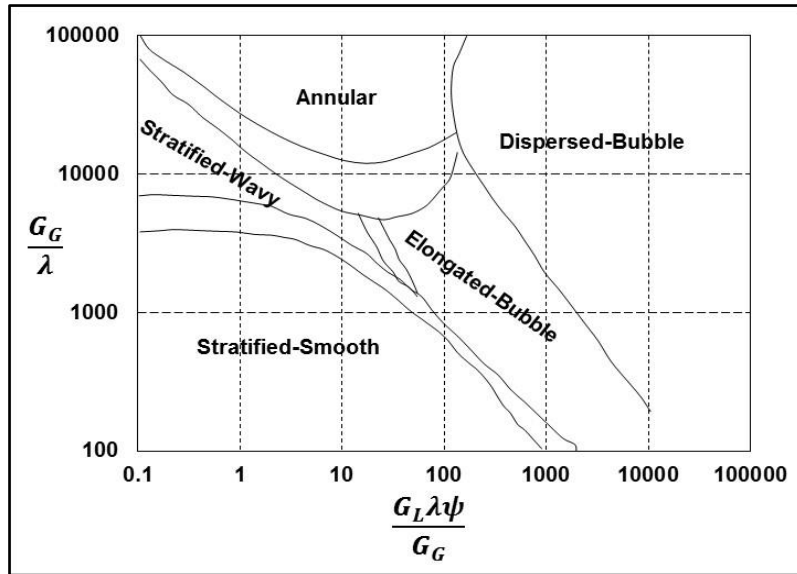


Figure 2-2: Flow regime map for horizontal two-phase flow after (Baker, 1954)

The flow regime map of Baker (1954) is still widely utilized in the petroleum industry because it was developed from actual field data. Mandhane et al., (1974) developed their flow regime map using a large data set containing 1,178 data points for air-water systems in small diameter (0.0127 - 0.051 m) circular pipes. The coordinate system used for their map were the gas and liquid superficial velocities and an illustration of the Mandhane et al., (1974) is shown in Figure 2-3.

The Beggs & Brill (1973) flow regime map is another widely used flow regime map. They categorised flow regimes based on three main classifications namely: separated, intermittent and distributed. They also had a transition zone classified. Stratified-smooth, stratified-wavy and annular flow regimes were grouped under separated flow; elongated-bubble and slug flow regimes were grouped as intermittent flow while dispersed-bubble was classed as distributed flow.

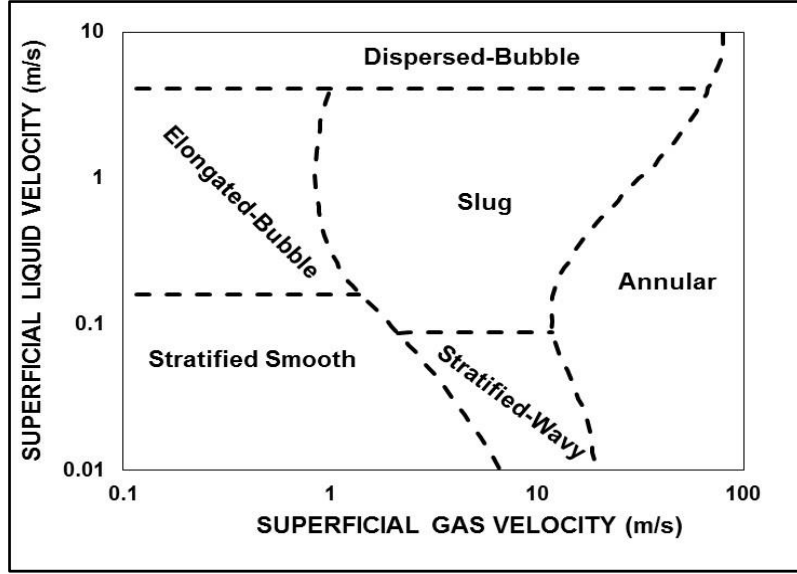


Figure 2-3: Flow regime for horizontal pipe flow (after Mandhane *et al.*, (1974))

The abscissa and ordinate of their flow regime map were the mixture Froude number, $Fr_M^2 = V_M^2/gD$ and no-slip holdup, $\lambda_L = V_{SL}/V_M$ respectively. To determine the horizontal flow regimes, the flow regime transition parameters in Equation (2-14) and (2-15) are employed.

$$L_1 = 316\lambda_L^{0.302}, L_2 = 0.0009252\lambda_L^{-2.4684} \quad (2-14)$$

$$L_3 = 0.10\lambda_L^{-1.4516}, L_4 = 0.5\lambda_L^{-6.738} \quad (2-15)$$

The following criteria must be satisfied for the different flow regimes to exist based on Beggs & Brill (1973) prediction as outlined in Eqn. (2-16) – (2-19).

$$\text{Segregated: } \lambda_L < 0.01 \text{ and } Fr_M^2 < L_1, \text{ or } \lambda_L \geq 0.01 \text{ and } Fr_M^2 < L_2 \quad (2-16)$$

$$\text{Transition: } \lambda_L \geq 0.01 \text{ and } L_2 \leq Fr_M^2 \leq L_3 \quad (2-17)$$

$$\text{Intermittent: } 0.01 \leq \lambda_L < 0.4 \text{ and } L_3 \leq Fr_M^2 \leq L_1, \text{ or } \lambda_L \geq 0.4 \text{ and } L_3 \leq Fr_M^2 \leq L_1 \quad (2-18)$$

$$\text{Distributed: } \lambda_L < 0.4 \text{ and } Fr_M^2 \geq L_1, \text{ or } \lambda_L \geq 0.4 \text{ and } Fr_M^2 > L_4 \quad (2-19)$$

For this study however, these parameters are taken into consideration but the coordinates are converted to the superficial liquid and gas superficial velocities as shown in Figure 2-4 below

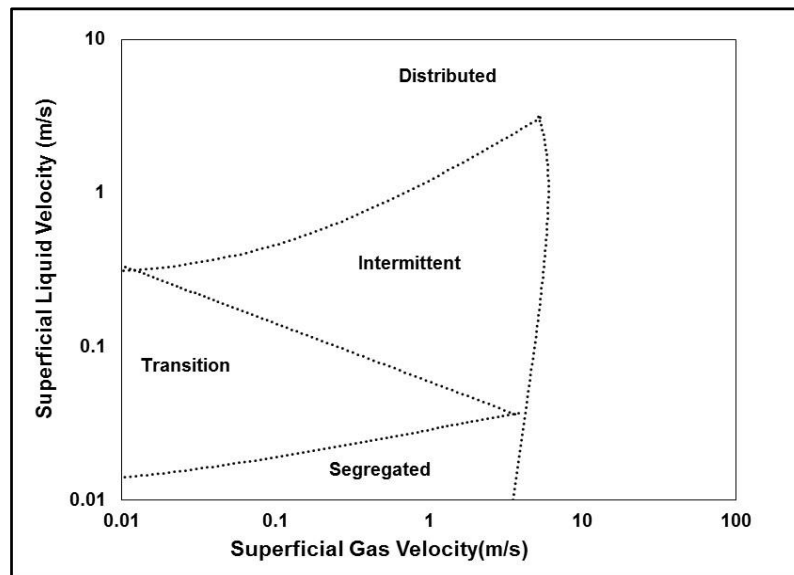


Figure 2-4: Flow regime map for horizontal pipe flow (Beggs & Brill 1973)

As time went on, attempts were made to characterise the flow regimes based on physical basis and mechanistic flow regime prediction models were developed and used to determine the transition between the different flow regimes. These models take into consideration the effect of different variables on the flow regimes include gas and liquid flow rates, pipe diameter and inclination, and the physical properties of the fluids. After the transition mechanism have been defined, a mathematical expression for the transition boundaries can be developed.

Taitel and Dukler (1976) based on semi-mechanistic analysis of flow regime transitions in gas-liquid flow developed a flow regime map. Dimensionless numbers such as the gas Froude number and the Martinelli parameter were used in conjunction with momentum equations for their analysis. Flow regimes characterised by the study include dispersed-bubble, intermittent flow, stratified-smooth, stratified-wavy and annular as presented in Figure 2-5 based on superficial gas and liquid velocities.

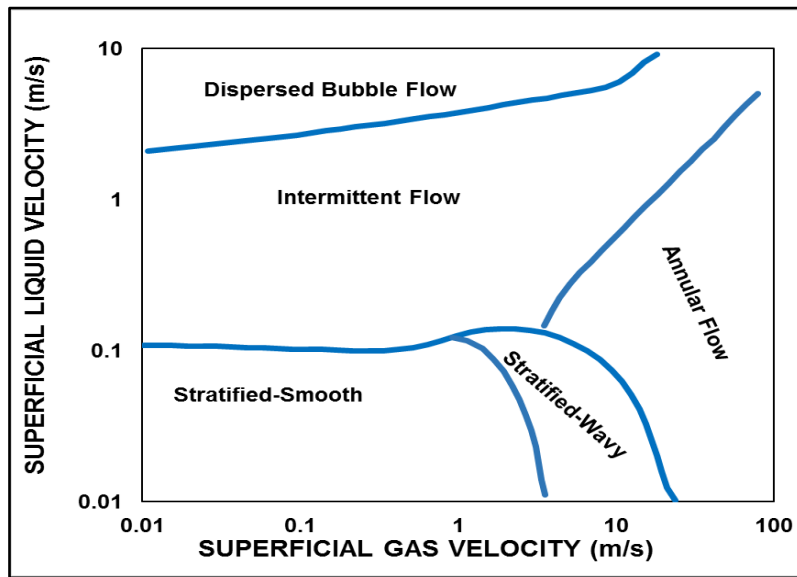


Figure 2-5: Taitel & Dukler (1976) flow regime map

2.1.4 Modelling Approaches in Gas-Liquid Flow in Pipes

The large number of flow variables involved with two-phase flow systems and the complexities associated with the flow means that rigorous solutions for such systems are complex and not available at present. Early models developed for two-phase flow systems were independent of the flow regimes. Such models simply avoided the complex nature of this flow systems and treated the flow with single-phase flow tools (Shoham, 2006). Some of these modelling approaches include the Homogeneous No-slip Model, the Separated Model, Similarity Analysis and the Drift-Flux Model.

2.1.4.1 Homogeneous No-Slip Model

This modelling approach although very simple, is adaptable for predicting different two-phase flow characteristics. The two-phase flow is considered as a single-phase with average fluid properties assuming no-slip between the phases. In developing the model Wallis (1969) assumed the following:

- No slip between the phases.
- Steady- state one-dimensional flow.
- Both phases are in equilibrium and are properly mixed.
- Compressibility of both phases
- The cross-sectional area of the pipe is not constant along the axial direction.
- Mass transfer takes place between both phases.

2.1.4.2 Separated Flow Model

On the other hand, the separated flow model assumes that both phases flow independently of each other. Therefore each phase is analysed as a single-phase fluid using single-phase flow equations and the hydraulic diameter concept such as the friction factor. Lockhart & Martinelli (1949) pioneered this approach and it is limited to calculating the frictional pressure drop in horizontal pipes.

2.1.4.3 Similarity Analysis

The technique of similarity analysis can be used to develop generalized solutions. Dimensionless groups which govern a particular flow system can be generated from variables of the system in a process known as (Dimensional Analysis); principal forces and kinematic relationship of the system can be analysed in a process known as (Similarity through Dynamic and Kinematic Ratios), or analysis of the governing equation of the system known as (Similarity through Basic Equations). A general solution can then be obtained which is applicable to all similar systems.

2.1.4.4 Drift-Flux Model

This modelling approach deals with the two phases as a homogeneous mixture but with slippage occurring between the gas and liquid phases. However,

averaged values of the velocity and void fraction are used specified as drift velocity. This implies that the actual in-situ liquid holdup can be determined. It may not always be possible to provide additional information about the relative movement of the phases (Wallis, 1969).

Recently, mechanistic modelling approaches have also been developed to predict the flow regimes, pressure drop and liquid holdup in two-phase flow systems. These models are usually developed based on physical mechanisms and are more complex to solve usually requiring some closure relationships (Shoham, 2006) . Details of the different modelling approaches employed for analysis in this study are presented in the various chapters where they are used to avoid repetition.

2.2 Two-Phase Flow in Annuli

An annulus refers to a configuration whereby a pipe of smaller diameter is located inside a pipe of larger diameter (Yu *et al.*, 2009). The flow of fluid takes place in between the inner wall of the larger outer pipe and the outer wall of the inner smaller pipe.

Several studies have been undertaken over the years experimentally and theoretical in order to understand the gas-liquid two-phase flow hydraulics in vertical annuli (see examples Sadatomi & Sato (1982), Kelessidis & Dukler (1989), Hasan & Kabir (1992), Papadimitriou & Shoham (1991), Caetano *et al.*, (1992b, 1992a), Nakoryakov *et al.*, (1992), Das *et al.*, (1999a; 1999b), Lage & Time (2000), Sunthankar *et al.*, (2000, 2001), Sun *et al.*, (2004), Ozar *et al.*, (2008), Julia *et al.*, (2009, 2011; 2010)). However only studies undertaken for gas-liquid two-phase flow in horizontal and near horizontal setups annulus are outlined. This part will be divided into two sections; (i) the experimental studies and (ii) modelling studies undertaken in horizontal annuli to characterize flow regimes, liquid holdup and pressure drop.

2.2.1 Experimental Two-Phase Flow Studies in Horizontal Annuli

The flow of gas-liquid two-phase fluids through horizontal and inclined annuli is frequently encountered in the petroleum and gas industry. The advent of Coiled

Tubing applications during the 1960's led to a feasible technique for drilling of oil and gas wells. It's economic advantage coupled with the growing areas where this technology is applicable has led to the coiled tubing technology becoming one of the fastest growing in the oil and gas industry. The application of coiled tubing technology in drilling operations has in recent years become very popular because of the advantages it shows such as; small weight, pressure control, fast rig-up and rig-down, low environmental impact and fast tripping time (Metin and Ozbayoglu, 2007).

The need to develop more challenging fields as well as depleted reservoirs has led to an increase in underbalanced drilling (UBD) operations in the oil and gas industry. This technology is very valuable in tackling the problems caused by invasion into the formation which is responsible for reducing oil and gas reservoir productivity. A carefully planned and executed UBD operation reduces or eliminates the effects of mud filtrate invasion into the reservoir, while also being effective for the treatment of vertical wells as well as shallow damage in horizontal wells (Lage, et al., 2000). It is very important to maintain an optimum combination of liquid and gas flow rates during UBD operations and this requires knowledge of the two-phase flow hydraulics. If the UBD operation is designed or executed poorly, a deeper formation damage may result. Based on the foregoing and the complex flow hydraulics encountered during UBD operations, it becomes rather difficult to predict accurately bottomhole pressures as a function of gas and liquid flow rates (Lage, et al., 2000; Sunthakar *et al.*, 2001; Zhou *et al.*, 2004). Despite the need for adequate prediction of gas-liquid flow hydraulics during UBD operations, very limited studies are available for modelling gas-liquid flow hydraulics in horizontal and inclined annuli. This section aims to review studies undertaken in gas-liquid two-phase flow in horizontal and inclined annuli with emphasis on flow regimes transitions, pressure drop and liquid holdup.

2.2.1.1 Flow Regimes in Horizontal Annuli

The flow regimes in horizontal and inclined annuli are affected by the distortion of the gas liquid interface due to the presence of the inner pipe. Although similar

flow regimes are observed in horizontal circular pipes, slight variations are observed in horizontal annuli. The different flow regimes are as follows:

Stratified Smooth Flow: this occurs when the liquid is flowing at the bottom of the conduit with the gas flowing on top. The gas-liquid interface is slightly affected by the presence of the inner pipe.

Stratified Wavy Flow: similar to what is obtainable in gas-liquid flow in circular pipes, this flow regime in horizontal and inclined annuli is characterized by a wavy gas-liquid interface.

Elongated Bubble flow: this flow regime is observed at relatively low superficial velocity of gas. It is characterized by a stream of elongated bubbles which flows consistently along the top of the tube.

Slug flow: this flow regime is characterized by large pockets of gas which are separated by liquid regions blocking the entire cross-section of the conduit. Also entrained tiny bubbles are contained in the liquid separating the gas pockets in huge numbers.

Churn flow: the formation of the churn flow regime begins by the breakdown of bubbles in the slug flow regime caused by an increase in the gas superficial velocity. The result is an oscillatory motion which is very chaotic in nature.

Annular flow: the annular flow regime occurs when a thin liquid film wets the walls of the conduit with the gas flowing at high velocity through the centre core of the annulus. The gas core usually has liquid droplets entrained in it.

Dispersed Bubble: this flow regime is characterized by small bubbles of gas distributed throughout the liquid phase which takes up the entire conduit cross section.

Several other hybrid flow regimes have been proposed by different researchers who carried out experimental investigations into gas-liquid two-phase flow regimes in horizontal and inclined annuli including:

Osamasali et al., (1988) who studied two-phase flow regime transition in horizontal pipe and annulus flow under gas-liquid flow. They undertook experiments in a 51 mm internal diameter pipe and annuli with inner to outer radius ratios between 0.375 and 0.625 at ambient conditions. Flow regime characterization in annuli was done using ultrasonic transmission method and flow regimes observed include; Stratified, Elongated Bubble, Slug, Churn, Annular and Wavy Annular flows.

Ekberg et al., (1999) carried out experimental investigations of two-phase flow in narrow horizontal annuli. Two test sections were used to undertake the experiments, with smaller test section having outer diameter of inner pipe $D_i = 6.60$ mm and inner diameter of outer pipe $D_o = 8.63$ mm while the larger test section had $D_i = 33.15$ mm and $D_o = 35.2$ mm respectively. Flow regime identification was done using a digital video camera. Identified flow regimes in both test sections include; Slug, Elongated Bubble, Stratified-Slug, Annular-Slug, Annular, Bubbly-Plug, Dispersed Bubble and Churn flow. Stratified flow was only observed in the larger test section and this was due to the experimental parameter range.

In their work, Lage et al., (2000) carried out experimental and theoretical study of two-phase flow in horizontal and slightly deviated fully eccentric annuli. Tests were conducted in a fully eccentric annuli with $D_i = 50.8$ mm and $D_o = 101.6$ mm and three inclination angles were investigated; horizontal, $+4^\circ$ slightly deviated from horizontal and -4° deviated from horizontal. Testing fluids were air-water and diesel-nitrogen mixtures. Flow regimes identified include Dispersed Bubble, Stratified, Intermittent and Annular flows.

Similarly, Sunthakar et al., (2001) studied gas-liquid two-phase flow in a 27 m long annulus with $D_i = 114$ mm and $D_o = 203$ mm. The inner pipe (D_i) could be rotated up to 150 rpm and the flow loop was inclinable between 10° to 90° . Air-water and air-viscous non-Newtonian aqueous polymer solution were the testing fluids. Flow regime identification was done visually using fixed high speed camera and hand camera. The test matrix chosen for their experiments meant that bubble flow and slug flow were the two flow regimes observed in their study.

On their part, Zhou et al., (2004) carried out experiments to study aerated mud flows in concentric annular test section 22 m long, with $D_i = 89$ mm and $D_o = 152$ mm. The experiments were carried out at different temperatures and pressures and air and water were used as the testing fluids. Flow regime identification was carried out by the use of a camcorder and flow regimes observed were; Slug, Stratified Smooth, Stratified Wavy as well as transition regimes like Slug-Dispersed Bubbly and Slug – Annular.

Somchai & Pipathattakul (2006) experimented on two-phase gas-liquid flow in inclined narrow annuli. The test section had $D_i = 8$ mm and $D_o = 12.5$ mm and length of 0.88 m. Inclination angles investigated were 0° , 30° and 60° . Air and water were the testing fluids. The superficial gas and liquid superficial velocities ranged between 0.0218 – 65.4 m/s and 0.069 – 6.02 m/s respectively. A high speed camera, digital camera and video recorder were used in visual observation and flow regime identification. The Slug flow regime was only observed in the horizontal annuli configuration and not in the inclined annuli.

Omurlu, Metin and co-workers (Omurlu et al., 2006; Metin & Ozbayoglu, 2007) studied extensively two-phase flow through fully eccentric horizontal annulus. Their experimental setups consisted of different D_o (0.0932, 0.1143 m) and D_i (0.0488 and 0.05715 m). Flow regime identification was by visual means and limitations in their setup meant that mainly the intermittent flow regimes were observed during their study. They proposed a mechanistic model based on representative diameter for flow regime determination in fully eccentric annulus.

Flow regime identification studies of gas-liquid flow through horizontal annulus were undertaken by Osgouei et al., (2010). The experiments were conducted in an annulus section with $D_i = 46$ mm and $D_o = 74$ mm having length of 3.7 m with variable inclination between horizontal and vertical. The flow regimes were identified using a high-speed digital camera and defined based on the visual observation of the investigators as follows; Stratified Smooth, Stratified Wavy Elongated Bubble, Slug, Churn, Wavy Annular, Dispersed Annular and Dispersed Bubble flow regimes.

Gschnaidtner, (2013) undertook experimental studies in a concentric annulus with Do of 51.5 mm and Di of 33.3 mm. Air and water were the testing fluids and flow regime identification was achieved using video camera recordings. Observed flow regimes were limited to intermittent and bubble flows due to the small range of liquid and gas superficial velocities investigated.

Recently, Nossen et al., (2017) conducted an experimental study of two-phase flow in horizontal and inclined annuli. The annulus test section was concentric, having outer and inner diameters as 101.6 mm and 50.8 mm respectively. Testing fluids used were SF6 gas-water and SF6 gas-Exxsol D60 oil. Flow regimes observed during their studies were Slugs, large waves, very low frequency slugs and transitional as a very limited range of gas and liquid superficial velocities were investigated

Some researchers reviewed here also developed flow regime maps from the experimental observations and these are considered in the next section.

2.2.1.1.1 Flow Regime Maps in Horizontal Annuli

As highlighted earlier, these maps are two dimensional and are used to represent the flow regime transitions observed during two-phase gas-liquid flow in annuli. Similar to what is observed in circular pipes, most of the flow regime maps encountered for horizontal annuli were constructed using superficial gas and liquid velocities as coordinates. However certain investigators also developed their flow regime map based on superficial gas and liquid Reynolds numbers.

Osamasali & Chang (1988) constructed experimental flow regime maps from their investigations in annuli of various inner to outer diameter ratios. The flow regime boundaries were visualized directly and in conjunction with time-averaged void fraction information. Maps comparing flow regime transitions between pipes and annuli of different diameter ratios were developed as well.

Ekberg et al., (1999) presented experimental flow regime map for two narrow annuli configurations. Their map was compared with those of Mandhane et al., (1974) and similar flow regime maps in micro-channels. Clear disagreements were noticed between the flow regime transition boundaries. The investigators

also disagreed with the assertion of Osamasali & Chang (1988) that the diameter ratio of the annuli had insignificant effect on the flow regime map.

During their experimental studies, Lage et al., (2000) developed twelve flow regime maps for air-water flow in a horizontal fully eccentric annuli. However, a limited number of experimental data points meant that the flow regime maps could not be produced completely or precisely.

Osgouei et al., (2010) developed flow regime maps for their air-water flow study in horizontal annuli based on Discriminant analysis. Their flow regimes were represented on the map using superficial velocity coordinates. The approach was to visualise the flow regimes by plotting the borders on the flow regime map and obtaining quadratic type boundary equations as follows:

$$F = a + bV_{SG} + cV_{SL} + dV_{SG}^2 + fV_{SL}^2 \quad (2-20)$$

The coefficients of the equation were as presented in Table 2-1 overleaf

Table 2-1: Boundary equation coefficients for Osgouei et al., (2010) flow regime map

Boundary Equation Between	a	b	c	d	f
SS&SW- EB	1.1496	-2.372	7.192	1.5132	-7.795
SS&SW - SF	3.846	-1.505	7.333	0.171	-7.781
SS&SW- CF	12.704	-2.493	6.8229	0.1288	-7.70
SS&SW- DA	3.8573	0.0683	7.4277	-0.01982	-7.798
EB- DBF	503.41	2.3024	-102.8	-1.50922	5.2232
EB- SF	-2.697	-0.867	-0.141	-0.0422	-0.015
SF- CF	8.8582	-0.989	-0.510	-0.0422	0.0807
SF- DB	500.71	1.4352	-102.9	-0.1670	52083

Boundary Equation Between	a	b	c	d	f
DB- DA	496.70	-0.20	-102.4	0.026	5.2148
DB- WA	-500.7	0.1377	103.01	-0.0238	-5.225
WA- CF	8.8471	-2.561	-0.604	0.1486	0.0977
WA- DA	4.0048	-2.561	-0.589	-0.00209	0.0105

To determine the actual flow regime using their developed boundary equations, for a given a given gas and liquid superficial velocity, Eqn. 2-20 is computed using the different coefficients to calculate equation of boundaries which separate the stratified flow from others. If the value obtained is greater than zero, then the flow regime is stratified. This is repeated for all the other flow regimes until the true flow regime is found. The flow regime map is as presented on Figure 2-6.

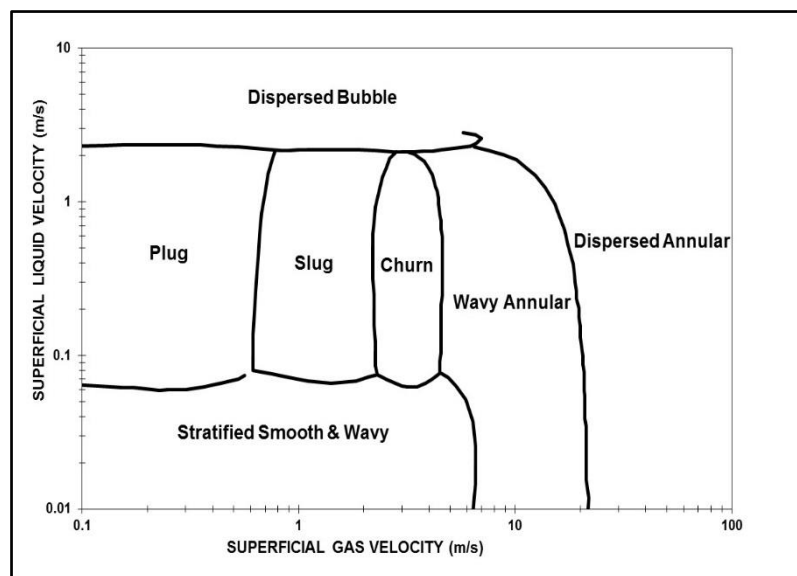


Figure 2-6: Osgouei et al.,(2010) flow regime map

2.2.1.1.2 Flow Regime Transitions in Horizontal Annuli

Flow regime transitions in horizontal and inclined annuli are influenced not only by shape of the conduit, superficial gas and liquid velocities and fraction of gas and liquid in the conduit but also by other parameters as highlighted by different

researches. Experimental investigations of flow regime transition criteria in horizontal and inclined annuli have been presented by several authors.

Osamasali & Chang (1988) showed that inner annulus rod had a huge impact on the flow regime transition in annuli. The stratified to intermittent transition was the most influenced when compared with flows in a pipe, occurring at lower superficial velocities of the liquid. Also the intermittent region was observed to be wider in annuli than for pipe flow. The annulus rod was observed to have a damping effect on bubbles that would have otherwise grown to become elongated bubbles and slugs in pipe flow.

In their work, Ekberg et al., (1999) observed a significant difference between the flow regime transitions in narrow rectangular channels when compared with those in narrow horizontal annuli.

Small upward inclination angles were also shown to have major effects of flow regime transition boundaries in annuli especially in the intermittent flow region which took place over wider flow rate ranges. This assertion was made by Lage et al., (2000) who also showed the sensitivity of the stratified flow boundaries to small inclination changes from the horizontal thereby agreeing with observations for flow in pipes.

The transition between bubble and slug flow in a 15° inclined annulus undergoing air-water two-phase flow was assumed to take place at a void fraction of 0.32 in a large geometry annular section. On the other hand however, when the testing fluids were air-aqueous polymer fluid flowing in the annulus, the void fraction necessary for dispersed bubble to slug flow transition is 0.25 similar to what is observed for flow in pipes (Sunthakar *et al.*, 2001).

According to Zhou et al., (2004), a change in temperature can affect flow regime transitions as well. Temperature effect on aerated mud flows is observed in the viscosity and surface tension of the liquid phase, and a temperature change increase from 27° C to 60° C led to flow regime transition from stratified smooth to stratified wavy flow regimes.

Wongwise & Pipathattakul (2006) highlighted the significant effect of inclination angles on the flow regime transitions. They observed that the transition from elongated bubble to slug flow regimes and elongated bubble to slug/bubbly regimes at inclinations of 0° and 30° respectively take place at lower superficial velocities of air even at constant liquid superficial velocities. At higher angles of inclination however, the opposite was observed to be the case as gravity was the dominant force driving the flow mechanism.

According to Gschnaidtner (2013), flow regime transition from bubble to intermittent flow takes place at superficial velocity of liquid of between 2 and 2.5 m/s depending on superficial gas velocity. Also an increase in superficial velocity of gas causes transition between intermittent and bubbly flow regimes to take place at higher values of superficial water velocity.

2.2.1.2 Liquid Holdup in Horizontal/Inclined Annuli

The liquid holdup is an important parameter for determining the flow regime and pressure drop which would exist for a given flow rate of gas and liquid. Different devices were used in literature for measuring the liquid holdup in horizontal annuli. For instance, Sunthankar et al., (2001) employed the “quick closing valve” technique for average holdup measurement. Valves located at both ends of their flow loop were simultaneously closed trapping liquid in the annulus and then diverting the flow through a by-pass line. The liquid trapped in the annulus exerts a hydrostatic pressure which is measured and the total volume of the liquid trapped inside the loop was calculated and used to determine the holdup.

Zhou et al., (2004) determined the liquid holdup by using the gamma-ray densitometer. The fluid density was noted during each experimental test run at steady state and used to compute the average liquid holdup. Readings of 1 and 0.35 were recorded by the densitometer; 1 indicating the annulus space was almost filled with liquid, while the 0.35 value indicated gas pockets passing through the densitometers.

Gschnaidtner, (2013) used the conductance probe method in estimation of experimental liquid holdup. Various models in literature including the

homogeneous model, separated models of (Lockhart and Martinelli, 1949; Zivi, 1964; Chisholm, 1973) and drift flux models were compared with experimental liquid holdup values. The homogeneous model was only able to predict holdup values above 80% with deviation of 20% or less. For the separated models, while that of Zivi (1964) overestimated the flow regimes even at 80% liquid holdup values, the model of Chisholm under predicts liquid holdup values below 60% and that of Lockhart and Martinelli gave the most accurate holdup values within error margins of about $\pm 20\%$.

Digital image processing techniques were employed by Osgouei et al., (2013; 2015) to determine the liquid holdup values. Measured holdup values were compared with Beggs & Brill (1973) and Lockhart and Martinelli (1949) holdup models by incorporating the hydraulic diameter concept. A huge difference was observed between the estimated liquid holdup based on Beggs & Brill (1973) model and the experimental value. On the other hand, the Lockhart & Martinelli method gave reasonable estimates of liquid holdup at moderate rates of gas flow in horizontal annular configuration but underestimates holdup at low and high rates of gas flow. The researchers were of the opinion that the observed discrepancies were because the hydraulic diameter concept used to extend the pipe flow model to annulus is inadequate to define the annular geometry.

Based on this fact, the Beggs & Brill (1973) model for liquid holdup was modified by redefining the relationship between the liquid holdup, non-slip void fractions and Froude number using nonlinear least square method as presented in the Eqn. 2-21 using the experimental results.

$$H_L = \frac{a\lambda_L^b}{Fr^c} \quad (2-21)$$

New constants were developed (a, b and c) for each flow regime and presented on Table 2-2. Similarly, the Lockhart and Martinelli model was modified to account for annular geometry and new constants were obtained for estimating the liquid holdup based on

$$H_L = a - (1 + X^b)^c \quad (2-22)$$

Table 2-2: New constants for Flow in Annuli

	Modified Beggs & Brill			Modified Lockhart & Martinelli		
	a	b	c	a	b	c
Flow Regime	0.862	0.342	0.014	1.000	0.912	-0.380
Churn	0.849	0.341	0.008	0.998	1.000	-0.337
Dispersed Bubble	0.901	0.494	-0.002	1.000	1.000	-0.354
Elongated Bubble	0.923	0.671	0.018	1.000	1.000	-0.332
Wavy annular	0.977	0.341	0.038	1.000	0.767	-0.393
Slug	0.895	0.393	0.008	1.000	1.000	-0.355
Dispersed annular	0.967	0.314	0.043	1.000	0.763	-0.380

After modifying the coefficients, the researchers used data obtained by Sunthakar (2002) and Eqn. 2-21 and 2-22 respectively to compute the liquid holdup. The model performance was observed to improve using the new coefficients in Table 2-2.

2.2.1.3 Pressure Drop in Horizontal/Inclined Annuli

The pressure drop is a parameter that must be tracked during two-phase gas-liquid flows in conduits. For horizontal pipes, the pressure drop is a function of flow regime, gas and liquid velocities, flow area geometry, slip ratio between the phases as well as void fraction (Wongwises and Pipathattakul, 2006; Osgouei *et al.*, 2013). In the past, most of the developed models for determination of frictional pressure loss were for circular pipes. However, in order to account for the annular configuration, the hydraulic diameter concept is mostly used to define the flow area geometry. Different researchers estimated the pressure drop during gas-liquid two phase flow in horizontal and inclined annuli experimentally and those

will be highlighted here. Pressure drop estimation using modelling will be considered in a different section.

Ekberg et al.,(1999) during their study of pressure drop in narrow horizontal annuli carried out measurements using pressure transducers. The pressure drop that is measured is composed of the frictional pressure drop component together with acceleration pressure drop. The Homogeneous model of McAdams (1954) was applied together with correlations of Beattie and Whalley (1982), Friedel (1979) and Chisholm & Laird (1958) in verifying experimentally measured pressure drop in their narrow annulus. Results shows that the homogeneous model under-predicts the experimental data significantly especially for the churn and annular flow regimes. The Friedel (1979) data has the best performance in terms of overall scatter of data followed by the correlation of Beattie & Whalley (1982).

Lage et al., (2000) compared their experimentally observed pressure drop in fully eccentric annulus to predicted frictional pressure drop values. This led to parameters used to evaluate the performance of the models. They also compared experimental data to frictional pressure drop models in literature.

On their part, Sunthakar et al., (2001) compared the total pressure drop measured during experiments for 45° inclined annulus with a modified pressure drop estimation model. A pipe flow model in literature was also compared with modified pressure drop model. The results were comparable although the modified model performed better. Also, experimental and calculated pressure drop comparisons were carried out for an annulus inclined at 15°. It was concluded in general that the modified model which they used in pressure drop estimation underestimated the pressure drop value. The reason for this observation is the fact that frictional pressure component is not the main contributor to pressure drop as inclination angle tends to vertical. It can be concluded from the following that the modified model proposed by the author cannot reasonably describe two-phase flow pressure drop in horizontal annular geometries.

Two-phase pressure drop in a horizontal thin annulus was also investigated experimentally by Dillon et al.,(2004). Air and water were the testing fluids and

the horizontal annular section had $D_i = 7.93$ mm and $D_o = 9.53$ mm. A one dimensional model and different two-phase frictional pressure drop correlations were compared with the total measured pressure drops. Also, pressure drop due to flow acceleration were evaluated using the homogeneous flow assumption. Beattie and Whalley (1982) correlation provided the closest agreement between the experimental results and the models compared from literature. The effects caused by lateral mechanical vibrations imposed on the centre of the test piece on total two-phase pressure drop were investigated.

Zhou et al., (2004) measured frictional pressure losses across their annular configuration. They indicated the differential changes in pressure with respect to liquid flow rate on a chart for the different test carried out. They observed that frictional pressure drops are not sensitive to the rate of air injection. An increase in frictional pressure loss is also observed when air flow rate is at a maximum. Also, the pressure drop decreases in an annulus as temperature increases.

In their study, Wongwises & Pipathattakul (2006) observed pressure drop in horizontal and inclined narrow annular channel. They observed that in the horizontal annular channel, as gas velocity increases at low liquid velocity and until the flow regime changes from elongated bubble flow to slug flow, the pressure drop increases rather quickly. Similarly, a further increase in gas velocity leading to flow regime change from slug to annular/slug flows causes more liquid to be displaced by the gas and hence pressure drop stops initially. However it is observed to increase again as gas velocity becomes sufficient to induce turbulence in the fluid. Also, for annular configurations inclined at 30° and 60° at low gas and liquid velocities, the effect of gravity is greater than those of friction for the transition between slug/bubbly flow regimes resulting in a gradual increase in pressure drop. It was concluded that at all inclination angles, changes observed in pressure drop conditions are dependent on the flow regime transitions.

The experimental pressure drop reported by Gschnaidtner.,(2014) were compared with five models in literature. These models are dependent on the conduit diameter and were evaluated based on different diameter concepts found in literature and reviewed in his work. Majority of the pressure drop predictions

based on the models are within $\pm 20\%$ deviation although they tend to overestimate the pressure drop at lower values of pressure drop while underestimating the pressure drop slightly at higher values. The model proposed by Beattie and Whalley performed the best of all the models compared while the Knudsen/Prengle/Rothus diameter concept was the best fit for annular configuration.

A similar approach was adopted by Osgouei et al., (2013) who applied Lockhart & Martinelli., (1949) and Beggs & Brill.,(1973) methods to experimental data from their study as well as those from Sunthankar., (2002), in order to determine the performance of those models for predicting frictional pressure drop through horizontal annulus. The results obtained from their comparison of the methods shows that Beggs & Brill (1973) model values matched the observed values with a deviation of less than 10% at low and moderate superficial velocity of gas, while overestimating pressure drop values as the superficial gas velocity is increased. The Lockhart & Martinelli method on the other hand under-predicts the pressure drop at higher values of gas superficial velocity. The investigators opined that gas-liquid two-phase flow in horizontal annuli can be characterized similar to flow in circular pipes at low and moderate superficial velocities due to a negligible slip between the phases. However, as the superficial velocities are increased and in effect the slip ratio between the phases, the properties of the annuli like the diameter ratios and eccentricity begin to play a significant role on the variation of flow regimes.

Most of the studies undertaken for gas-liquid two-phase flow in horizontal and inclined annuli have mainly been experimental in nature. However, few modelling studies have been undertaken and those will be presented in the sections that follow.

2.2.2 Modelling Studies in Horizontal/Inclined Annuli

Extensive experimental and theoretical investigations have been recorded in literature for two-phase gas-liquid flow in horizontal pipes. Two categories of models have been proposed namely; general models and mechanistic models. The general models were typically flow regime independent, ignoring complex

configurations of flow known as flow regimes. Also, these models considered the two-phase flow as either single-phase fluid (homogeneous model) or two fluids flowing separately (separated model). Typical examples of these models for two-phase flow in pipes are Lockhart & Martinelli (1949), Wallis (1969) etc. Later on, investigations were shifted to flow regime determination and this led to the development of empirical and mechanistic models. The empirical models involved proposing equations based on experimental data for flow regime identification as well as pressure drop estimation. Typical examples of such models include Beggs & Brill (1973) and Dukler et al (1964).

Mechanistic modelling combines studies of the mechanism of flow as well as the two-phase fluid system physics independently for each flow regime. Different comprehensive and unified models have been developed over the years. Models proposed by Taitel & Dukler (1976), Petalas and Aziz (2000) and Barnea (1987) are examples of mechanistic models proposed for two-phase flow in horizontal pipe.

Unlike two-phase gas-liquid flow in pipes, only very few mechanistic modelling studies have been undertaken for gas-liquid two-phase flow in annulus over the years. Majority of the studies have been carried out by researchers such as Osgouei et al (2012; 2013), Sorgun et al (2010; 2011, 2013) and Omurlu et al (Omurlu, 2006; 2007, 2009). Similarly, the mechanistic modelling studies will be reviewed under subheadings including flow regime identification and transition, liquid holdup and pressure drop.

2.2.2.1 Flow Regime Identification and Transition Models in Horizontal/Inclined Annuli

According to Omurlu et al., (2006), in mechanistic modelling it is important to accurately determine the flow regimes. This is the initial step for correct prediction of the frictional pressure drop. Most mechanistic models in literature for flow regime determination and transitions in annuli are based on the original work of Taitel & Dukler (1976) and Barnea (1987). These models account for the annulus geometry by replacing the diameter term with the concept of hydraulic diameter. This practise has however been observed by various investigators as inadequate

on its own to define the flow area in the annulus as it results in huge errors (Gschneidner, 2014). Several alternative concepts to define the flow area have been attempted by researchers with varying levels of success.

Akbar and Ghiaasiaan (2003) were among the earliest investigators that studied flow regimes and their transitions in horizontal annular channels. They attempted to develop a criterion for predicting the instability threshold of stratified flow in horizontal annuli using experimental data. Taitel and Dukler (1976) instability criterion of stratified flow was adopted as the basis for their study and modified using experimental data presented by Osamusali & Chang (1988) as well as Ekberg et al., (1999). Their research produced a simple method for predicting flow regime transition out of the stratified-wavy regime.

On their part, Omurlu, Metin and co-workers (2006; 2007, 2009; 2007) proposed an areal representative diameter approach for defining the flow area of horizontal fully eccentric annuli. The representative diameter was defined by Eqn. (2-23) as follows:

$$D_r = \sqrt{(D_o^2 - D_i^2)} \quad (2-23)$$

The following geometrical parameters were presented for fully eccentric annuli which makes it possible to determine parameters such as gas and liquid perimeter, liquid and gas flow area as well as liquid level.

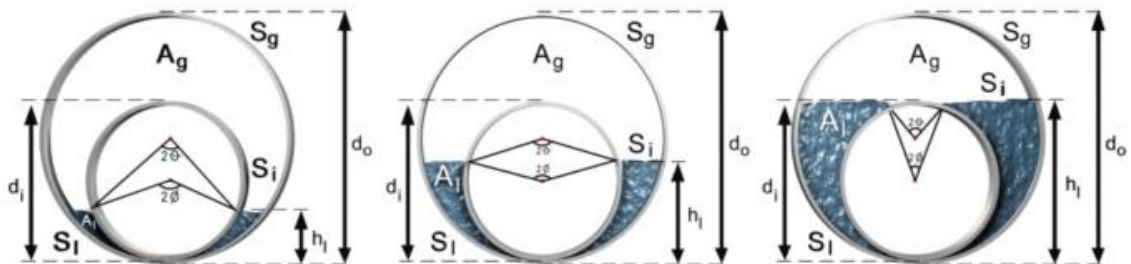


Figure 2-7: Geometrical parameters for fully eccentric annuli (Metin & Ozbayoglu, 2007)

The criterion for flow regime transition from stratified flow to non-stratified flow was based on the original work of Taitel & Dukler (1976) is presented in Eqn. (2-24):

$$V_G > \left(1 - \frac{h_l}{D_r}\right) \left[\frac{(\rho_L - \rho_G)gA_G}{\rho_G \left(\frac{dA_l}{dh_l}\right)} \right]^{\frac{1}{2}} \quad (2-24)$$

Gas velocity V_G can be computed from Eqn. (2-25)

$$V_G = \frac{V_{SG}}{\alpha_G}, \text{ where } \alpha_G = \frac{A_G}{A} \quad (2-25)$$

For flow regime transition between intermittent flow and annular flow, the liquid level in the annular configuration is the determining factor. It was suggested by the researchers that the critical dimensionless liquid level which for the annular configuration represents the one half of the flow area is as presented in Eqn. (2-26)

$$\frac{h_l}{D_o} < 0.41 \quad (2-26)$$

If the fluctuations due to turbulence are strong enough to overcome buoyancy forces and keep the gas phase at the top of the annulus, then the transition between intermittent and dispersed bubble flow would occur. This was proposed for pipe flow by Taitel & Dukler (1976) and the criterion is shown in Eqn. (2-27).

$$V_L \geq \left[\frac{4gA_G}{S_i f_i} \left(1 - \frac{\rho_G}{\rho_L}\right) \right]^{\frac{1}{2}} \quad (2-27)$$

The liquid velocity V_L is computed from the expression below in Eqn. (2-28)

$$V_L = \frac{V_{SL}}{H_L}, \text{ where } H_L = \frac{A_L}{A} \quad (2-28)$$

On the other hand, the transition between stratified smooth and stratified wavy flow regimes is based on the Jeffrey's wave initiation theory as obtained from Eqn. (2-29). The viscous dissipation force in the liquid phase is overcome by the pressure and shear forces exerted by the gas. It was concluded that the hydraulic diameter concept cannot be applied to a fully eccentric annulus as the stratified flow regimes are developed at values higher than those obtained using the hydraulic diameter concept

$$V_G > \left[\frac{4\mu_L(\rho_L - \rho_G)g}{S\rho_L\rho_{GV_L}} \right]^{\frac{1}{2}} \quad (2-29)$$

Annular flow occurs if the ratio of the area shown in Eqn. (2-30) is less than 0.50

$$\frac{A_L}{A} < 0.50 \quad (2-30)$$

Ozbayoglu and Omurlu (2007) modelled two-phase flow through concentric annuli. The annulus geometry is represented as a narrow slot where flow takes place between two parallel plates. This is a new diameter concept known as equivalent diameter. For their study the equivalent diameter used was defined as follows. If $\frac{D_i}{D_o} \leq 0.5$

$$D_e = \left[0.9983 - 1.4472 \left(\frac{D_i}{D_o} \right) + 7.2649 \left(\frac{D_i}{D_o} \right)^2 - 16.833 \left(\frac{D_i}{D_o} \right)^3 + 13.564 \left(\frac{D_i}{D_o} \right)^4 \right] (D_o - D_i) \quad (2-31)$$

Also if $\frac{D_i}{D_o} > 0.5$,

$$De = 0.816(D_o - D_i) \quad (2-32)$$

The flow regime transition models are similar to those proposed in their original research although the determination of interfacial friction factor, f_i , and friction between the liquid and wall phase, f_L was inherited from Petalas and Aziz (2000). Obtained results shows that the proposed model estimates flow regimes reasonably but that the geometry has a strong influence on flow regime transition.

2.2.2.2 Liquid Holdup Modelling in Horizontal/Inclined Annuli

Different modelling approaches have been used to estimate liquid holdup in horizontal/inclined annular geometries. Following on from their study to determine the flow regime transition in horizontal annulus, Ozbayoglu and Omurlu (2007) determined liquid holdup, H_L based on geometrical considerations as follows:

$$H_L = \frac{\pi - \cos^{-1} \left(2 \frac{h_L}{De} - 1 \right) + \left(2 \frac{h_L}{De} - 1 \right) \sqrt{1 - \left(2 \frac{h_L}{De} - 1 \right)^2}}{\pi} \quad (2-33)$$

Metin and Ozbayoglu (2007) modified the Petalas and Aziz (2000) model to determine the liquid holdup in intermittent flow region using the Omurlu diameter concept to define the annular geometry. The liquid holdup in the slug unit is determined using Equation (2-34) below:

$$\epsilon_L = \frac{\epsilon_{LS} V_T + V_G (1 - \epsilon_{LS}) - V_{SG}}{V_T} \quad (2-34)$$

Where V_T is the translational velocity of the elongated bubble and ϵ_{LS} is the liquid fraction in the slug body computed using Eqn. (2-35)

$$\epsilon_{LS} = \frac{1}{1 + \left(\frac{V_M}{8.66}\right)^{1.39}} \quad (2-35)$$

Gschneidner (2014) highlighted four approaches used for liquid holdup estimation in annular geometries. These are:

The homogeneous model based on the void fraction correlation and calculated from Eqn. (2-36)

$$\alpha_{G,hom} = \frac{1}{1 + \frac{1-x}{x} \cdot \frac{\rho_G}{\rho_L}} \quad (2-36)$$

Liquid holdup can be estimated by subtracting the void fraction using Eqn. (2-37)

$$H_L = 1 - \alpha_G \quad (2-37)$$

The separated model treats the void fraction based on Eqn. (2-38) as follows:

$$\alpha_{G,sep} = \frac{1}{1 + \frac{1-x}{x} \cdot \frac{\rho_G}{\rho_L} \cdot S} \quad (2-38)$$

S is known as the slip ratio and is the ratio of the gas to liquid mass ratios. Different approaches have been used to determine the velocity ratio values, including the velocity ratios proposed by Zivi (1964), Chisholm (D. Chisholm, 1973) and Butterworth (1975).

The drift flux model for void fraction is obtained from Eqn. (2-39) as follows:

$$\alpha_{G,DFM} = \frac{U_{SG}}{C_0(U_{SL} + U_{SG}) + U_D} \quad (2-39)$$

Parameters such as the drift velocity U_D and distribution parameters C_0 need to be determined.

2.2.2.3 Pressure Drop Modelling in Horizontal/Inclined Annuli

As indicated earlier, the approach adopted for two-phase gas-liquid flow in pipes and by extension annuli is to appropriately map or predict the flow regimes and then estimate the pressure drop. For flow through horizontal channels, the frictional pressure drop is the fundamental contributor to pressure drop and as a result, most researches were focus on frictional pressure drop determination.

Omurlu and Ozbayoglu (2006) studied the flow mechanism of each flow regime independently and then estimated frictional pressure drop for each. The introduced the areal representative diameter to define the annular geometry.

For stratified flow, the frictional pressure drop was calculated by momentum balance of the gas or liquid phases. The correlation is presented on Table 2-3 and requires adequate calculation of the interfacial shear stress which is determined from Eqn. (2-40)

$$\tau_i = \frac{f_i \rho_G (V_G - V_L)^2}{2} \quad (2-40)$$

Also, the shear stresses exerted by the liquid and gas phases on the wall are obtained from Equation (2-41) and (2-42) respectively

$$\tau_{wL} = \frac{f_L \rho_L V_L^2}{2} \quad (2-41)$$

$$\tau_{wG} = \frac{f_G \rho_G V_G^2}{2} \quad (2-42)$$

The approach adopted for pressure drop calculation for intermittent flow is similar to the one initially proposed by Petalas & Aziz (2000). It involved taking the momentum balance over a slug unit. The total pressure drop is computed as shown on Table 2-3 and is dependent on T_μ , a function of the ratio of slug length to slug unit length. T_μ can be computed from Eqn. (2-43) as follows:

$$T_{\mu} = 0.3805e^{(1.6552H_L)} \quad (2-43)$$

Parameters such as the liquid slug translational velocity computed from Eqn. (2-44)

$$V_T = C_0 V_M + V_D \quad (2-44)$$

The value for C_0 was taken as 1.2, while the drift velocity was determined as follows:

$$V_d = f_m V_{d\infty} \quad (2-45)$$

Drift at high Reynolds numbers $V_{d\infty}$ is computed from Eqn. (2-46) as follows:

$$V_{d\infty} = \left[0.54 - \frac{1.76}{B_o^{0.56}} \right] \sqrt{\frac{g D_r (\rho_L - \rho_G)}{\rho_L}} \quad (2-46)$$

Where the Bond number is given as

$$B_o = \frac{(\rho_L - \rho_G)}{\sigma} (g D_r^2) \quad (2-47)$$

f_m in Eqn. (2-45) is equal to 1 in all situations unless in scenarios where $f_m < 1$ where it is computed from Eqn. (2-48)

$$f_m = 0.316 \sqrt{N_{Re\infty}} \quad (2-48)$$

Where

$$N_{Re\infty} = \frac{\rho_L V_{d\infty} D_r}{2\mu_L} \quad (2-49)$$

The determination of these parameters paves the way for the slug liquid volume fraction and average liquid volume fraction of the slug unit to be estimated. Similarly, the entrainment fraction, dimensionless liquid film thickness, mixture density and viscosity are determined. The frictional pressure drop for slug body is defined from Eqn. (2-50)

$$\left(\frac{\Delta P}{\Delta z}\right)_{fsl} = \frac{2f_{ml}V_M^2\rho_M}{D_r} \quad (2-50)$$

The gas pocket/liquid film pressure drop is determined as follows:

$$\left(\frac{\Delta P}{\Delta z}\right)_{fgp} = \frac{4\tau_{wL}}{D_r} \quad (2-51)$$

The investigators report that frictional pressure drop prediction was reasonably accurate using the proposed models. Computed pressure drop values were compared with experimental results, and the models were reported to predict pressure drop reasonable especially in intermittent flow regimes. Having said that, it must be stated that only limited range of data was tested and hence the results cannot be adequately validated. Also, they only presented results for stratified and intermittent flow regimes and did not consider the effect of eccentricity on flow regime determination and pressure drop estimation.

Subsequently, Ozbayoglu & Omurlu (2007) presented frictional pressure drop models for annular flow and dispersed bubble flow. The approach for modelling annular flow was by combining momentum equation for the liquid and gas phase in a trial and error process. The liquid film thickness is determined by combining the liquid and gas phase momentum equation according to the follow expression

$$\tau_{wf} \frac{S_f}{A_f} - \tau_i S_i \left(\frac{1}{A_f} + \frac{1}{A_c} \right) = 0 \quad (2-52)$$

For dispersed bubble flow, a simple homogeneous flow was assumed since the gas phase is dispersed as gas bubbles and moves at the same velocity as liquid phase. Pressure drop estimation is based on the following expression in Eqn. (2-53)

$$\left(\frac{\Delta P}{\Delta z} \right) = \frac{2f_m \rho_M V_M^2}{D_r} \quad (2-53)$$

The researchers tried to compare the performance of the models modified when using the hydraulic diameter concept versus when using the representative diameter concept for pressure drop prediction in fully eccentric annulus. Huge errors were however observed as a result of the use of the representative diameter concept although it performed better than the hydraulic diameter in this annulus setup.

Another important parameter for the estimation of two-phase pressure drop in conduits is the friction factor. As an extension of their work, Omurlu and Ozbayoglu developed friction factor correlations in (2006; 2009) for a two-phase system flowing in a fully eccentric annuli. Data obtained from experimental investigations were analysed by statistical methods and formed the basis for the development of the correlations. The initial friction factor correlation presented for all flow regimes was of the form:

$$f_f = 1.13297 \times 10^{12} (Re_M)^{-2.71} \quad (2-54)$$

Where Re_M is computed from Eqn. (2-55)

$$Re_M = \frac{D_r \rho_M V_M}{\mu_M} \quad (2-55)$$

ρ_M and μ_M are obtained from Eqns. (2-56) and (2-57) respectively

$$\rho_M = \rho_L(H_L) + \rho_G(1 - H_L) \quad (2-56)$$

$$\mu_M = \mu_L(H_L) + \mu_G(1 - H_L) \quad (2-57)$$

They also proposed friction factor correlations for the stratified and intermittent flow regimes. For stratified flow, the friction factor correlation was as given in Eqn. (2-58)

$$f_f = 9880(Re_M)^{-1.1734} \quad (2-58)$$

A mixture Reynolds number was proposed for the intermittent flow regime as follows:

$$Re_{M\lambda_L} = \lambda_L Re_{SL} + (1 - \lambda_L) Re_{SG} \quad (2-59)$$

Where the no-slip holdup is calculated from Eqn. (2-60) as follows:

$$\lambda_L = \frac{V_{SL}}{V_{SL} + V_{SG}} \quad (2-60)$$

For Re_M values less than 100,000, the friction factor for intermittent flow was computed from Eqn. (2-61)

$$f_f = 0.0085(Re_M)^{-0.0594} \quad (2-61)$$

While for $Re_M \geq 100000$ the friction factor correlation was given as

$$f_f = 0.9435(Re_M)^{-0.4676} \quad (2-62)$$

Later on, Osgouei et al.,(2012) developed mechanistic models for predicting the gas and liquid volumetric distributions and estimating frictional pressure drop. A

conformal mapping approximation approach to solve problems involving eccentric annulus using cylindrical coordinates as shown in Figure 2-8.

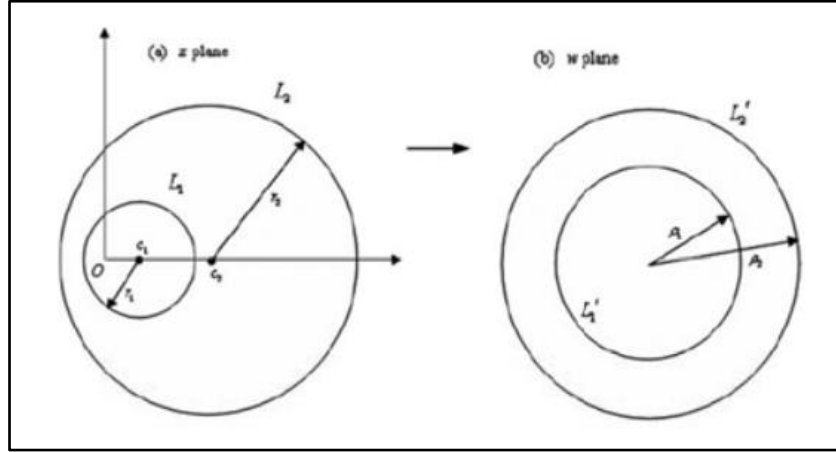


Figure 2-8: Mapping Eccentric annulus to a concentric annulus (from Chen et al., (2009) cited in (Osgouei et al., 2012))

Two parameters were used to identify the eccentric annulus and these are; the radius ratio (r_e^*) and eccentricity ratio (ϵ) defined from Eqns. (2-63) and (2-64) respectively.

$$r_e^* = \frac{r_i}{r_o} \quad (2-63)$$

$$\epsilon = \frac{e}{r_o - r_i} \quad (2-64)$$

The frictional pressure drop and gravitational effects were computed from Eqns. (2-65) and (2-66) respectively

$$\left(\frac{dP}{dz}\right)_f = \frac{2f_f \rho_M V_M^2}{(D_o - D_i)} \quad (2-65)$$

$$\left(\frac{dP}{dz}\right)_g = g\rho_M \quad (2-66)$$

Comparison of the experimentally measured pressure drop with the developed model showed that the model underestimated the system pressure drop by a deviation of less than 20%.

The trend also shifted towards computer based mathematical modelling approaches to study gas-liquid flow in horizontal annuli. Sorgun et al., (2010; 2011, 2013) have lead studies in this regard. They used computational Fluid Dynamics based on a commercial software package to simulate gas-liquid flow in horizontal fully eccentric annuli.

In their study, the researchers used an Eulerian-Eulerian CFD model for two-phase flow regimes in annulus as well as frictional pressure drop evaluation. An inhomogeneous model was used to simulate the gas-liquid flow through an annulus. The models are mixture model which correlate non-dimensional interphase coefficients in terms of mixture Reynolds number and Prandtl number and the free surface model which is an attempt at resolving the interphase between the fluids.

The mixture Reynolds number and Prandtl numbers are given in Eqns. (2-67) and (2-68) respectively

$$Re_{\alpha\beta} = \frac{\rho_{\alpha\beta}|U_{\beta} - U_{\alpha}|d_{\alpha\beta}}{\mu_{\alpha\beta}} \quad (2-67)$$

$$Pr_{\alpha\beta} = \frac{\mu C_{p\alpha\beta}}{\lambda_{\alpha\beta}} \quad (2-68)$$

If there are only two phases in the simulation, the equation used to determine the interfacial area density is:

$$A_{\alpha\beta} = |\nabla r_{\alpha}| \quad (2-69)$$

To carry out the simulation, the eccentric annular geometry was drawn using ANSYS Workbench. Specified boundary conditions for annulus inlet were volume fractions of gas and water while the outlet were static atmospheric pressure and volume fraction of gas and water. A structured mesh having 2.8×10^6 tetrahedral meshes was created and a drag coefficient of 0.44 was used for momentum transfer. Frictional pressure drop simulations were based on finite element method for gas-liquid flow. The CFD model estimated the frictional pressure drop with an error of between 20 and 30% and a maximum error value of 31.1%. A summary of some of the pressure drop correlations reviewed in this section are as presented on Table 2-3.

2.2.3 Geometric Parameters Affecting Two-Phase Flow in Horizontal/Inclined Annuli

Gas-liquid flow parameters through any conduit are affected by the flow rates of the phases, phase properties, geometry of the conduit as well as the presence of any body of force field. For flow through annuli, the following geometric parameters have been observed to play an influential role in the two-phase flow hydraulics. These parameters include;

2.2.3.1 Eccentricity

The eccentricity of annulus is an important geometric parameter that could affect two-phase flow hydraulics in horizontal/inclined annuli. The degree of eccentricity shows the deviation of the inner pipe's centre from that of the larger pipe and can be expressed mathematically as follows:

$$e = \frac{2DBC}{(D_o - D_i)} \quad (2-70)$$

Where DBC refers to the distance between the pipe centres. In annular configurations, the eccentricity could range from zero which is concentric to one which is referred to as fully eccentric (Caetano et al., 1992b). Figure 2-9 shows different annulus cross sections having different eccentricity values.

Table 2-3: Different pressure drop correlations used for horizontal annuli.

Author(s)	Equation	Remarks
Lage et al, (2000)	$\left(\frac{dp}{dx}\right)_{Total} = \rho_M g \sin \alpha + \frac{2f_M}{D_H} \rho_M V_M^2$	D _H = 50.8 mm, Pressure drop correlation for dispersed Bubble flow.
Omurlu & Ozbayoglu (2006)	$\left(\frac{\Delta P}{\Delta Z}\right) = \frac{-\tau_{wG} S_G - \tau_i S_i}{A_G}$	Mechanistic model was developed for frictional pressure drop in stratified flow as presented.
Ozbayoglu & Omurlu (2007)	$-A_F \left(\frac{\Delta P}{\Delta Z}\right) - \tau_{wF} S_F + \tau_i S_i = 0$	Pressure drop correlation for annular flow regime.
Metin & Ozbayoglu (2007)	$-A_l \left(\frac{\Delta P}{\Delta Z}\right)_l - \tau_{wl} S_l - \tau_i S_i = 0,$ $\left(\frac{\Delta P}{\Delta Z}\right) = \frac{2f_M \rho_M V_M^2}{D_r}$	Presented are the pressure drop correlations for stratified flow and dispersed bubble flow respectively.
Metin & Ozbayoglu (2009)	$\left(\frac{\Delta P}{\Delta Z}\right) = \frac{2f_M \rho_M V_M^2}{D_r}$	The pressure loss determination procedure suggested by Garcia et al. (2003) is modified

for annulus using D_r .

Osgouei
et al
(2013)

$$\left(\frac{\Delta P}{\Delta L}\right)_{SL} = \frac{2}{D_H g} C_G \left[\frac{1488 V_{SL} D_H (\rho_L / 7.48)}{\mu_L} \right]^n (\rho_L / 7.48) V_{SL}^2,$$

$$\left.\frac{\Delta P}{\Delta L}\right|_{total} = \frac{f_{TP} \rho_M V_M^2}{2g D_H}$$

Modified Beggs &
Brill (1973) and
Lockhart &
Martinelli (1949)
for pressure drop
estimation

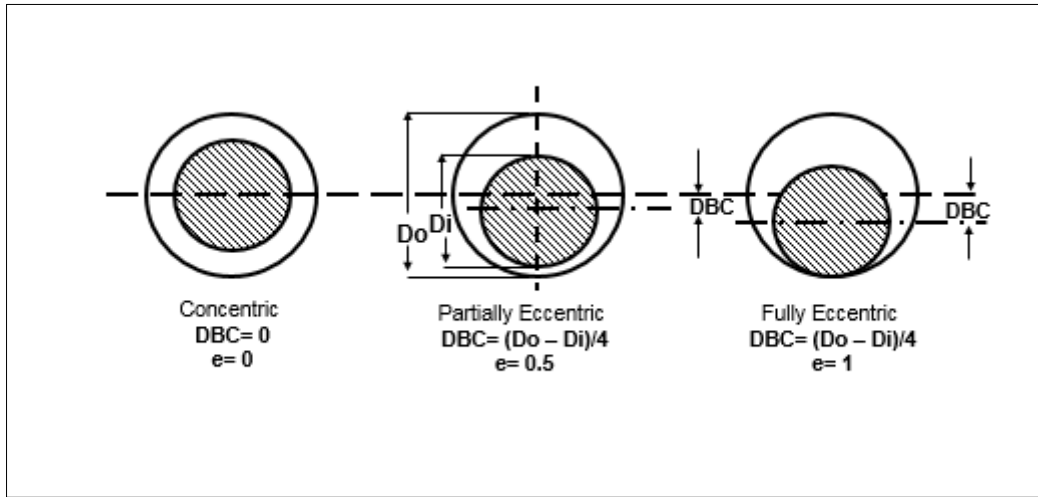


Figure 2-9: Typical Configuration for annuli showing different eccentricity
(Caetano et al.,1992b)

2.2.3.2 Diameter Ratio

Another geometric parameter that is important for defining the annulus flow area is the ratio between the annulus diameters. The diameter ratio can be expressed as follows:

$$K = \frac{Di}{Do} \quad (2-71)$$

In their study, Osamasali & Chang (1988) showed that variation in flow regime transition boundaries depending on the annulus diameter ratio employed.

2.2.3.3 Equivalent Diameter Concept

Most studies carried out to study two-phase flow in horizontal annulus have been based on the hydraulic diameter concept. The hydraulic diameter which is four times the flow area divided by the wetted perimeter reduces for annulus to Eqn. (2-72)

$$D_H = D_o - D_i \quad (2-72)$$

However, most researchers report that the hydraulic diameter concept for defining annulus geometry particularly when extending two-phase models and correlations developed for circular pipes. Discrepancies in observed results made these researchers state that is not representative of the characteristic flow dimensions in annulus.

Omurlu, Metin and co-workers (2006; 2007, 2009) used different diameter concept including the Omurlu diameter concept, equivalent diameter concept and the slot diameter concept to try to address this issue. However, large errors were still observed using their concepts with the models they developed. It is required therefore to check the applicability of the hydraulic diameter or other concepts proposed in literature for extending pipe flow models and correlations to annular geometries. A summary of different diameter concepts used during this study to extend different models and correlations developed for flow through pipes to annular geometries is presented on Table 2-4.

2.2.3.4 Inclination

Another very important parameter that could affect two-phase flow properties in annuli is the inclination angle. This is because in operations where annulus geometries may be encountered, the inclination may change between vertical and horizontal and as such, the effect of gravitational forces maybe become a more or less significant contributor to pressure drop. Only very limited studies

have been undertaken to study inclination effects on two-phase gas-liquid flow parameters in annuli. Researchers including Hasan & Kabir.,(Hasan and Kabir, 1992), Lage et al.,(Lage *et al.*, 2000), Sunthankar et al.,(2001), Wongwises & Pipathattakul.,(Wongwises and Pipathattakul, 2006) and Osgouei et al.,(2012) all investigated two-phase flow in inclined annuli. Hasan & Kabir discussed the effect of inclination angles on the Taylor bubble rise velocity and flow parameter for slug flow in annulus. They suggested different correlations for determining the Taylor bubble rise velocity depending on the inclination angle up onto 32° . Lage and co-authors consider three inclination angles which include; horizontal, $+4^\circ$ and -4° . They stated that small inclination angles in the upward direction have a huge effect on flow regime transition boundaries. Sunthankar et al (2001) investigated two-phase flow in annular geometry in 15° and 45° inclined positions from vertical. The effect of inclination angles were observed as the pressure drop of the annulus was measured. The frictional pressure drop component was found to be more in the horizontal configuration while it decreased as the inclination angles increased towards vertical flow. Also, a shift was observed in the flow regime transition as inclination angle changed to near vertical annuli especially in the bubbly to slug flow regimes. Wongwises & Pipathattakul studied horizontal, 30° and 60° inclined annuli. They also observed a shift in flow regime transition due to change in inclination angles and an increase in pressure drop as inclination angle changes from 30° and 60° .

2.3 Chapter Summary

In this chapter, an overview of the gas-liquid two-phase flow is provided, looking at parameters like horizontal and inclined flow regimes, flow regime maps, modelling approaches for flow regime determination as well as liquid holdup and pressure drop prediction. Also, an introduction to some of the variables that are used in two-phase flow is presented. Following on from these, a detailed review is provided of the gas-liquid two-phase flow in horizontal and inclined annuli state of the art. This section is divided into experimental studies and modelling studies, looking in-depth at three key flow parameters: flow regimes, liquid holdup and

pressure drop. From the review conducted, the following observations could be summarised:

- The flow structure in the annulus setup is different to that of the circular pipe due to the flow obstruction caused by the central pipe. As a result, the characteristics of the flow regimes are different.
- There is lack of detailed information on the flow regimes encountered in horizontal annuli, as most of the studies undertaken to characterize flow regimes were based on visual observation alone. The challenge with this is the fact that the unique annulus geometry would make visual observation difficult particularly at higher gas and liquid flowrates.
- There is no systematic study of the two-phase flow regimes and their transitions in horizontal annuli.
- Data available on gas-liquid two-phase flow in horizontal and inclined annuli is very limited particularly when compared with available data on circular pipe flow.
- The two-phase flow parameters in annuli generally including the flow regimes, liquid holdup and pressure drop depend on the size and diameter concept of the annulus, eccentricity and inclination.
- Models were developed or extended from pipe flow to annuli by implementing the hydraulic diameter concept. It is necessary to check the applicability of this concept as well as different diameter concepts for extending or developing models for flow in annuli.
- The effect of annulus eccentricity on gas-liquid two-phase flow parameters including flow regimes, liquid holdup and pressure drop in horizontal annuli have not been investigated.
- Development of new models and or closure relationships as well as validation of existing models using different diameter concepts needs to be undertaken.

Table 2-4: Different diameter concepts for flow through annuli

Diameter Concept	Correlation	Comments
Hydraulic Diameter	$D_H = D_o - D_i$	The equivalent circular diameter for a noncircular conduit is usually given as the ratio of the cross sectional area to wetted perimeter of the flow channel.
Slot Diameter	$D_H = 0.816(D_o - D_i)$	This was developed analytically by taking the annular gap as a fissure formed by two plane plates. Valid when the ratio of inner to outer pipe diameters is greater than 0.3.
Lamb's Diameter	$D_H = \sqrt{D_o^2 + D_i^2 - \frac{D_o^2 - D_i^2}{\ln\left(\frac{D_o}{D_i}\right)}}$	Proposed by Lamb (1945). It is used to predict friction loss for Newtonian fluids in concentric annular and circular pipe flow. For annular geometries with diameter ratio above 0.3, gives similar results as the slot diameter

Crittendon Diameter	$D_H = \frac{\sqrt[4]{Do^4 - Di^4 - \frac{(Do^2 - Di^2)^2}{\ln(Do/Di)}} + \sqrt{Do^2 - Di^2}}{2}$	Developed by Crittendon (1959) empirically from hundreds of diameter ratios.
Omurlu Diameter	$D_H = \sqrt{Do^2 - Di^2}$	Proposed by Omurlu (2006) based on the area between the outer diameter and inner diameter of the annulus.
Largest Gap	$D_H = \left(\frac{Do}{2} - \frac{Di}{2} \right)$	Used to represent the annulus gap in the concentric annulus setup

3 EXPERIMENTAL SETUP

In order to carry out detailed systematic experimental studies into gas-liquid two-phase flow in horizontal annulus, aimed at better understanding the flow hydraulics in such geometries, experimental test facilities were designed and implemented in the Process Systems Engineering laboratory of Cranfield University. In this chapter, details of the test facilities, procedure and instrumentation utilized for conducting experimental investigations for this study. The annulus test rig has inner diameter of outer pipe (D_o) of 76.8 mm and outer diameter of inner pipe (D_i) of 60.0 mm respectively. The main instrumentation used during this study include conductance probes, point pressure transducers and thermocouple. Detailed description of the instrumentation used and their calibration is provided. Finally, the operation of the test facility and experimental procedure is outlined.

3.1 Description of Experimental Test Facility

A semi closed loop experimental test facility system, where the gas phase used in the test section is vented to the atmosphere and the liquid is recycled continuously is employed. Air and water were the testing fluids employed for this study. The facility is comprised of the fluid supply/metering section, the test section and the fluid return section. The experimental flow loop is constructed using stainless steel pipes, PVC clear, perspex pipe and flexible hose. The total length of the flow loop is 41.32 m. The first part of the flow loop consist of a 2 m long 4" flexible hose which connects the water tank to main test rig. Following on from this section is a 4" stainless steel section 2 m in length which incorporates the fluids mixing point. A reducing flange is used to reduce the 4" stainless steel section to a 3" PVC clear section which is 1 m in length. The annulus test section is then implemented on a 3" PVC section with a total length of 10.8 m. The inner diameter (D_o) of the outer pipe is 0.0768 m and the outer diameter of the inner pipe (D_i) is 0.060 m. The annulus section is followed by a 1 m long 3" section which is then expanded back to the 4" stainless steel section which forms the remaining part of the flow loop. The experimental flow loop is shown in Figure 3-

1 and the items on the flow loop are presented on Table 3-1. The flow loop was designed to operate up to 4 barg.

Table 3-1: Description of Test rig items

Item	Description
VW01, VW04, VW05, VW06, VW07	Ball Valve DN100
VW02, VW03	Ball Valve DN80
Water pump	Model PMC MV90i5 Motor: 9kW Flowrate: 8-40 m ³ /hr Speed: 53 – 265 rpm Discharge pressure: 4 bar
PRV	Pressure Relief Valve set at 4 bar
Water Flow Meter	Endress+Hauser, Promag 50
AIRV01, AIRV02	Manual Gate Valve DN 50 PN20
PT1, PT2, PT3	Pressure Transducer DN15 from 0 to 6 bar
PT312	Pressure Transducer
FT302	Flow Transmitter DN50 from 0 to 150 Sm ³ /hr
FT305	Flow Transmitter DN15 from 100 to 4250 Sm ³ /hr
VC301	Control Valve DN50
VC302	Control Valve DN15
VBPA	Ball Valve DN 50
Air Compressor	Air Compressor Atlas Copco GA 55

3.1.1 Fluid Supply and Metering Section

3.1.1.1 Gas Supply System

Air supply is achieved using a screw compressor manufactured by AtlasCopco® model GA55 with a maximum discharge pressure of 7.5 barg and free air delivery maximum capacity of 638 m³/hr.

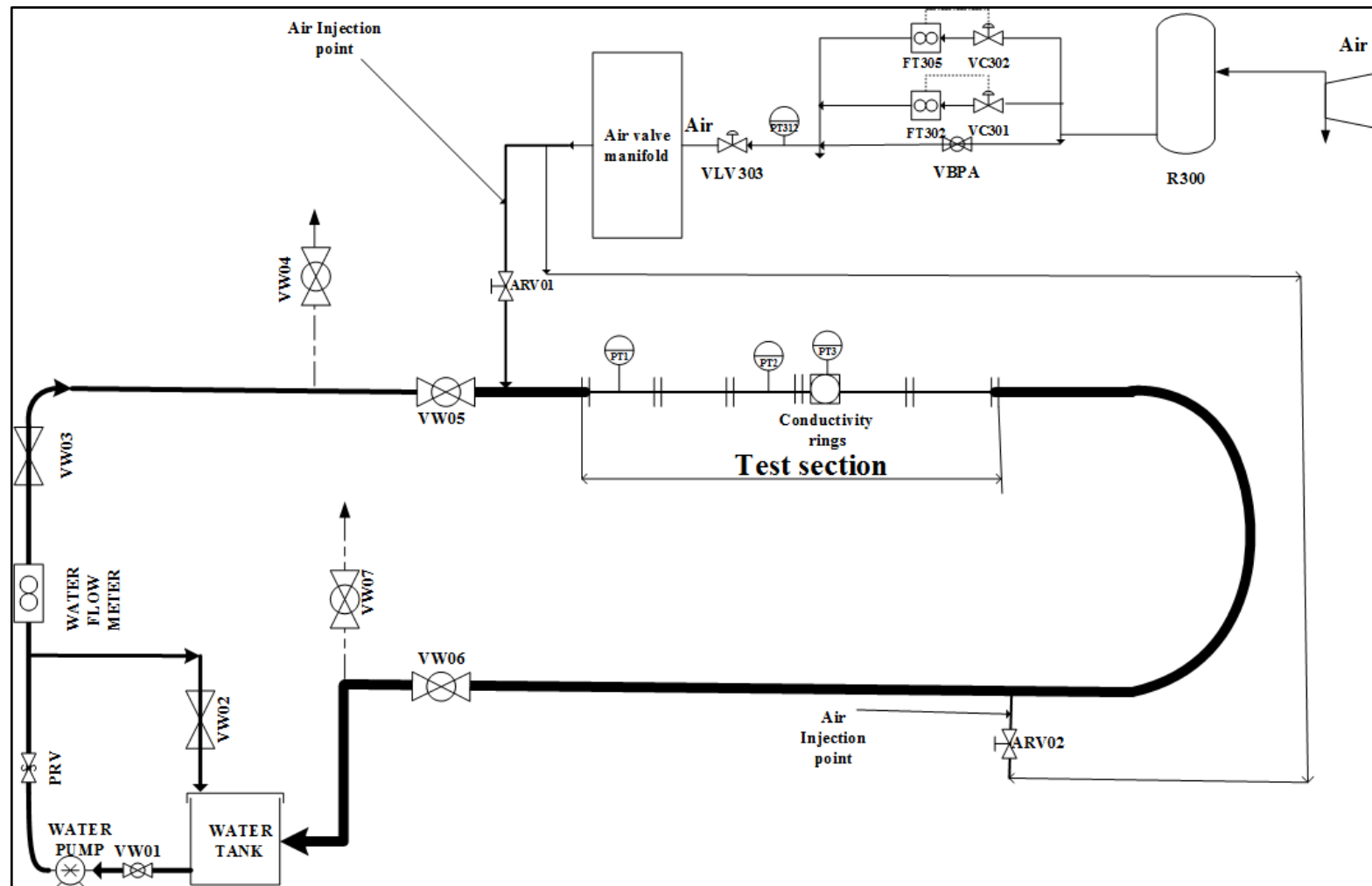


Figure 3-1: Schematic of Experimental Setup

The compressor takes in air from the atmosphere and compresses it before supplying it to the flow loop. Compressed air from the compressor is discharged into an 8 m³ air receiver to prevent pulsating air supply before it is delivered to the test facility. The air goes through three filters, a dryer and then a cooler installed on the compressor supply lines to get rid of any moisture and or debris. This ensures ease and accuracy of flow metering. Two automated valves (namely VC301 & VC302) are used in regulating the air flow rate while measurement is undertaken by one of two Rosemount Mass Probar flow meters (FT302 and FT305) with accuracy of $\pm 1.4\%$. Air flow rates ranging between (0–150) Sm³/h are measured by FT302 while flowrates of air above 150 Sm³/h are measured by FT305. Air is injected into the flow loop via a 2 inch stainless steel pipe at 90° to the horizontal where it mixes with the water at a tee junction of the air entrance before flowing downstream into the test section. Observation/ measurement points are located about 446 pipe diameters from the injection point of the facility. Preliminary experimental observations show this length to be adequate for fully developed flow to be established within the flow variable limits being studied.

3.1.1.2 Water System

Water flow to the flow loop is provided from a water tank with a capacity of 2 m³ using a progressive cavity pump with maximum discharge pressure of 6 barg. It is partitioned into the pump suction section and the fluid return section. The water flow is measured using an Endress & Hauser Promag 50 electromagnetic flow meter ranging between (0 -18) m³/hr, with an accuracy of $\pm 0.5\%$. A 4-20 mA HART output connects the water flow meter to the data acquisition system (DAS) for logging of data during experimental test runs.

3.1.1.3 Annulus Test Section

The annulus test section is formed using two Polyvinyl Chloride (PVC) pipes with the outer pipe having internal diameter of (Do) of 0.0768 m and the inner pipe having outer diameter (Di) of 0.060 m respectively. The hydraulic diameter of the annulus is 0.0168 m and the ratio of the inner pipe diameter to the outer pipe diameter is 0.78. The annulus test section length is 10.8 m in length and the flow observation and measurement points are placed 6.01 m away from the point

where the fluid mixture enters the annulus which gives a length of 357 pipe diameters. The observation point is made from perspex glass and is an important part of instrumentation used during this study. Two different eccentricity positions were investigated during this study. In order to hold the inner pipe inside the outer pipe either concentrically or in a fully eccentric position, eccentricity adjusters were designed and fabricated from PVC rods. The eccentricity of the annulus is adjusted using 4 mm stainless steel pins fed through a single probe element and vacuum sealing assembly in the eccentricity adjuster by moving the pins in or out depending on the eccentricity position desired. With this design, it would be possible to adjust the eccentricity to a myriad of positions, while holding the inner pipe firmly in place and preventing any leaks during experimental runs. In order to reduce vibration effects, the test section was coupled in segments with each segment having approximate length of 2 m. To link the inner pipe of each segment, an inner pipe connector was designed and fabricated using PVC rod and these also served as the points where the eccentricity adaptor pins hold the inner pipe to set the eccentricity. Figure 3-2 and Figure 3-3 show the eccentricity adjuster and the experimental test section respectively.

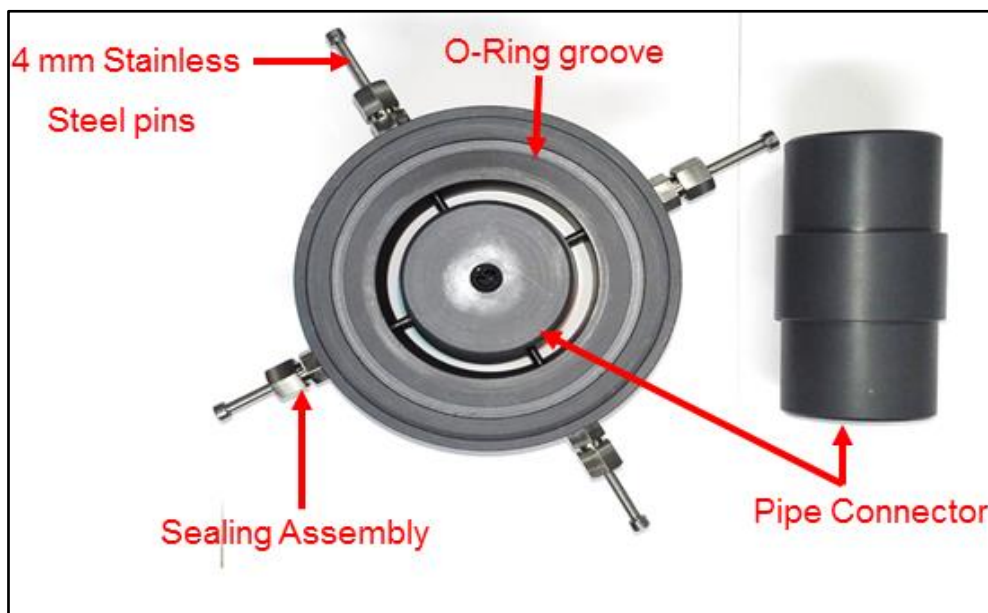


Figure 3-2: Eccentricity Adjuster

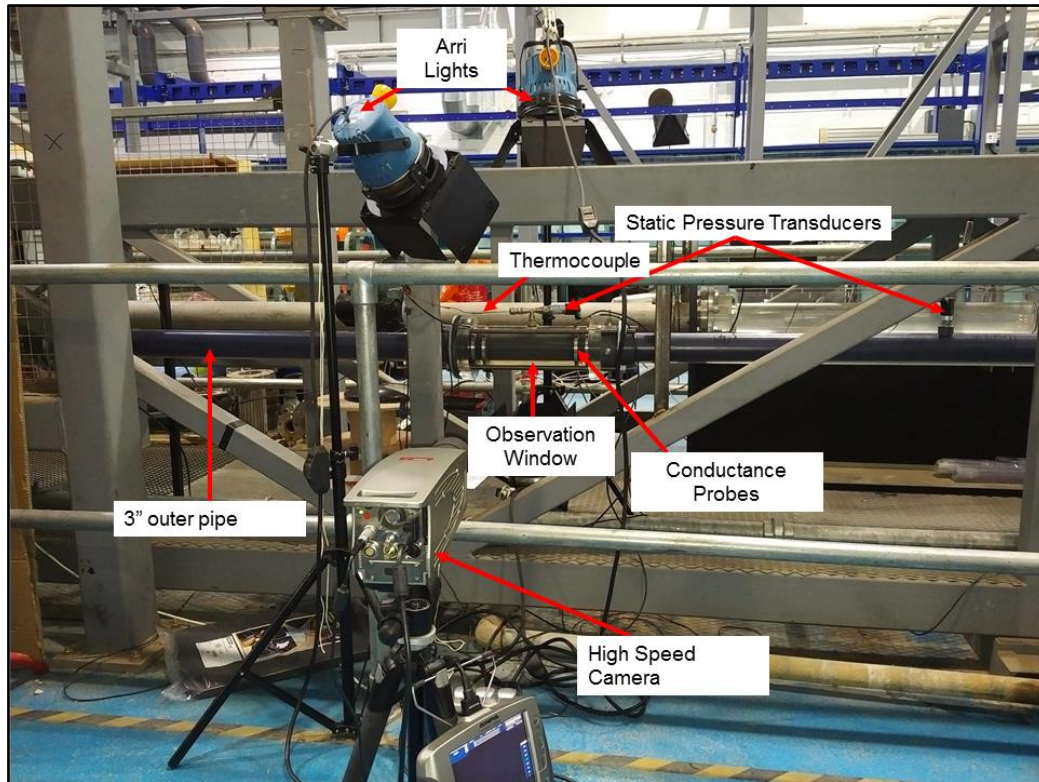


Figure 3-3: The experimental test section

The two annulus eccentricity studied are the concentric annulus and the fully eccentric annulus and the schematic of these annulus are presented on Figure 3-4 below:

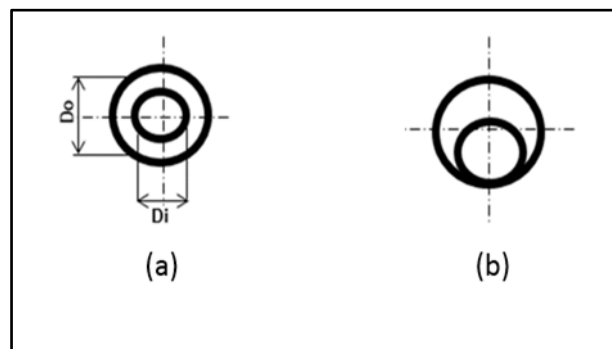


Figure 3-4: Schematic of (a) Concentric annulus (b) Fully Eccentric annulus

3.1.1.4 Fluid Return Section

When the liquid and gas mixture exits the annulus test section, it enters the 3" PVC circular pipe section before being expanded into the 4" stainless steel pipe

section from where it flows to the water tank where the water is stored before being recycled and the gas is vented to the atmosphere.

3.1.2 Instrumentation and Data Acquisition System

Two GE Druck static pressure transducer model PMP 1400, and a WIKA model A-10 static pressure transducer ranging between 0-6 barg and accuracy of $\pm 0.25\%$ of full scale are used to obtain static pressure in the test section. The first, second and third pressure transducers are placed 1.1 m, 4.86 m and 6.01 m away from the last injection point. The distance between the first and last pressure transducer used to determine the pressure drop in the test section is 4.91 m apart. Temperature of the fluid mixture in the test section is measured using a J-type thermocouple with an accuracy of $\pm 2.5^\circ \text{C}$.

Data acquired from the flowmeters, pressure transducers, conductance probes and temperature sensor are saved to a Desktop Computer using a LabView® version 2010 SP1 based system consisting of National Instruments (NI) connector board interface and connected to the instrumentation using coaxial cable.

3.1.2.1 Calibration of Pressure Transducers

Pressure transducers are calibrated in order to ensure accurate performance. The main task during pressure transducer calibration involves determining the relationship between the measured pressure and its conversion into a voltage value. A plot is usually made of the readings taken off the Pressure calibrator of the voltage readings as a function of pressure measurement. The slope and intercept of that plot are used in the Data Acquisition (DAQ) system to set the offset or zero values for any discrepancies from the exact readings. A typical calibration curve for one of the pressure transducers used in this study is as shown in Figure 3-5 overleaf.

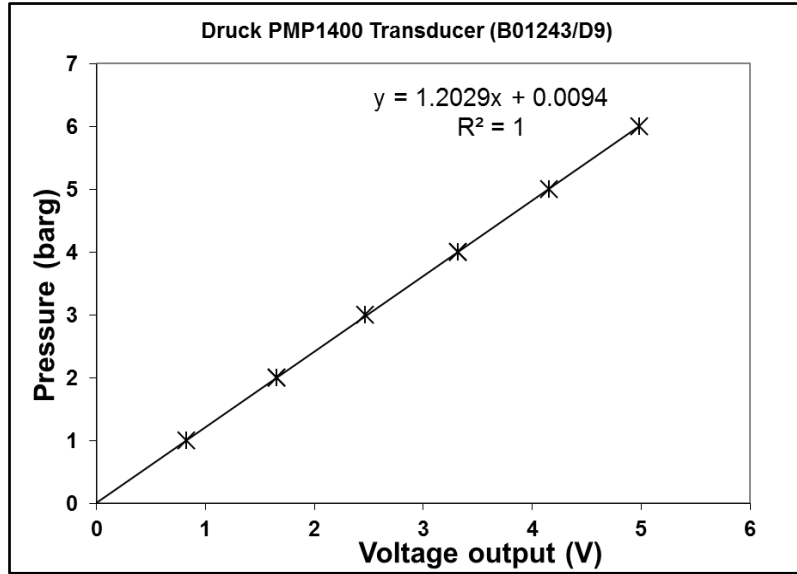


Figure 3-5: Typical calibration curve for pressure transducers

3.1.3 Conductance Probe

Conductance probes are also known as electrical impedance probes and can be used to measure the liquid holdup in a conduit. Also, with statistical analysis, the can be used for slug flow characterization (Fossa et al., 2003).

For this study, two pairs of ring-type electrodes consisting of stainless steel ring electrodes each having a width (S_P) of 6 mm, spacing (D_e) of 26 mm and length between the both electrode pair (L_{AB}) of 270 mm apart are employed for liquid holdup estimation, flow regime identification and slug flow characterization. The conductance probe were designed based on the recommendations of Fossa (1998) and flush mounted onto a 430 mm length of 3" perspex glass which formed part of the annulus test section and served as the visual observation section.

The geometry aspect ratio of the conductance probe (D_e/D) and (S_P/D) were chosen close to values recommended by Fossa (1998) to be 0.34 and 0.078 respectively. A schematic design and pictorial view of the conductance probe section are presented in Figures 3-6 and 3-7 respectively. A detailed drawing of the probe section is presented in Appendix A.

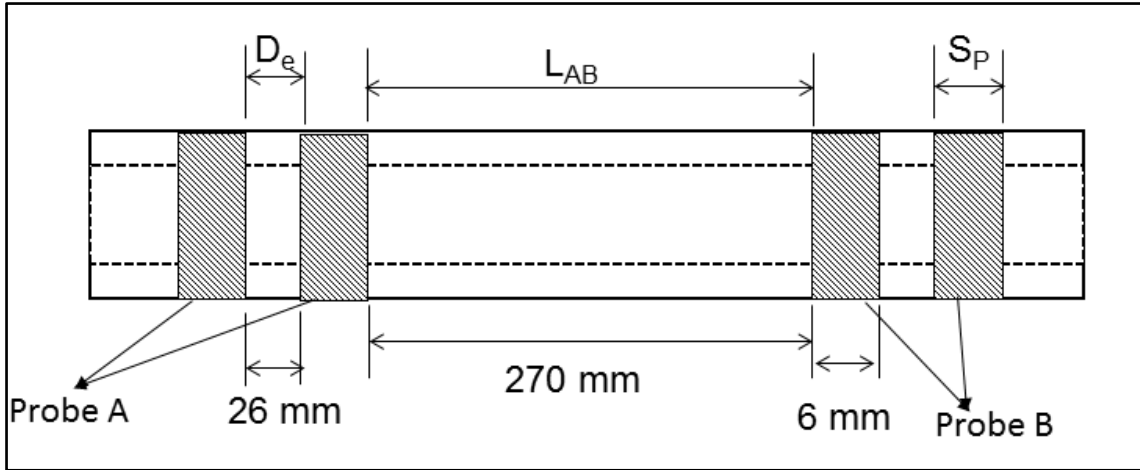


Figure 3-6: Design of Conductance probe



Figure 3-7: Image of conductance probe

3.1.3.1 Calibration of Conductance Probe

The essence of calibrating the conductance probes is so that a relationship is obtained between the liquid holdup in the conduit and the normalised voltage output. This correlation is required to estimate the liquid holdup under experimental test conditions. The conductance probes are calibrated for flow in circular pipe as well as the two annuli (concentric and fully eccentric) setup investigated during this study. The probes were calibrated offline for stratified flow

based on the recommendation of Fan & Yan (2014) by connecting the two pairs of electrode to the Conductivity Electronic Box device. The device supplies 5 kHz and 13 kHz of a.c carrier signal to Probes A and B respectively.

To simulate the gas-liquid phase distribution in the conduits, known volumes of liquid is introduced into the horizontally positioned annulus section. Tap water is used for testing and voltage output (5 V) when the probe was completely filled water is equivalent to 100% liquid holdup in the conduit. On the other hand, the voltage value (0 V) when the pipe is empty (filled with air) corresponds to 0% liquid holdup. The volume of water is added in 10% increments and corresponding voltage values are recorded, after which the process is reversed by reducing the water volume from the conduit and recording the corresponding voltage value. For each probe, a total of 60 measurements were performed to cover the liquid holdup between 0-1. Figure 3-8 shows the setup for calibration of the probes in horizontal annulus.

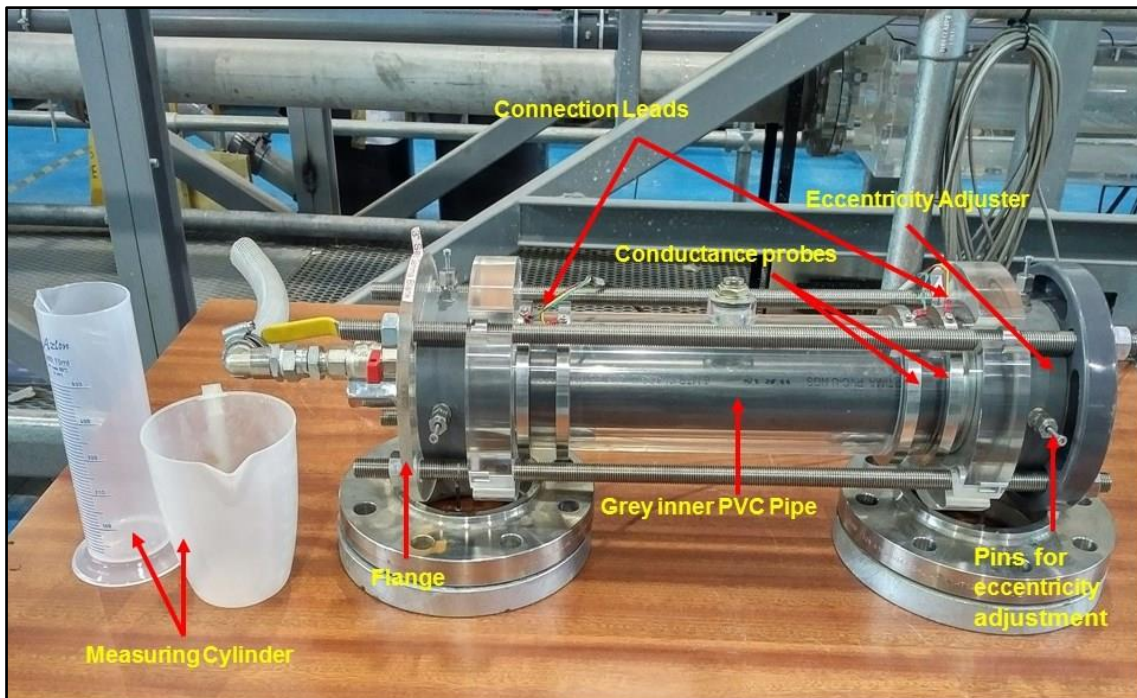


Figure 3-8: Setup for conductance probe calibration in horizontal annulus

A calibration curve was obtained for each probe pair as illustrated in Figures 3-9 to 3-11 for circular pipe, concentric annulus and fully eccentric annulus respectively. To normalise the voltages obtained from the probes, the voltage of

the gas-liquid mixture is subtracted from the voltage value when the conduit is empty divided by the difference between the maximum voltage when the completely filled with water and when it is empty according to Equation 3-1

$$V_{Norm} = \frac{V_{WA} - V_A}{V_W - V_A} \quad (3-1)$$

Where V_{Norm} is normalised voltage, V_{WA} , V_W and V_A are the voltage outputs for water-air mixture, water and air respectively.

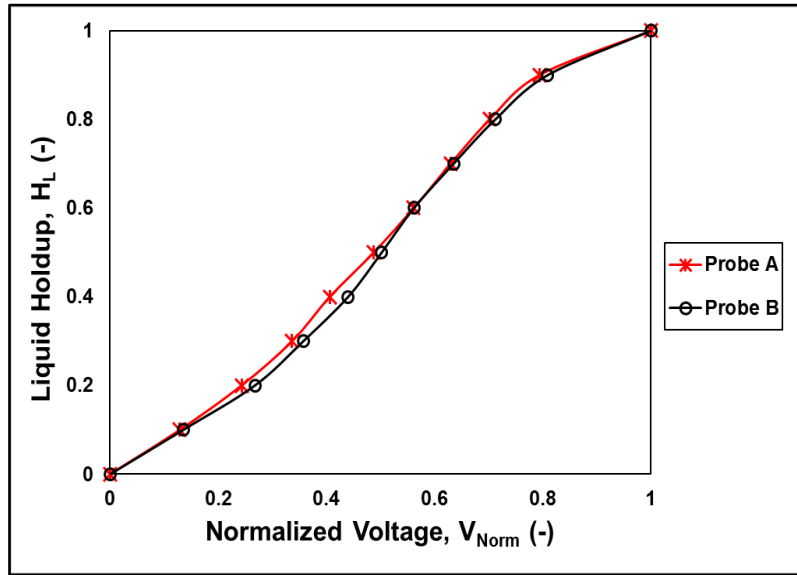


Figure 3-9: Calibration curve for conductance probes in circular pipe

Figure 3-9 shows the relationship between the normalized voltage and the liquid holdup in circular pipes. As expected, the conductivity increases with increase in the liquid phase fraction in the circular pipe while it reduces with increase in gas phase fraction. This shows that the design of the conductance probe used for this study gives similar trends as reported by other investigators and as such can be used to explore conductance in the annular geometry.

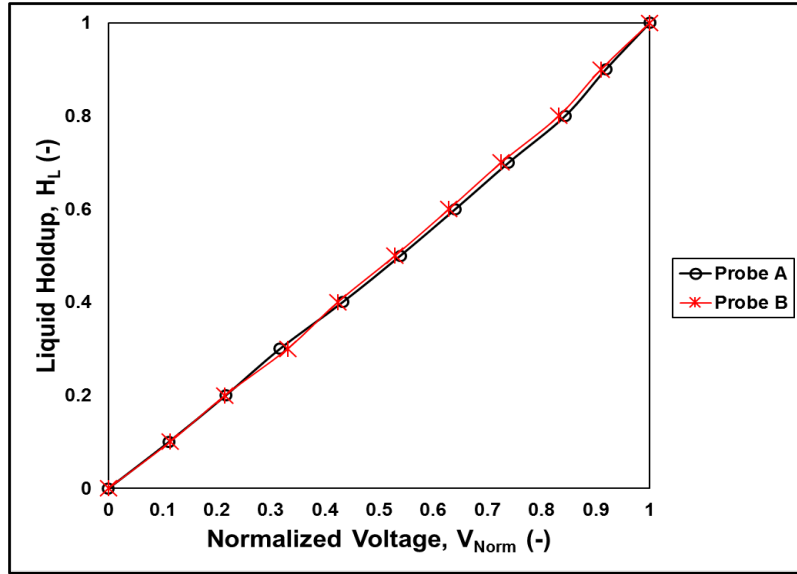


Figure 3-10: Calibration of conductance probe in concentric annulus

The calibration curves for Probes A and B in concentric annulus are given as follows:

$$H_{L(A)} = 0.278V_{Norm}^3 - 0.2794V_{Norm}^2 + 1.0027V_{Norm} - 0.0038 \quad (3-2)$$

$$H_{L(B)} = 0.0798V_{Norm}^3 - 0.0033V_{Norm}^2 + 0.9243V_{Norm} - 0.002 \quad (3-3)$$

The calibration of conductance probe in concentric annulus geometry is presented in Figure 3-10. Repetitive calibration runs for concentric annulus are as shown in Figure 3-11 and the values were found to have a repeatability of 0.72.

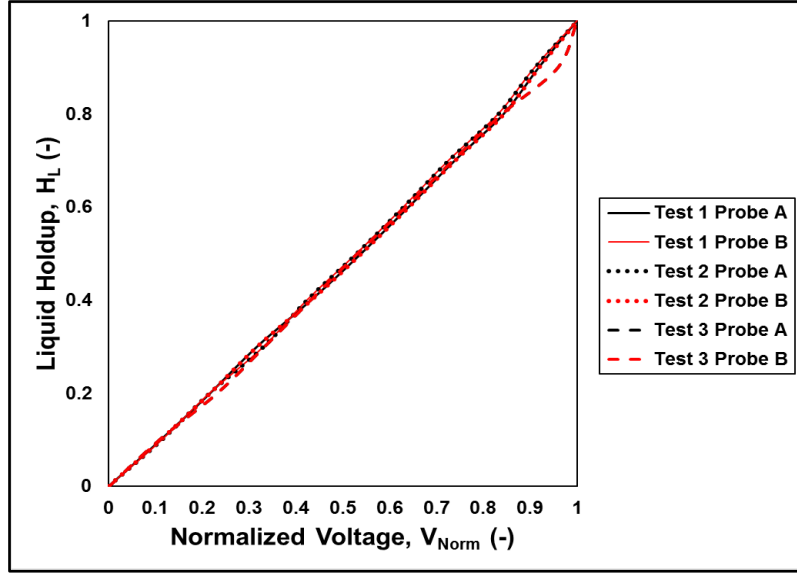


Figure 3-11: Repetitive calibration runs in concentric annulus

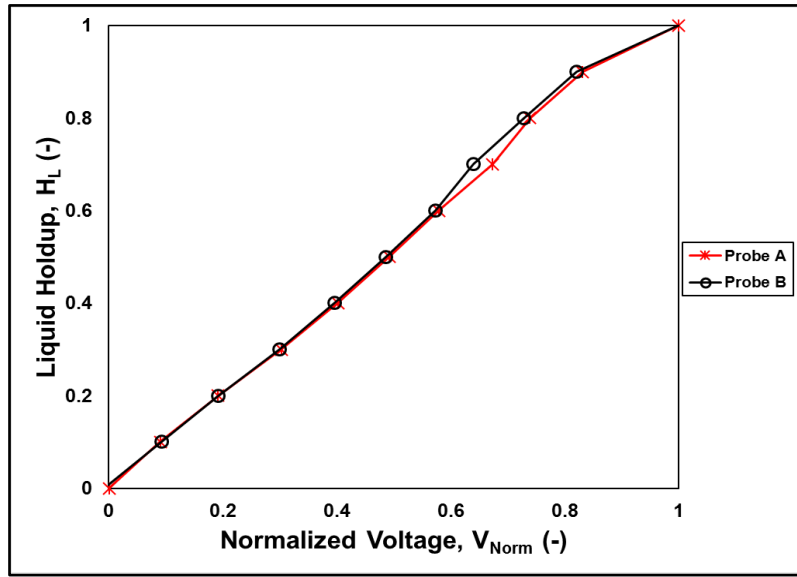


Figure 3-12: Calibration of conductance probe in fully eccentric annulus

The calibration for the fully eccentric annulus is shown in Figure 3-12 while the repetitive calibration runs are shown in Figure 3-13. The repeatability of the probes in fully eccentric annulus was 0.68. Equations 3-4 and 3-5 show the calibration curves for Probe's A and B respectively obtained in the fully eccentric annulus setup.

$$H_{L(A)} = -2.25V_{Norm}^4 + 3.9342V_{Norm}^3 - 1.984V_{Norm}^2 + 1.3027V_{Norm} - 0.0017 \quad (3-4)$$

$$H_{L(B)} = -2.0369V_{Norm}^4 + 3.2379V_{Norm}^3 - 1.3489V_{Norm}^2 + 1.14V_{Norm} + 0.0078 \quad (3-5)$$

As in the case of circular pipe calibration, the conductivity increases with increase in liquid phase fraction while it reduces with an increase in the gas phase fraction. However, it is observed that the calibration curve becomes a lot more linear in annuli than in a circular pipe. This is probably the effect of the inner pipe on the liquid fraction – conductance relationship. The uncertainty in the liquid holdup measurement during the calibration is $\pm 2\%$. As the calibration was carried out on a bench and under stratified flow condition, it is slightly different from actual experimental conditions because the fluids are not static and flow regimes are changing from intermittent to dispersed bubble to annular flows. This means that the uncertainty in liquid holdup estimation using the regression equation could be high. However, the uncertainty could be within the $\pm 10\%$ range because the liquid holdup is averaged.

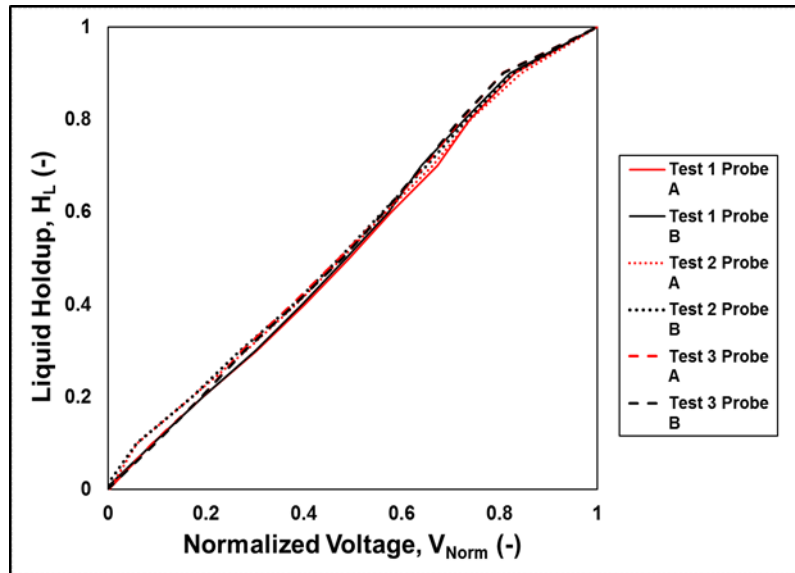


Figure 3-13: Repetative runs for fully eccentric annulus calibration

3.1.4 Testing Fluids

The testing fluids used in the study were water and air. The water was from the public water supply obtained through the Cranfield University water network. It's has viscosity and density values of 0.001 Pa.s and 998.2 Kg/m³ respectively. The gas phase throughout out the experimental campaigns was air. See Table 3-2 below for a summary of the fluid properties.

Table 3-2: Fluid Properties and experimental conditions

Testing Fluid	Density (25°C, Kg/m ³)	Viscosity (Pa.s)	Surface Tension (25° C, N/m)
Water	998.2	0.001	0.0728
Air	1.225	0.00001725	

3.1.5 High Speed Camera

An OLYMPUS model i-SPEED 3 high speed camera was employed for video recording and image capturing of the experimental runs. The images were taken at 1000 frames per second (fps) and adequately lighting was provided using Arrilite 800- Watt lights such that reflections on the test section was minimized.

3.2 Experimental Procedure

The experimental campaigns were carried out on two different annulus setups, a horizontal concentric annulus and horizontal fully eccentric annulus flow facilities. A general procedure for the various multiphase flow studies conducted is presented in this section.

Before any test are conducted on the test rig, data is first obtained from a completely empty test and single phase facilities to ensure that zero errors and noise associated with the instrumentation are eliminated during the data analysis. During the two-phase flow test proper, the water is first fed into the flow loop and the desired flow rate is set adjusting the pump speed and/or using the manual valves installed on the flow loop for that purpose. After the desired flow rate of the water has been achieved, compressed air is injected subsequently into the

test section using the Emerson Delta-V PID controller implemented in the air supply section via a Tee section connecting the top of the flow loop. Both fluids mix in a 4-inch section of the flow loop initially before entering the 3-inch circular pipe section and then finally the annulus section where mixing and flow development takes place along the annulus with varying flow parameters and flow regimes depending on the flow conditions.

The flow is allowed a minimum time of five minutes for stability before data is logged. A total of 180 seconds of data is logged for each flow condition using LabView® at a sampling frequency of 100 Hz. The high speed camera is used then to record videos at 1000 fps for a total of 60 seconds. Similarly, data from the conductance probes are logged using the same sampling frequency recorded above.

For each experimental run, the gas volumetric flowrate is held constant and the liquid flowrate is increased at intervals of $0.0005 \text{ m}^3/\text{s}$. This is repeated until the entire range of flowrates is covered. The range of experimental superficial velocities of water and air investigated during this study range between $0.15 - 2.78 \text{ m/s}$ and $0.16 - 24 \text{ m/s}$ respectively.

3.3 Summary of Measurement Uncertainties

Measurements are usually not exact and could be subject to uncertainties as a result of random effects including temperature, etc. Instrument errors, measurement procedure and operator skill are other factors which could affect the results obtained from measurements. It is however expected that a measurement be reliable to within a certain level of the measured variable when repeated. The uncertainty is defined as that parameter related to the calibration or test result whose range could reasonably be attributed to the measured quantity. Table 3-3 presents the uncertainty of each of the instruments used during this study. A detailed uncertainty estimation of experimental variables measured during this study are presented in Appendix B2.

Table 3-3: Uncertainty of instruments

Instrument	Parameter	Uncertainty/Errors
Electromagnetic flow meter	Water flow rate	$\pm 0.5\%$ of full scale
Rosemount mass probar flow meters	Air flow rate	$\pm 1.4\%$ of full scale
Pressure transducers	Annulus pressure	$\pm 0.25\%$ of full scale
J- type thermocouple	Mixture temperature	$\pm 2.5^\circ \text{C}$
Conductance Probe	Annulus liquid holdup	$\pm 2\%$ based on bench calibration

3.4 Chapter Summary

In this chapter, a detailed description of the experimental facility is presented. The test section design and implementation is described as well as the instrumentation employed for investigating gas-liquid flow parameters. The calibration of instrumentation is also described in detail and a general experimental procedure is presented. However, each chapter will detail the actually techniques used for two-phase flow parameter studies.

4 FLOW REGIMES AND THEIR IDENTIFICATION

Chapter Highlights

- A new flow regime is classified in this study as wavy slug flow. It is characterized as such because it is observed to have different features than the conventionally observed slug or wavy flow regimes.
- The annulus eccentricity is observed to affect the observed flow regimes at low air and lowest water superficial velocities investigated in this study; where elongated bubble flow is encountered in the concentric annulus while slug flow is observed in the fully eccentric annulus.
- The bubble shape observed in the elongated bubble flow regime and the liquid film height during the wavy annular and annular flow regimes are affected by annulus eccentricity, visually observed difference were also confirmed from statistical PDF trends.
- The flow regime transitions observed to take place at higher liquid superficial velocities and lower gas superficial velocities in the fully eccentric annulus when compared to the concentric one.
- A flow regime transition criteria is proposed which can be used successfully to determine two-phase flow regimes in horizontal annuli.
- An Objective/Real time flow regime identification technique is proposed using Support Vector Machine and conductance probe data.

4.1 Overview

Multiphase flow modelling relies on determination of the topology or distribution of the phases and the interface geometry which are not usually known beforehand. The accurate determination of the flow regimes in conduits is one of the major challenges facing two-phase flow modelling. Design parameters including pressure drop and heat transfer etc. depend on the gas phase distribution in conduits and without a knowledge of the flow regimes, these parameters would not be computed accurately (Yadigaroglu, et al., 2018).

This chapter presents results of experiments carried out to investigate the flow regimes observed during gas-liquid two-phase flow in horizontal concentric and

fully eccentric annuli. The experimental setup are as described in Chapter 3. Testing fluids were air and water and qualitative flow regime identification was achieved using visual observation based on high speed camera recordings and images, together with the time series plots and Probability Density Function (PDF) plots of mean liquid holdup measured using conductance probes. Obtained flow regime maps are compared with maps developed for gas-liquid flow in circular pipe and horizontal annulus. The effect of annulus eccentricity on flow regimes and their transitions is also studied and flow regime transition parameters covering a wider range of flow, fluid and conduit properties than previously reported are proposed based on over 1000 data points integrated from experimental studies and literature. Finally, an objective real-time flow regime identification technique using conductance probe data and Support Vector Machine (SVM) has been developed as a part of this study. The accurate identification of gas liquid two-phase flow regimes provides a basis for understanding the flow hydraulics. This is because flow properties including the pressure drop, liquid holdup as well as the system stability are influenced greatly by the regimes and this determines the modelling approach employed. Therefore, this chapter is very important in this study.

4.2 Flow Regimes in Concentric Annulus

During multiphase flow, the variation in the physical distribution of the phases in the flow conduit is the most distinguishing aspect. This distribution is known as flow regimes. These depend on the relative magnitudes of the forces acting on the fluids. The forces include turbulence, inertia, buoyancy and surface-tension forces, which all vary significantly with pipe diameter, flow rates, geometry, inclination angle and fluid properties of the phases. Also the flow regimes can be affected significantly by mass and momentum transfer between the phases and the solid boundaries of the flow channel geometry. As a result, the flow mechanism and hydrodynamics change greatly from one flow regime to the other.

4.2.1 Test Matrix

Over 300 experiments were conducted for air-water two-phase flow in horizontal concentric and fully eccentric annulus with hydraulic diameter $D_H = 0.0168$ m.

The superficial water and air velocity ranged between 0.15 – 2.78 m/s and 0.14 – 24 m/s respectively.

4.2.2 Flow Characterization

The design and optimal operation of multiphase flow processes and equipment requires adequate knowledge of existing flow regimes in the system during operations. This is because most process control issues as well as flow assurance are linked with this knowledge. This section gives a detailed results and discussions of flow regime identification based on high speed camera analysis.

Visual observation and analysis of high speed camera recordings for each test conditions were undertaken and flow regimes were identified in the air-water two-phase flow in concentric horizontal annulus. They include dispersed bubble, elongated bubble, slug, wavy slug, churn, wavy annular and annular flow regimes. The stratified flow region was not observed during this study because the minimum liquid superficial velocity V_{SL} investigated was 0.15 m/s which is higher than the value below which complete stratification would occur. It was impossible to operate at lower V_{SL} because of the limitation of the accuracy of flow meter used. Each flow movie was analysed in slow motion using the high speed camera software to characterize each flow regime. Generally speaking, the flow regimes observed in horizontal concentric annulus were similar to those observed for gas-liquid two-phase flow in circular pipes. However some subtle differences are observed due to the presence of the inner pipe in the middle of the outer circular pipe which interferes with how both phases are distributed in conduit. For presenting the flow regimes in figures to follow, the superficial gas velocities of the depicted annulus were computed by using the measured pressure obtained at the centre of the measurement section of the test rig where the flow regimes were photographed. A photographic representation of the flow regimes obtained are as presented in Table 4-1 and a brief description of the flow regimes are presented below:

Dispersed Bubble Flow: observed at the lowest gas superficial velocity studied and high liquid superficial velocity, the dispersed bubble flow regime consists of

a continuous liquid phase which has discrete gas phase bubbles dispersed in it. Initially, the gas bubbles are dispersed near the top of the concentric annulus but become uniformly dispersed throughout the annulus cross section as the liquid superficial velocity is increased. The mechanism for the formation of this flow regime is the breakdown of gas plugs during the elongated bubble or slug flow regimes.

Elongated Bubble Flow: It is the limit case of slug flow and is observed at the lowest gas superficial velocity investigated in the study. It consisted of two units; a region of film where both phases are flowing together with the gas phase trapped as a flat worm shaped bubble close to the top of the annulus in the denser liquid phase flowing below it. The second unit is a liquid slug body with no noticeable gas bubbles entrained in it. At low liquid superficial velocities, the bubble shape is slim and long but becomes larger and appears more frequently with increased liquid superficial velocity.

Slug Flow: This regime is similar to the elongated bubble flow but occurs at higher gas superficial velocities. Initially preceded by a stratified smooth or wavy interface depending on the superficial gas velocity. This stratified system is followed by faster and shorter moving liquid body with higher energy intensity than those observed in elongated bubble flow. The liquid body wraps itself around the inner pipe of the annulus and contains entrained gases flowing close to the annulus top. This is as a results of increased flow turbulence and decrease in liquid holdup of flow.

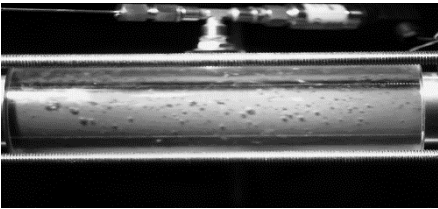
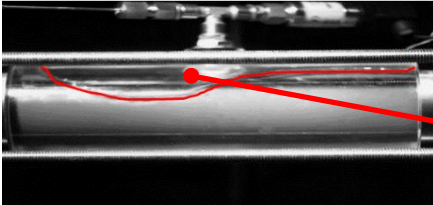
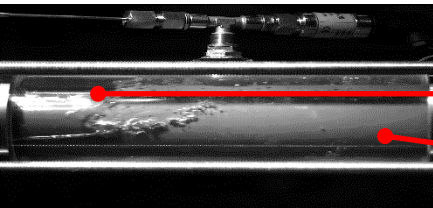
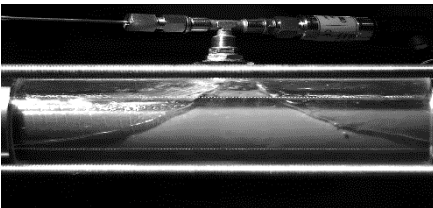
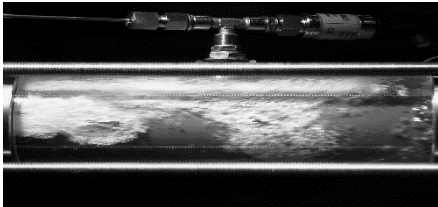
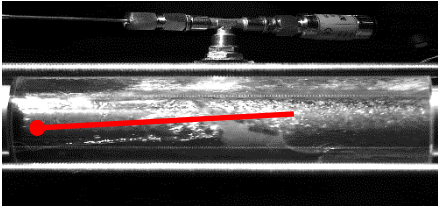
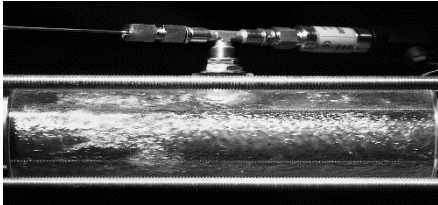
Wavy Slug Flow: This flow regime was classified as such for this study and is similar to what was observed by Nossen et al.,(2017) and classified as large wave flow. It is observed at higher gas superficial velocities than those for slug flow and is probably induced by the annulus geometry. It has a long liquid film region during wave development followed by a small wave shaped liquid body which briefly bridges the top of the annulus after which it seems to lose energy and is pushed away by the following wave. Entrained gases are present in the small liquid body at higher liquid superficial velocities. It has some of the features of slug flow but possesses its own unique feature to be classified as a flow regime.

Churn Flow: The churn flow regime is similar to the slug flow regime but is characterized by a chaotic liquid phase containing a large amount of entrained bubbles travelling with an oscillatory motion. No clear boundaries can be observed for both phases. The mechanism of this regime is an increase in the gas void fraction resulting in the breakdown of the continuous nature of the liquid body that follows each successive Taylor bubble. This causes a collapse of the slug which falls back and is mingled with the one following. It has been confirmed in the past from experimental studies that the churn flow regime could not exist in horizontal or shallow inclined two-phase flow. In vertical upward flows, people use “churn flow” to describe an intermediate region between slug and annular flows in the flow regime map (Hewitt and Jayan, 1993). Similar to this, churn flow observed in the annulus also sits between the slug and annular flow regimes and is induced by the annulus geometry.

Wavy Annular Flow: The wavy annular flow regime in concentric annulus occurs at low liquid and high gas superficial velocities. The liquid holdup in the annulus is inadequate to form a liquid body capable of bridging the gas phase at the top section of the annulus. This results in some of the liquid being swept up to the top of the annulus forming a thin liquid film while a thick liquid layer is observed at the bottom with a wavy interface. The gas phase travels in the annulus core. The thickness of the liquid layer is dependent flowrates of the gas and liquid phases.

Annular Flow: At higher gas superficial velocities than for wavy annular flow the annular flow regime is encountered. A smooth liquid film is observed at the top and bottom of the annulus and are thinner when compared with those of the wavy annular flow. A pictorial representation of the flow regimes are as presented in Table 4-1 overleaf.

Table 4-1 Representative Flow regimes in horizontal concentric annulus

Dispersed Bubble flow		
Elongated Bubble flow		Gas pocket
Slug flow		Film Region Slug Body
Wavy Slug flow		
Churn flow		
Wavy Annular flow		Ripple Waves
Annular flow		

4.2.3 Flow Regime Map

Flow regimes are typically displayed on two-dimensional maps showing the transition boundaries between each flow regime. Selection of appropriate coordinates to clearly display the different flow regimes have been researched extensively. Gas and liquid superficial velocities have been used frequently as dimensional coordinates in practice and has been selected also for use in this study. From experiments conducted in horizontal concentric annulus, a flow regime map was constructed with abscissa and ordinate as the gas and liquid superficial velocities respectively. The elongated bubble flow is first encountered at lowest gas and liquid superficial velocities investigated. The transition to dispersed bubble flow takes place at V_{sl} of 1.2 m/s, while the transition to slug flow regime occurs at V_{sg} of 0.4 m/s. Bubble to slug flow transition is observed at V_{sg} of 0.4 m/s. Transition from slug to wavy slug flow regimes takes place at V_{sg} of 3.7 m/s while slug to churn transition occurs at similar V_{sg} as observed for wavy slug but at V_{sl} of 0.7 m/s. Churn to wavy annular flow regime transition is observed at V_{sl} and V_{sg} of 0.8 m/s and 6 m/s respectively. While the transition from wavy slug to wavy annular occurs at V_{sl} lower than 0.8 m/s. Finally, the transition to annular flow regime occurs at V_{sg} of 9.1 m/s. The experimental flow regime map is as presented in Fig. 4-1.

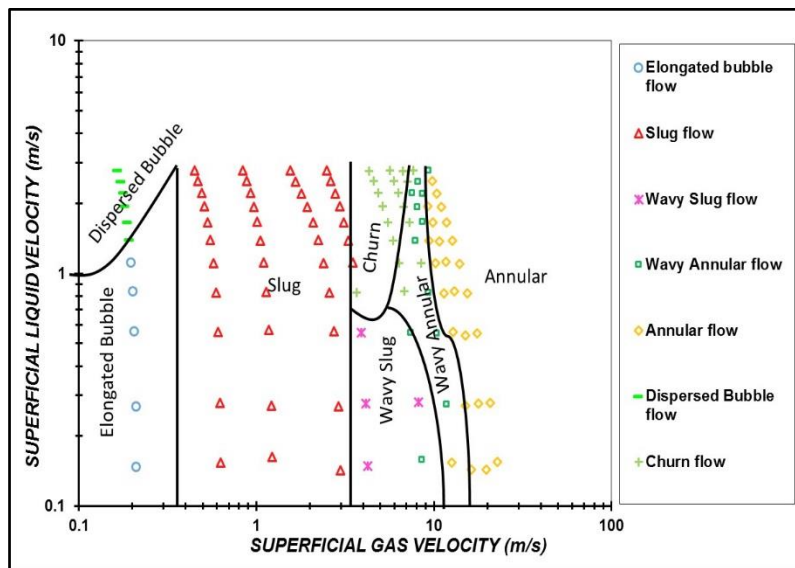


Figure 4-1: Flow regime map for horizontal concentric annulus

4.2.4 Comparison of Flow Regime Maps in Literature with Experimental Map

The experimentally obtained flow regime map is compared with four flow maps from literature. These are the flow maps of Beggs & Brill (1973), Mandhane et al.(1974),Taitel and Dukler (1976) and Osgouei (2010). The first three were developed for gas-liquid two-phase flow circular pipe, and have been selected for comparison because they were developed over a wide range of experimental data, have diameters similar or close to the hydraulic diameter of the annuli investigated during this study or have wide industrial and academic acceptance. The diameter of the circular pipe used by Taitel and Dukler (1976) was 0.025 m which is slightly bigger than the hydraulic diameter of the annuli of this study, 0.0168 m. Also, it was necessary to draw attention to the fact that due to differences in geometry, the approach of using two-phase flow models developed for circular pipes for annulus geometry might be insufficient. The last map was developed for gas-liquid flow in horizontal concentric annular channels. The Beggs and Brill map has been adapted for concentric annulus by introducing the hydraulic diameter concept into the transition models specified by the researchers, while the other maps have been digitally extracted and constructed on the maps as shown in Fig's. 4-2 to 4-5

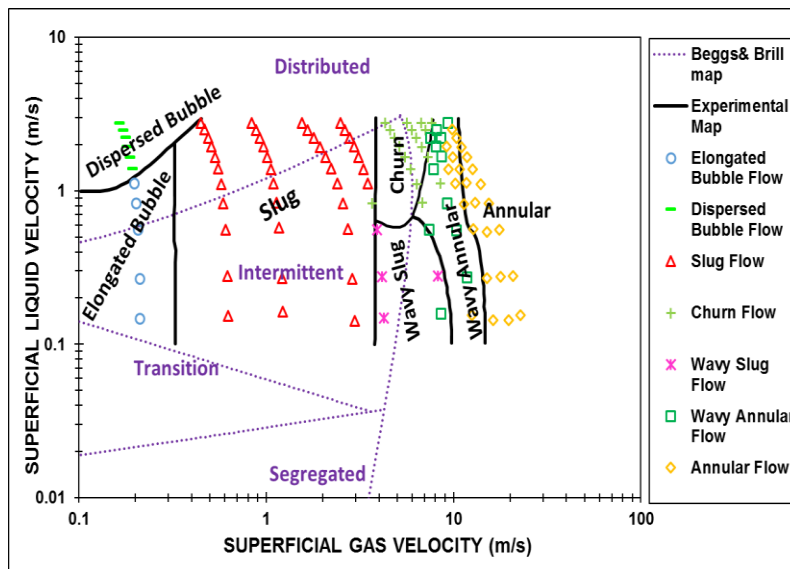


Figure 4-2: Comparison of experimental flow regime map in horizontal concentric annulus with Beggs & Brill (1973), (b) Mandhane et al., (1974), (c) Taitel & Dukler (1976) and Osgouei (2010) flow regime maps.

The comparison of experimental observations and the Beggs & Brill flow regime map show huge discrepancies in the transition boundaries of the different encountered flow regimes. For example the transition from intermittent to distributed flow regime occurs at lower liquid superficial velocities in the Beggs and Brill map when compared to the map obtained for horizontal concentric annulus.

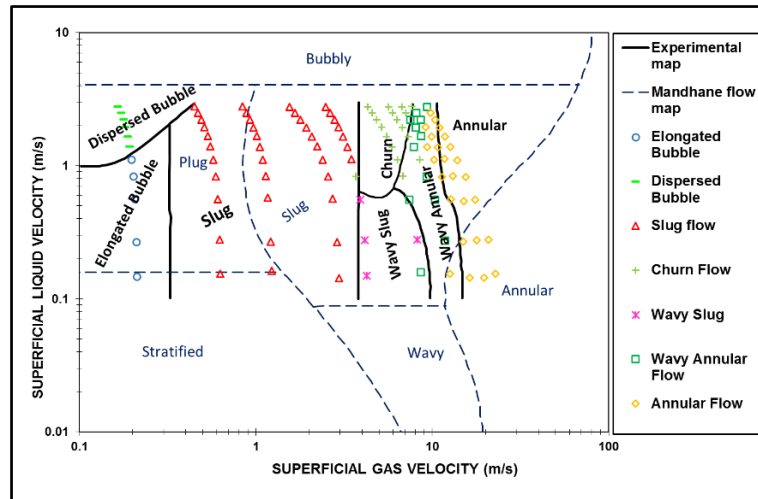


Figure 4-3: Comparison of experimental flow regime map in horizontal concentric annulus with Mandhane et al. (1974)

The Mandhane et al., (1974) flow regime map was formulated from 5,935 data points for horizontal two-phase in circular pipe flow regimes for a wide range of physical properties. It is the most common basis for flow regimes transitions in horizontal pipes. Similarly, this flow regime map disagreed substantially with experimental regime transitions of this study as can be observed in Fig. 4-3.

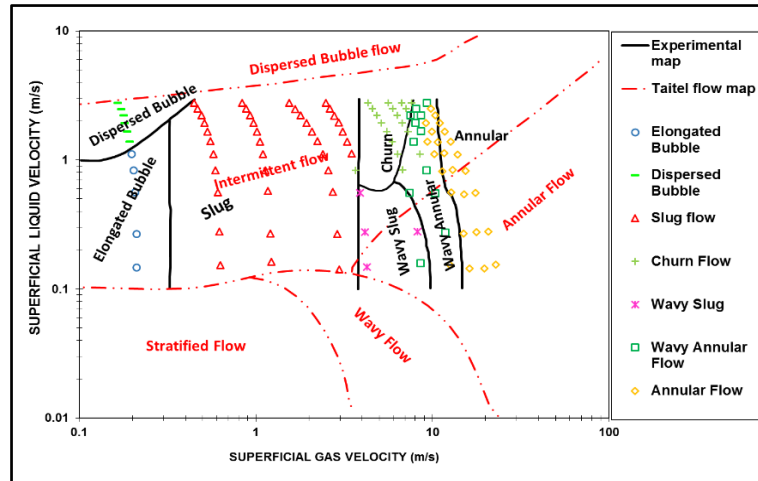


Figure 4-4: Comparison of experimental flow regime map in horizontal concentric annulus with Taitel & Dukler (1976)

Comparison with the Taitel & Dukler (1976) flow regime map is as presented in Fig. 4-4. The map was developed based on the physical concepts of the transition mechanisms for steady flow. The transition criterion provided by this map also show marked difference with observed experimental flow regime map. It can be observed from these comparisons, that the transition criteria provided by the work of Beggs & Brill (1973), Mandhane et al., (1974) and Taitel & Dukler (1976) did not account for the geometry effect of the setup employed in this study because they were developed mainly for flow in pipes. It is possible that the effect of gravity in the annulus setup is less dominant than in the circular pipes, as a result of the unique geometries of the channel: the gas/liquid separation due to density difference in such a channel is suppressed and this may be the reason for the observed difference in the flow regime maps observed for circular pipes and horizontal annuli respectively.

On the other hand, Osgouei et al., (2010) flow regime map was based on diaggquadratic discriminant analysis to theoretically describe the flow regime transitions and were developed for a horizontal eccentric annulus. Although the geometry on which the flow regime map was developed is similar to the one used in this study, the flow regime transitions do not accurately characterize those observed during experiments in this study. For instance, the transition from elongated bubble to slug flow takes place at lower gas superficial velocity in the

experimental observation than those proposed by the Osgouei map. Similarly, the transition from elongated bubble to dispersed bubble flow takes place at lower liquid superficial velocities than those of Osgouei (2010). It can be seen even a slight difference in diameters as well as the annulus eccentricity results in marked differences in observed flow regime transitions. Therefore, it is necessary to developed flow regime transition criteria that would eliminate the effect of physical properties, geometry and flow properties on transitions observed.

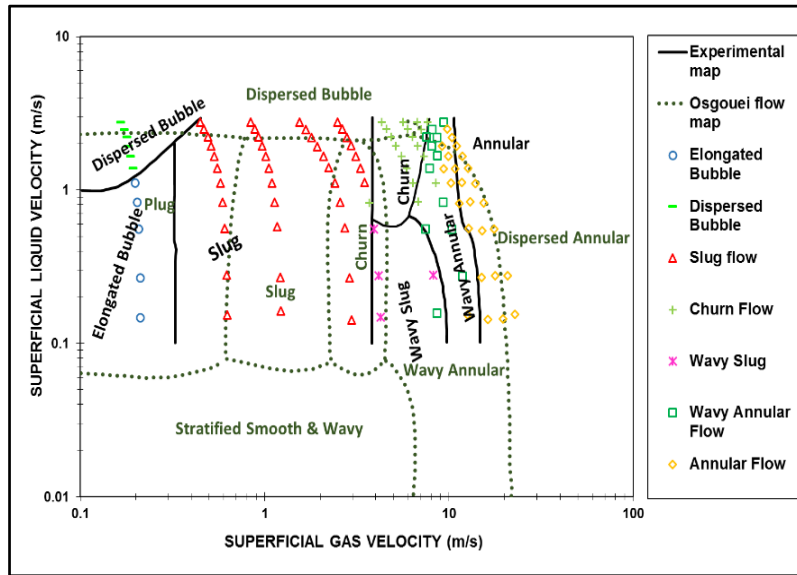


Figure 4-5: Comparison of experimental flow regime map in horizontal concentric annulus with Osgouei (2010) map.

4.3 Flow Regimes in Fully Eccentric Annulus

Flow regimes in horizontal fully eccentric annulus were obtained using the same test matrix and in a similar fashion to those of the horizontal concentric annulus. Table 4-2 shows the photographic representation of the flow regimes observed in this study.

Generally, the flow regimes observed in the horizontal fully eccentric annulus are similar to those in horizontal concentric annulus. However, slight deviations are observed in some of the flow regimes due to the difference in geometry and as a result distribution of phases in the conduit. A description of the flow regimes in fully eccentric annulus is detailed below:

Dispersed Bubble Flow: Observed at high liquid flow rates and low gas flowrates, tiny gas bubbles are dispersed in a continuous liquid phase and concentrated close to the top of the inner pipe of the annulus which is lying at the bottom of the outer pipe. The mechanism for the formation of this flow regime is the breakdown of the gas plugs during the elongated bubble or slug flow regimes. Increasing the liquid superficial velocity results in a more even distribution of the gas bubbles in the annulus cross section.

Elongated Bubble Flow: characterized by alternating liquid body which fills the entire annulus cross section and larger gas plugs than observed in the concentric annulus due to a bigger gap at the top of the annulus for the gas phase to occupy. No discrete gas bubbles are entrained in the liquid body similar to what is observed in the concentric annulus setup.

Slug Flow: The slug flow regime in fully eccentric annulus occurs after an initial period of stratification. A higher liquid level is observed in the eccentric annulus when compared with concentric annulus. Entrained gas bubble are initially observed close the slug front close to the top of the annulus with some tiny bubbles generated at the bottom of pipe. Increasing gas and liquid superficial results in an increase in entrained gas bubbles evenly distributed in the annulus cross section.

Wavy Slug Flow: Initially a wavy stratified interface is observed during the wavy slug flow regime in fully eccentric annulus but with increase in gas superficial velocity, the development of waves on the interface gains sufficient energy just to bridge the top of the annulus and then is dislodged by the liquid film following it.

Churn Flow: The churn flow regime is similar to the slug flow but is characterized by a chaotic liquid phase containing a large amount of entrained bubbles travelling with an oscillatory motion. No clear boundaries can be observed for both phases. The mechanism of this regime is an increase in the gas void fraction resulting in the breakdown of the continuous nature of the liquid body that follows each successive Taylor bubble. This causes a collapse of the slug which falls back and is mingled with the one following.

Wavy Annular Flow: The wavy annular flow observed in eccentric annulus shows a thicker liquid film observed at the bottom of the annulus with a wavy interface and thin one at the top. The inner pipe sitting on the bottom of the outer pipe means the bottom film is moving relatively slower in comparison to the thin film on the top.

Annular Flow: The liquid film observed in the annular flow regime in eccentric annulus to flow around the walls of the annulus. The film is thicker at the bottom of the annulus than on the other sides of the annulus. At increased liquid and gas superficial velocities, the observed liquid film become frothy in nature as they travel on the walls of the annulus.

4.3.1 Flow Regime Map for Fully Eccentric Annulus

A flow regime map was developed for experimentally observed flow regimes in fully eccentric horizontal annulus. The same coordinates used in the concentric setup were employed as well. At the lowest gas and liquid superficial velocities encountered, the slug flow regime is encountered but as the liquid superficial velocity is increased, the flow regime transitions to the elongated bubble flow and finally to dispersed bubble flow. The slug flow region is the most predominant flow regime similar to what was observed with the concentric annulus. It is observed at gas superficial velocity between 0.21 m/s to 3.93m/s due to increased kinetic energy and momentum as gas is entrained in the elongated liquid body of the elongated bubble flow regime. The increased kinetic energy causing turbulence which shortens the elongated liquid body. As the gas superficial velocity is increased above 3.93 m/s, the liquid content in the annulus is reduced causing a liquid height that is insufficient to form a complete slug body rather, a tiny liquid body with just enough energy to bridge the top of the annulus and a long film region which quickly pushes the liquid body away from the top of the pipe. This flow regime is classified as wavy slug flow. A corresponding increase in liquid superficial velocity results in churn flow regime. This regime is observed at liquid superficial velocity above 0.83 m/s and is characterized by chaotic liquid body with a large amount of entrained gases. The liquid body interacts with the inner pipe of the annulus resulting in more chaos and oscillatory motion. As the gas

superficial velocity is increased above 6.70m/s, the gas phase becomes more energized sweeping the liquid content to the top of the annulus geometry resulting in wavy annular flow. There is a thick wavy film interface at the bottom of the annulus with a thinner interface at the top. Further increase of the gas superficial velocity ushers in the annular flow regime due to even higher kinetic energy of the gas phase. This results in the liquid phase being swept up faster to the top of the annulus and a film at the bottom. It can be observed from the map that an increase in liquid superficial velocity which results in an increase in the liquid fraction enhances the slug flow region.

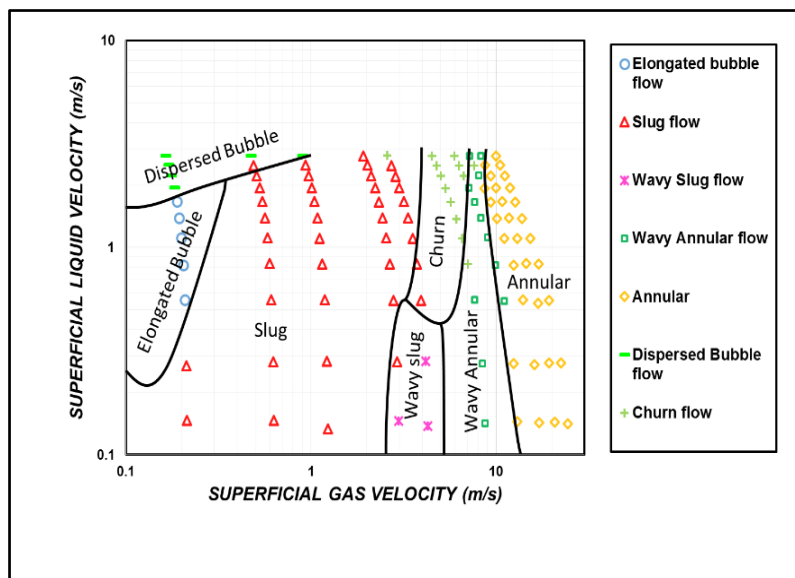
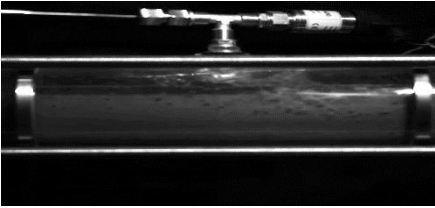
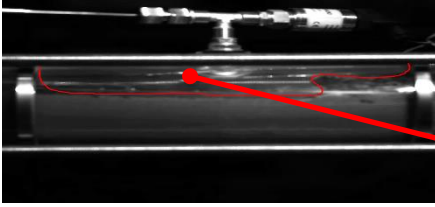
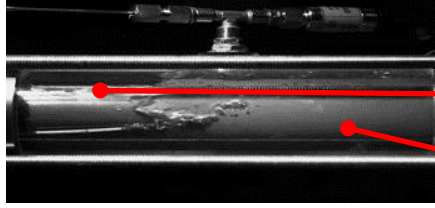
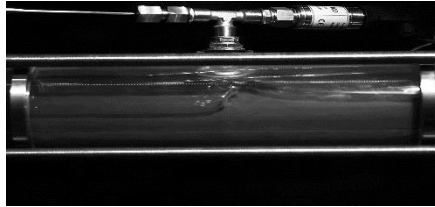
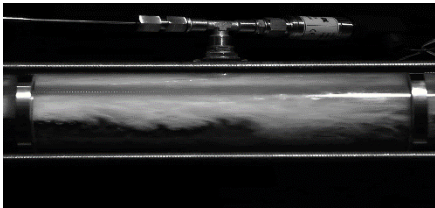
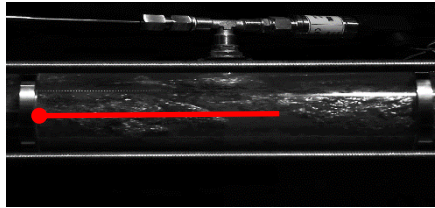
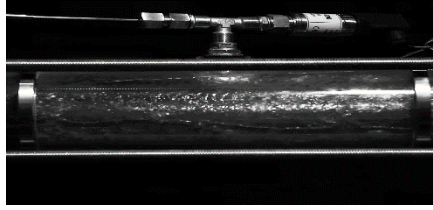


Figure 4-6: Experimental flow map for fully eccentric horizontal annulus

Table 4-2 Representative Flow regimes in horizontal fully eccentric annulus

Dispersed Bubble flow		
Elongated Bubble flow		Gas pocket
Slug flow		Film Region Slug Body
Wavy Slug flow		
Churn flow		
Wavy Annular flow		Ripple Waves

Annular flow



4.3.2 Comparison of Flow Regime Maps in Literature with Experimental Fully Eccentric Map

Fig. 4-7 to 4-10 present comparisons between horizontal flow regime maps in literature and experimental flow regime maps for flow through fully eccentric horizontal annulus. Fig. 4-7 shows the Beggs & Brill (1973) flow regime transition lines when compared with those obtained during this study in a fully eccentric horizontal annulus. A huge difference is observed between the experimental flow regime map and the transitions proposed by Beggs & Brill.

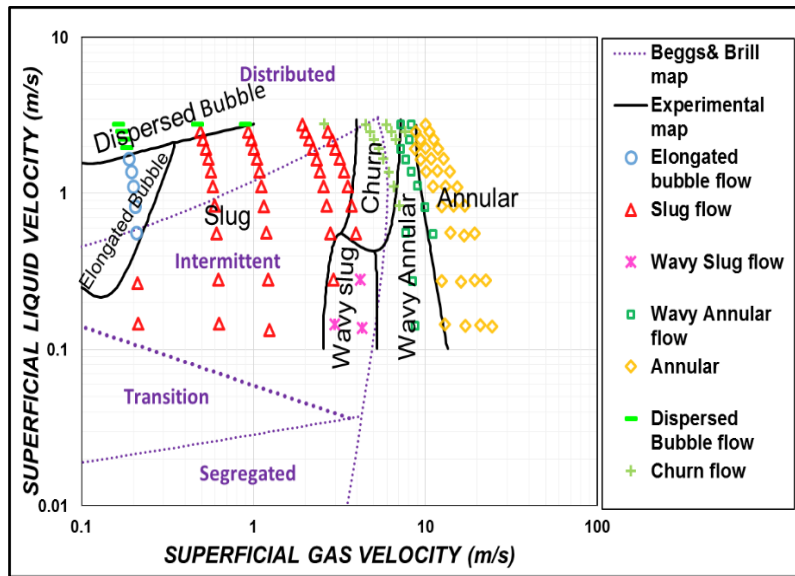


Figure 4-7: Comparison of experimental flow regime map in horizontal fully eccentric annulus with Beggs & Brill (1973) map

Similarly, a look at the comparison between the Mandhane et al., (1974) and the experimental flow regime map as presented in Fig 4-8 shows significant disagreements. Most of the flow regimes encountered in the horizontal fully eccentric annulus fall within the plug and slug flow regime regions of the

Mandhane map, although different flow regimes other than these are observed in this study.

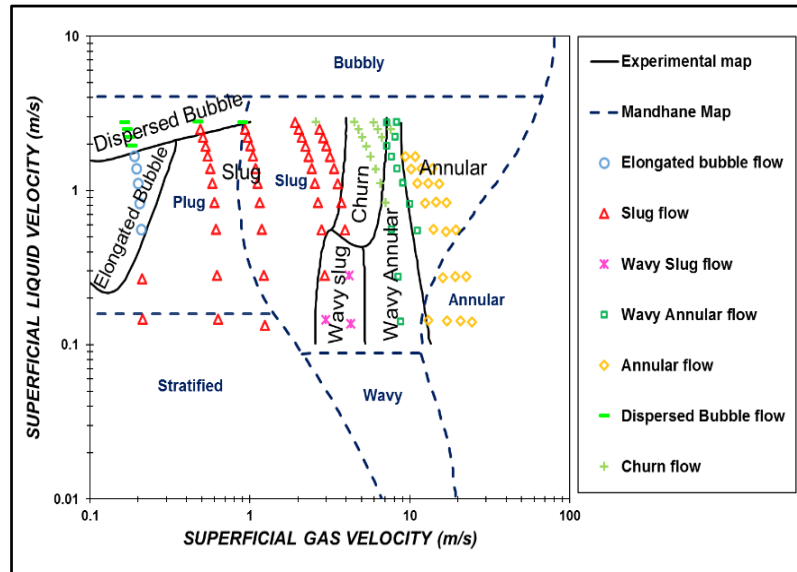


Figure 4-8: Comparison of experimental flow map in horizontal fully eccentric annulus with Mandhane et al., (1974) map

The flow regime transition lines proposed by Taitel & Dukler (1976) as shown in Fig 4-9 also fails to predict correctly the flow regimes observed in this study. The intermittent flow region is predicted correctly although the wavy annular, annular and dispersed bubble flow regimes are all predicted within this region.

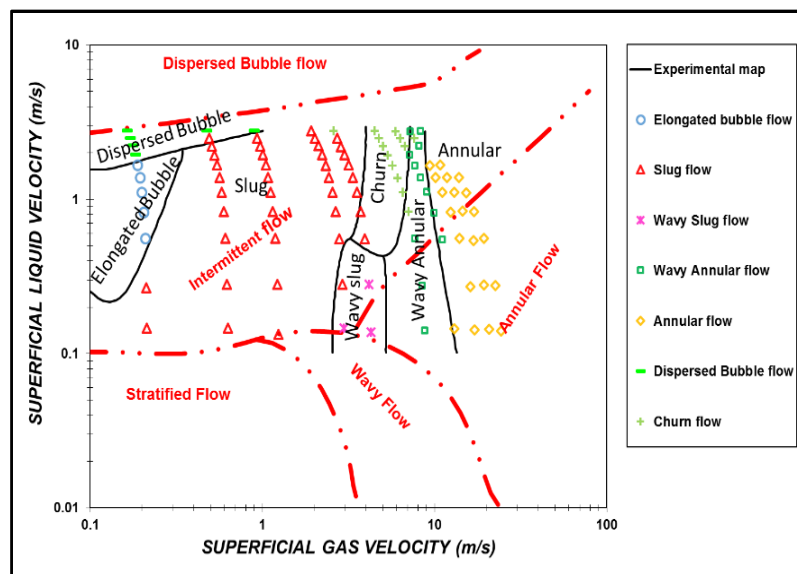


Figure 4-9: Comparison of experimental flow regime map in horizontal fully eccentric annulus with Taitel & Dukler (1976) map

These flow regime transitions proposed by Beggs & Brill (1973), Mandhane et al.,(1974) as well as Taitel & Dukler (1976) were developed as stated earlier for two-phase flow in circular pipes. The discrepancies observed are due to the different geometry studied (in this case fully eccentric annulus).

Fig 4-10 shows the Osgouei et al.,(2010) developed flow regime transition for horizontal eccentric annulus. Some differences are observed when both maps are compared. For instance, the dispersed bubble flow occurs at lower superficial liquid velocity than predicted. Also, the slug region is wider in the experimental prediction than predicted and the churn flow region occurs at higher gas and liquid superficial velocities than predicted by the map of Osgouei et al.,(2010). The only flow regimes that are predicted accurately by the map of Osgouei et al., (2010) are the elongated bubble and wavy annular flow regimes. The experimentally observed annular flow regime falls within the wavy annular flow regime of their prediction. The observed difference may be because the annulus geometry and eccentricity used in developing the flow regime transition are different from those used in this study.

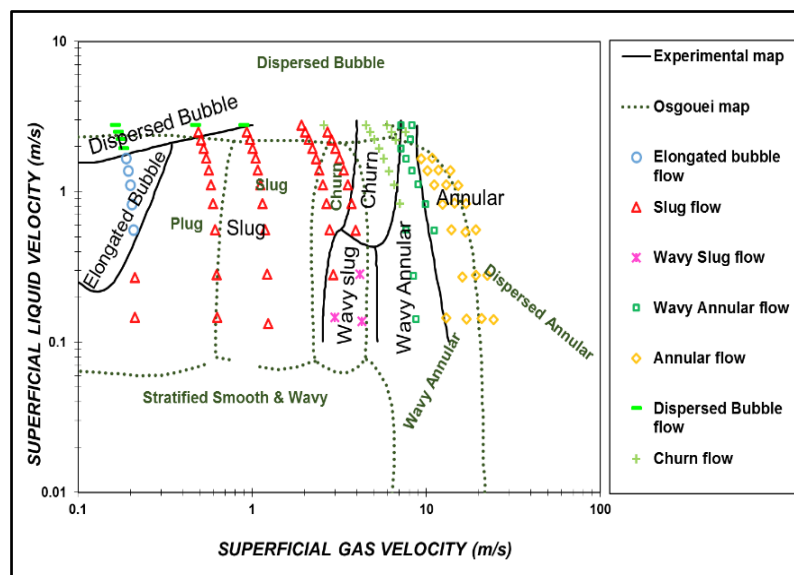


Figure 4-10: Comparison of experimental flow regime map in horizontal fully eccentric map with Osgouei et al.,(2010) map.

It can be seen that flow regime maps developed for two-phase flow in circular pipe and one developed for horizontal eccentric annulus show marked differences when compared with experimentally observed flow regime transitions. This shows the need to develop flow regime transition criteria in horizontal annulus that would be applicable to a wide range of flow geometry, fluid properties and flow properties.

4.4 Effect of Annulus Eccentricity on Flow Regimes and their Transition

4.4.1 Effect of Annulus Eccentricity on Flow Regimes

In this section, the effect of the eccentricity of annulus on the gas liquid two-phase flow regimes is explored. Experiments were carried out in fully eccentric horizontal annulus and compared with those of a concentric horizontal annulus using high speed camera images together with a combination of time series and Probability Density Function (PDF) plots of the liquid holdup obtained from conductance probes. Applications such as underbalanced drilling usually have the annulus eccentricity changing between concentric and eccentric positions as the inner pipe (drill pipe) rotates when the well is drilled. The fully eccentric annulus is formed by the inner pipe lying on the bottom of the outer pipe. This creates a flow geometry shaped like crescent which is different from the geometry of the concentric annulus. The inner structure of the annulus affects the distribution of the phases and as such would influence the flow regimes observed.

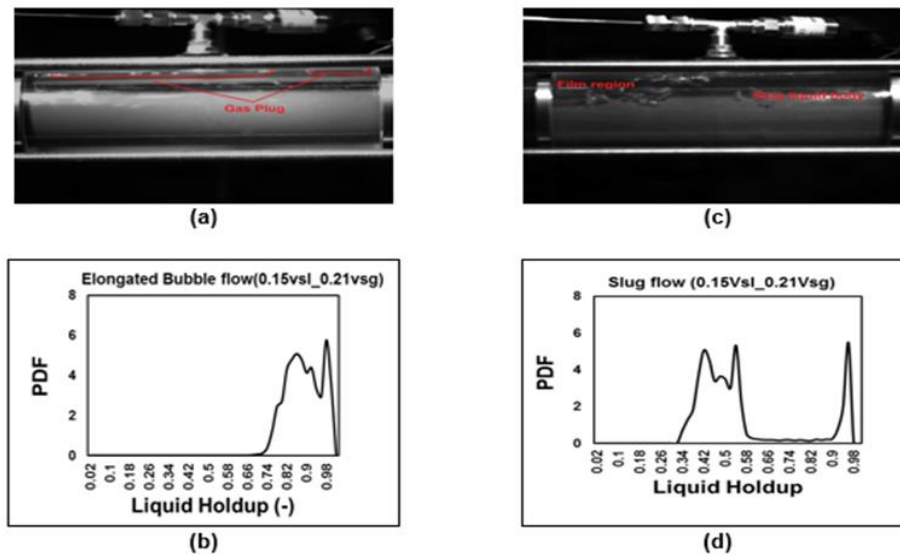


Figure 4-11: Effect of annulus eccentricity on flow regimes ($V_{sl} = 0.15$ m/s; $V_{sg} = 0.21$ m/s) (a) Elongated bubble flow in concentric annulus (b) Elongated bubble flow PDF trend in concentric annulus (c) Slug flow in fully eccentric annulus (d) PDF trend for Slug flow in fully eccentric annulus.

Fig 4-11(a), (b), (c) and (d) show the effect of annulus eccentricity on the flow regimes observed at low gas and the lowest liquid superficial velocities investigated in this study using images and PDF trends for the different annulus configurations. As can be observed when liquid and gas superficial velocities are 0.15 m/s and 0.21 m/s respectively, the elongated bubble flow regime is observed in the concentric annulus while slug flow is observed in the fully eccentric annulus. This is explained by the geometry difference in the fully eccentric annulus. The inner pipe sits at the bottom of and as a result there is a larger flow area at the top of the annulus for the gas phase to occupy. As a result of this, at the flowrates described above the gas phase has sufficient area and energy to sweep the liquid phase to bridge the top of the annulus forming slug flow. In the concentric annulus on the other hand, there is a small gap at the top for the gas phase to occupy and at the low gas and liquid superficial velocities, the gas phase is trapped as an elongated bubble in the liquid slug body.

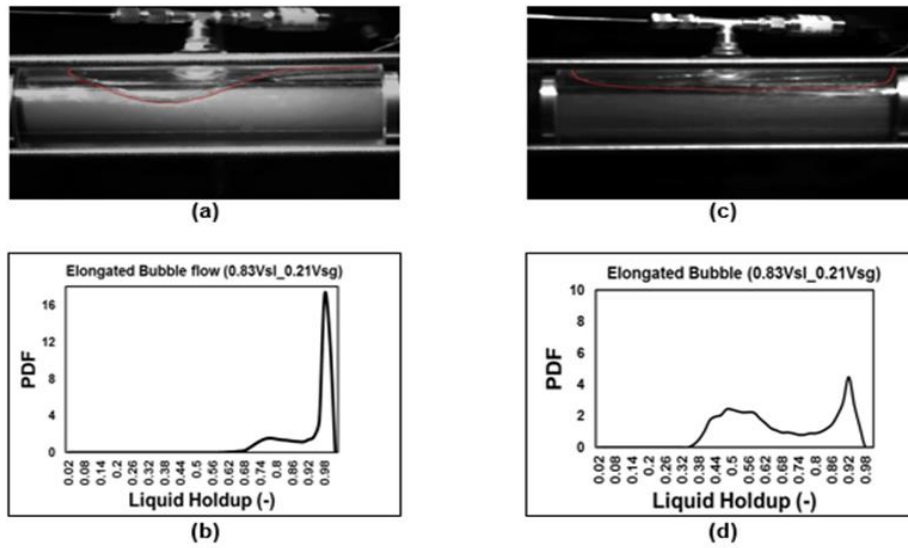


Figure 4-12: Typical elongated bubble flow ($V_{sl} = 0.83$ m/s; $V_{sg} = 0.21$ m/s) (a) concentric annulus (b) PDF trend for concentric annulus (c) fully eccentric annulus (d) PDF trend for fully eccentric annulus

The bubble shape in the elongated bubble flow regime is affected by the eccentricity of the annulus. As can be observed in Fig 4-12(a) the bubble shape in the concentric annulus is shaped as a flat worm and is shorter in length when compared with the shape of the bubble observed in Fig 4-12(c). The PDF trends for both annulus are shown in Fig. 4-12(b) and 4-12(d) for concentric and fully eccentric annulus respectively. The effect of the bubble shape is captured in this trend where for the concentric annulus, the tiny bubble shape and length is reflected in the observed peaks at high liquid holdup values. On the other hand, the PDF trend for the elongated bubble flow regime in fully eccentric annulus captures the large bubble length and size which is reflected in the observed peaks high and lower liquid holdup values. Also, the highest peak in the concentric annulus has a higher PDF value when compared with that of the fully eccentric annulus.

Generally speaking, the slug flow region is largely unaffected by the eccentricity of annulus and is the predominant flow regime in both annulus setups.

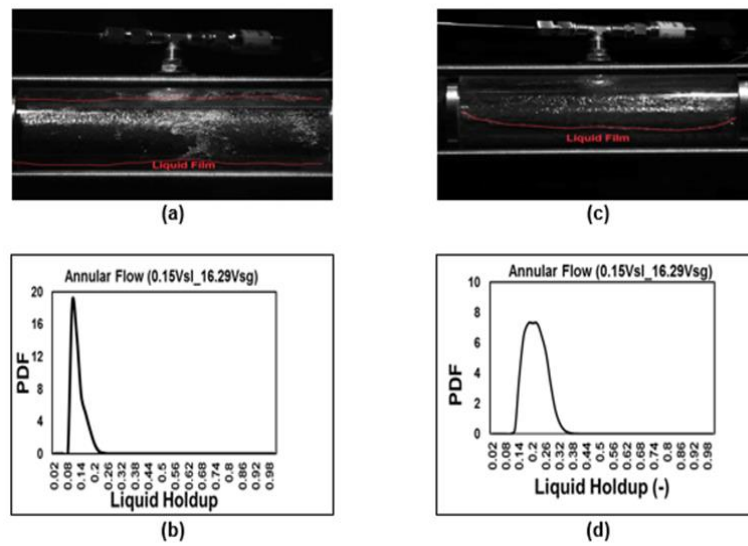


Figure 4-13: Typical annular flow regime ($V_{sl} = 0.15$ m/s; $V_{sg} = 16.29$ m/s) in (a) concentric annulus, (b) PDF trend for concentric annulus (c) fully eccentric annulus (d) PDF trend for fully eccentric annulus

The liquid film height observed in the wavy annular and annular flow regimes are also affected by annulus eccentricity. In Fig.4-13, typical annular flow regime images are presented for both the concentric annulus and the fully eccentric annulus. Fig 4-13(a) shows representative liquid film height in the concentric annulus during annular flow while Fig. 4-13(c) shows that for a fully eccentric annulus. A higher liquid film height is observed in the fully eccentric annulus when compared with the concentric annulus. This is because of the impact of the flow geometry in the fully eccentric annulus. The inner pipe restricts the flow of the liquid phase at the bottom of the annulus resulting in a higher liquid film. This is captured by the PDF trends presented in Fig 4-13(b) and 4-13(d) for concentric and fully eccentric annulus respectively. A similar scenario is observed for the wavy annular flow regime. It is envisaged that the variation of the flow channel geometry due to eccentricity would affect phase separation of the flow, i.e. the larger the eccentricity, the easier the gas/liquid separation. This in the end would influence the flow regimes formed.

Similarly, the effect of gas and liquid superficial velocities on the flow regimes was also studied using PDF features as presented on Fig.4-14. The flow regimes

are observed to transition with increasing gas and liquid superficial velocities from elongated bubble at the lowest gas superficial velocity to annular flow at the highest gas superficial velocity and this is reflected on the PDF plots. Also, the shape and structure of the PDF trends are affected due to increase in flowrates.

For example, the influence of gas superficial velocity increase can be observed at liquid superficial velocity of 0.27 m/s. The elongated bubble flow observed at gas superficial velocity of 0.21 m/s transitions to slug flow regime at V_{SG} towards 1.21 m/s due to an increase in the area occupied by the gas phase. This is observed in the liquid holdup time series plot where the average liquid holdup value is reduced as well as the length of time the liquid holdup is observed at very high liquid holdup values. Similarly, the PDF trend shows two distinct peaks with the higher peak observed at lower liquid holdup values showing the effect of the gas void fraction increase in the annulus. A further increase in V_{SG} to a high value (16.29 m/s) results in further increase in the gas void fraction which is reflected in the lower averaged liquid holdup values observed in the holdup time trace which has wavy spikes indicating the wavy nature of the flow. The PDF trend shows the disappearance of the peak observed at higher holdup values, rather a single peak is observed at very low holdup.

The effect of increase in liquid superficial velocities can also be observed in Fig. 4-14. An increase in V_{SL} from 0.27 toward 1.94 m/s at V_{SG} of 0.21 m/s results in an increase in the liquid holdup and corresponding reduction on the area occupied by the gas phase in the annulus setup. Large gas plugs are broken down to smaller gas bubbles reflected in the higher frequency of downward spikes noticed on the holdup time traces. The PDFs on the other hand shows with increase in V_{SL} , the gradual disappearance of the lower value peak observed in the elongated flow regime, leaving just a single peak at holdup value of around 0.95 for the dispersed bubble flow.

At V_{SG} from 1.21, increasing V_{SL} from 0.27 towards 1.94 m/s gives some understanding of the effect of increased liquid holdup on the slug flow regimes observed in the annulus configuration studied. Increased liquid holdup results in more frequent slug body being observed by the probes as shown by increased

peaks and troughs in the holdup time series plots. On the other hand, the PDFs show a more dominant second peak at higher holdup values at higher V_{SL} values with the peak at lower holdup values gradually diminishing in value.

During two-phase flow at V_{SG} of 16.29 m/s, increasing V_{SL} from 0.27 to 1.94 m/s showed the effect of increasing liquid flowrates in the annular flow region. The short spikes noticed at the lowest V_{SL} gradually become more frequent and occur at higher holdup values as observed on the holdup time series plot. This gives an indication of the increased wavy interface of the liquid film at the bottom of the annulus. With regards to the PDF trend, the area under the PDF curve increases with increase in V_{SL} and shift the single observed peak from near enough zero to higher holdup value up to 0.28. At V_{SL} of 1.94 m/s, the flow transitions to wavy annular flow is due to reduced energy of the gas phase.

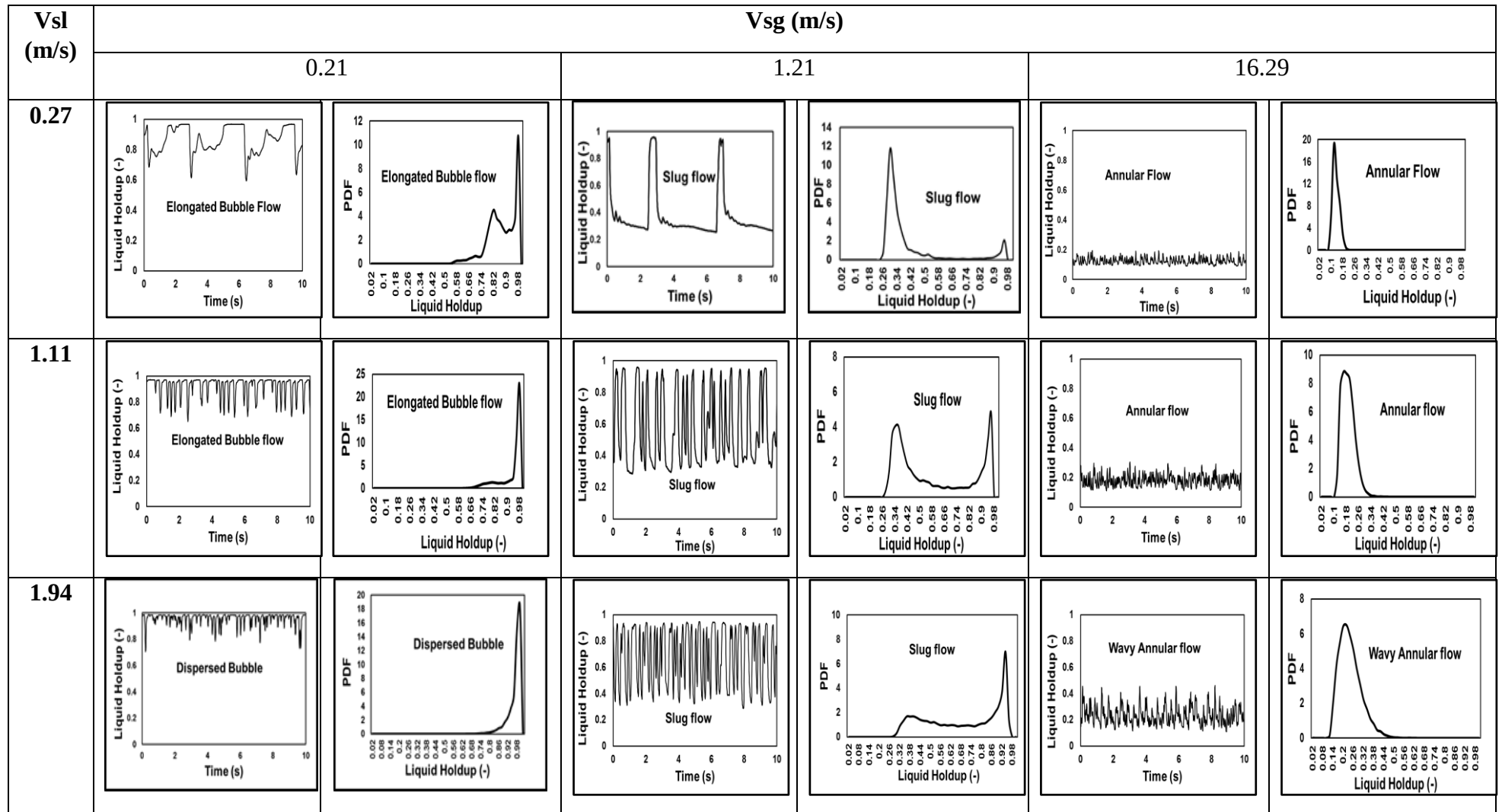


Figure 4-14: Effect of gas liquid superficial velocities on Time series and PDF trends in horizontal concentric annulus

4.4.2 Effect of Annulus Eccentricity on Flow Regime Transitions

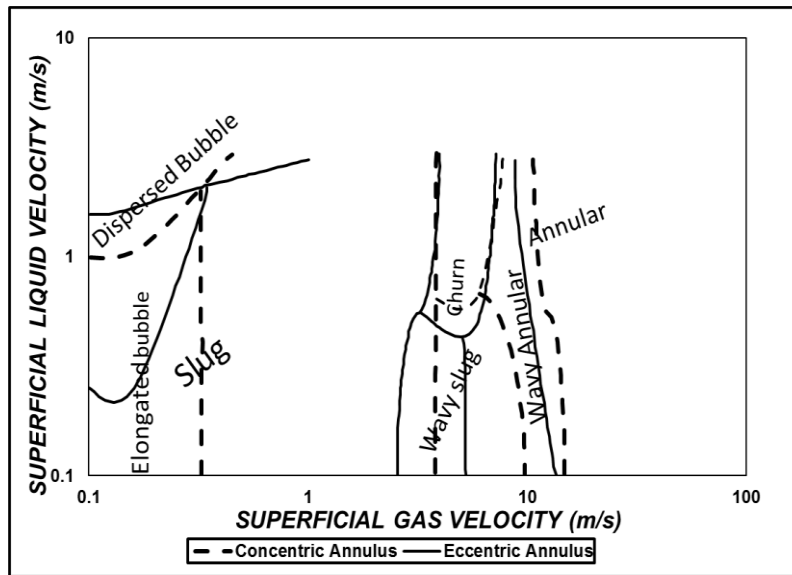


Figure 4-15: Effect of annulus eccentricity on flow regime transitions

The eccentricity of annulus also affects the flow regime transitions in horizontal annulus. Experimental flow regime transitions observed in the concentric and eccentric horizontal annulus geometries show slight difference when compared. The transition to elongated bubble flow takes place at V_{sl} of 0.22 m/s in the fully eccentric annulus which is higher than that observed in the concentric annulus (0.10 m/s) in this study. Similarly, the transition to dispersed bubble flow takes place at higher liquid superficial velocity (1.56 m/s) in the fully eccentric annulus than in the concentric annulus (0.99 m/s). This is because the gas phase occupies a larger annulus gap at the top of the fully eccentric annulus than in the concentric annulus and as a result, higher liquid flowrates are required to reduce the size of the elongated gas bubble to tiny bubbles dispersed in the liquid body. Also the transition to slug from elongated bubble flow occurs at gas superficial velocity of 0.1 m/s in the fully eccentric annulus while in the concentric annulus it occurs at V_{sg} of 0.33 m/s. The transition from slug flow to wavy slug and churn flow regimes occur at lower gas superficial velocity than observed in the concentric annulus, while increased liquid superficial velocities are required to transition from wavy slug flow to churn flow. Finally, transition to the annular flow regime (including wavy annular flow) occurs at a lower gas superficial velocity in

the fully eccentric annulus. Fig 4-15 presents these flow regime transition lines. Generally speaking, the transitions from elongated bubble to slug, slug to wavy slug and wavy slug to annular flow regimes occur at lower gas superficial velocities in the fully eccentric annulus when compared with the concentric one. This shift appears to be consistent with the observed effect of eccentricity on phase separation.

This study shows that discrepancies exist in the flow regime transitions models developed in the past based on theoretical correlations and experimental observations in circular pipes and annular conduits, when compared with observations from experiments conducted in horizontal concentric and fully eccentric annulus. Therefore the next section is devoted to integrating available experimental flow regime data to develop a generalised flow regime map for flow in horizontal annulus.

4.5 Development of Flow Transition Parameters

Studies undertaken for flow regime identification in conduits have mainly been undertaken in controlled laboratory environments where observation through a pipe is possible because direct flow regime observation and identification in industrial applications are difficult or impossible. These industrial applications take place at high temperature and pressures, flowing mainly in stainless steel pipes. Attempts have been made to correlate the laboratory experiments to industrial applications using flow regime maps based on gas and liquid superficial velocities with theoretical models developed for prediction between the flow regimes, however no universal map of flow regimes which is accurate exists yet even though several transition criteria have been developed (Wu *et al.*, 2017).

Only very few studies have been undertaken to accurately characterize flow regimes and their transitions in horizontal annulus. In this section, available experimental flow regime data in horizontal annuli is integrated to develop a robust generalised flow regime map based on dimensionless parameters. A summary of data utilized for the development of the flow regime transition parameters in this study is presented in Table 4-3. A total of 1174 data points is used to develop the flow regime transition criteria for this study based on different

annulus eccentricities, hydraulic diameters, fluid properties and superficial gas and liquid velocity ranges. Apart from data obtained from Sunthakar et al.,(2000), Mendes et al.,(2011) and Nossen et al., (2017) which have gas and liquid properties different from air and water, the rest of the data are based on air and water as the testing fluids. Their properties have been assumed to be based on ambient temperature and pressure as their operating conditions are not reported in the journal articles.

Table 4-3: Experimental data for development of flow regime transition parameters

Study	Gas	Liquid	Annulus dia. (m)	No. of data points	Annulus geometry	V_{SL} (m/s)	V_{SG} (m/s)	Flow regime identification technique
Sunthakar et al., (2000)	Air	Water + CMC +XCD	$D_I = 0.2032$ $D_O = 0.1143$ $D_H = 0.0889$	114	Concentric	0.21-1.04	0.11-22.73	Visual observation
Zhou et al., (2004)	Air	Water	$D_I = 0.152$ $D_O = 0.089$ $D_H = 0.063$	39	Concentric	0.30-1.48	0.17-0.44	Visual observation
Omurlu et al., (2006)	Air	Water	$D_I = 0.1143$ $D_O = 0.05715$ $D_H = 0.05715$	165	Eccentric	0.12-1.63	0.27-4.55	Visual observation
Omurlu & Ozbayoglu (2007)	Air	Water	$D_I = 0.09326, 0.0734$ $D_O = 0.0488, 0.047$ $D_H = 0.0445, 0.0264$	189	Eccentric	0.12-2.63	0.05-4.50	Visual observation
Osgouei (2010)	Air	Water	$D_I = 0.074$ $D_O = 0.046$ $D_H = 0.028$	358	Concentric	0.005-2.76	0.006-43.34	Visual observation
Mendes et al.,(2011)	Air	Water Oil	$D_I = 0.111$ $D_O = 0.075$ $D_H = 0.036$	91	Concentric	0.02-5 0.005-0.5	0.02-30	Visual observation Pressure-signature analysis

Study	Gas	Liquid	Annulus dia. (m)	No. of data points	Annulus geometry	V_{SL} (m/s)	V_{SG} (m/s)	Flow regime identification technique
Tobias (2014)	Air	Water	$D_I = 0.0515$ $D_O = 0.0333$ $D_H = 0.0182$	83	Concentric	0.25 - 2.91	0.02-4.28	Visual observation
Nossen et al., (2017)	SF ₆ gas	Exxsol D60 Water	$D_I = 0.1016$ $D_O = 0.0508$ $D_H = 0.0508$	26	Concentric	0.2 -2.0	0.5 – 4	Visual observation
This study	Air	Water	$D_I = 0.0768$ $D_O = 0.06$ $D_H = 0.0168$	109	Eccentric	0.15-2.77	0.15-24	Visual observation Conductance probes (Ring type)

A flow regime map is proposed based on modified gas and liquid Froude number for both the concentric and eccentric annulus geometries as shown in Fig. 4-16. The Froude number gives an indication of the ratio of inertial forces to the external field and is an important dimensionless parameter for flow regime identification. The gas and liquid Froude numbers are defined as follows:

$$Fr_G = \frac{V_{SG}}{\sqrt{\frac{\rho_G}{(\rho_L - \rho_G)} D_H g}} \quad (4-1)$$

$$Fr_L = \frac{V_{SL}}{\sqrt{\frac{\rho_L}{(\rho_L - \rho_G)} D_H g}} \quad (4-2)$$

Where V_{SL} , V_{SG} , g , D_H are the liquid superficial velocity, gas superficial velocity, gravitational acceleration and hydraulic diameter while ρ_L , ρ_G are the liquid and gas density respectively. The flow regimes classified in the studies from where the data set is obtained have mainly been by visual observation and in some cases, similar flow regimes have been classified using different names. In order to develop the flow regime transition criteria, certain flow regimes have been group under one broad heading. Churn, wavy slug, elongated bubble and slug flow regimes are classed as intermittent flow, dispersed bubble and bubble flow are classed as bubble flow while the wavy annular and annular flow regimes are classified as annular flow regimes.

The transition parameters are as follows:

Stratified Flow to Intermittent Flow

$$Fr_L \geq -0.078 \ln Fr_G + 0.129 ; \quad Fr_G \leq 0.025 \quad (4-3)$$

Stratified Flow to Annular Flow

$$Fr_L \geq -0.0247 \ln Fr_G - 0.2 ; \quad Fr_G < 0.04 \quad (4-4)$$

Intermittent to Bubble Flow

$$Fr_L \geq 4.115e^{19.4Fr_G} \text{ and } Fr_G < 0.04 \quad (4-5)$$

Intermittent to Annular Flow

$$Fr_L \geq -122.9Fr_G^2 - 12.28Fr_G + 10.7 \text{ and } Fr_G > 0.04 \quad (4-6)$$

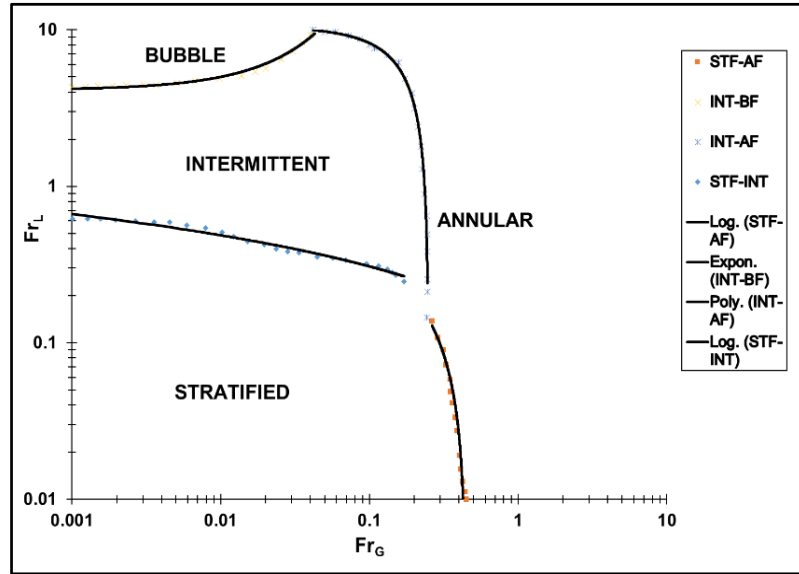


Figure 4-16: Developed flow regime boundaries based on experimental data

It should be noted that the transition parameters are limited and can only be applied to annulus with hydraulic diameter less than 0.089 m, liquid density range between (798 – 1000) kg/m³, gas density range between (1.0 – 24) kg/m³, liquid viscosity range above 0.22 kg/ms and gas viscosity range between (1.5x10⁻⁵ – 1.81x10⁻⁵) kg/ms. Further testing of the transition parameters could be carried out as more experimental data becomes available to confirm the accuracy of these parameters. Also these parameters may require modification if they are to be extended to liquid phase having viscosity above 0.22 kg/ms.

Flow regimes can therefore be determined step by step as shown in the flow chart presented in Fig.4-17

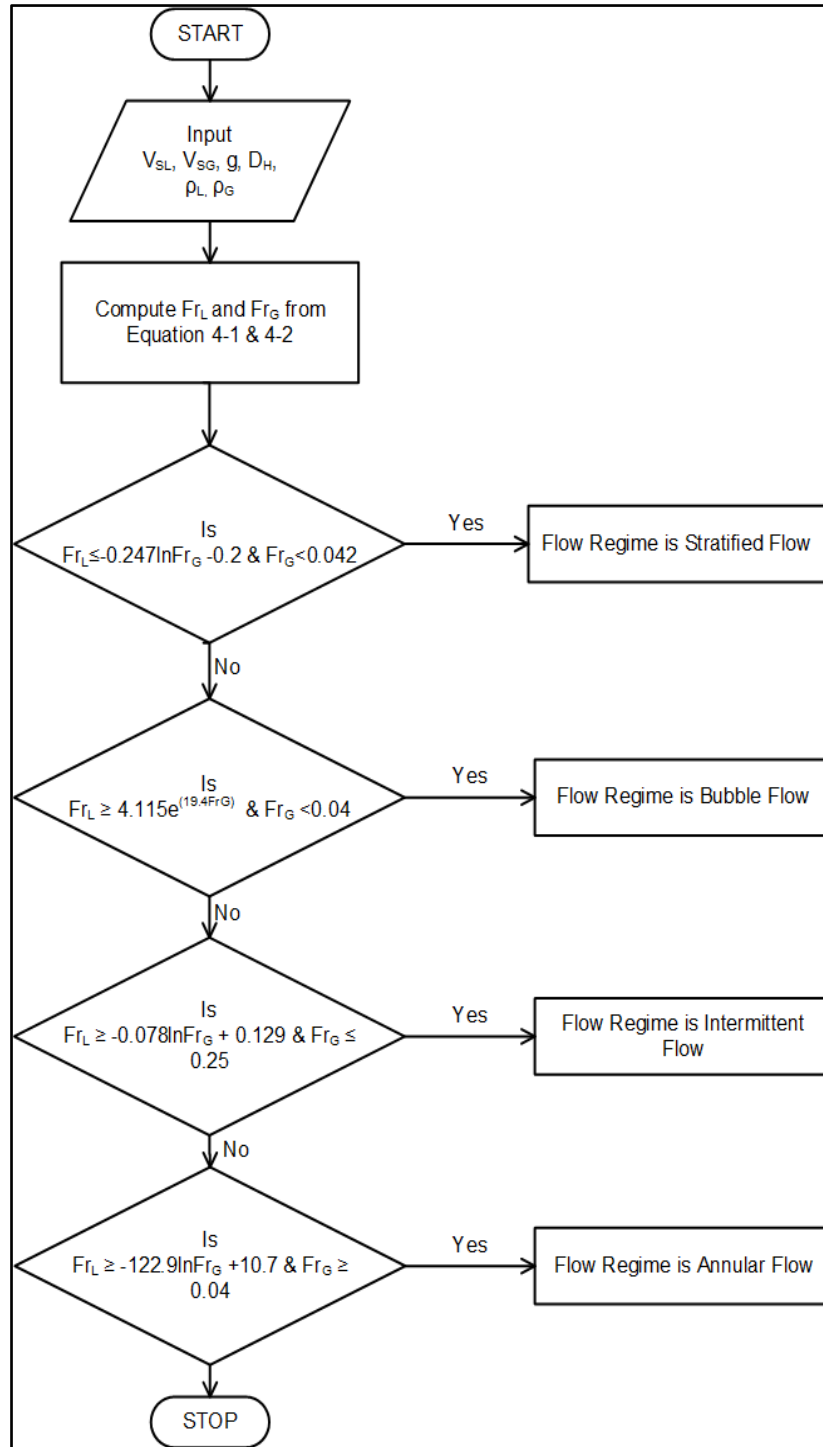


Figure 4-17: Flow chart for flow regime determination

The transition criterion are tested using 109 data points from the concentric annulus investigated in this study and the flow regimes were predicted with an accuracy of 90%, 81% and 85% respectively for bubble, intermittent and annular

flow regimes respectively. The breakdown of the performance of transition parameters on the different flow regime data used for testing are presented below

Table 4-4: Performance of transition parameters on test data set

Flow Regimes	Number of data points	Accurately classified based on transition parameters	Misclassified based on transition parameters
Bubble Flow	10	9	1
Intermittent Flow	59	48	11
Annular Flow	40	34	6

4.6 Objective Real-Time Flow Regime Identification

This section details an objective method for flow regime identification developed for horizontal concentric annulus but which can be extended for two-phase gas-liquid flow regime identification in several conduits. Wu et al.,(2017) carried out a review of flow regime identification techniques and assert that two main flow regime identification techniques employed to date are:

- (a) Direct methods which include visual and high speed photography, X-ray attenuation picture, gamma-ray density measurements and the use of electrical conductance probes.
- (b) Indirect methods include X-ray attenuation fluctuation analysis, thermal neutron scattering noise analysis, drag-disk signal analysis and static pressure oscillation analysis.

The direct methods involve flow regime categorization based on the visual interpretation of the flow image by the researcher, while the indirect methods are carried out in two stages. First, the researcher must accurately measure the characteristic intrinsic feature of each flow during properly designed experimental campaigns and secondly objectively analyse the flow features to classify the flow regimes. A detailed study of literature shows that the main issue that arise from

the use of high speed cameras alone is the difficulty with dealing with conduits which are opaque or hidden from view and at high flow rates of the phases where transition boundaries are unclear. This also means that real-time flow regime identification is pretty difficult. Most flow regime identification studies undertaken in horizontal annulus setup have mainly been by video or high speed camera imagery.

It is often desirable to have flow regime identification techniques which are objective, reliable and quantitatively based on flow feature measurements. Several factors must be taken into consideration when deciding key issues that would enable accurate flow regime characterization. For instance measurement and observation distances must be selected such that sufficient time and distance is allowed for the two-phase flow to develop fully. Also chosen instruments must be considered for potential interference to the flow in the conduits. This is particularly important during flow through annulus where it is desired to avoid measurement techniques that are intrusive due to the small annular gap available for flow. Ultimately an important consideration is the cost of equipment employed for the chosen experimentation method required for flow regime identification. A compromise is required between the affordability, accuracy and simplicity.

In the past Jones & Zuber (1975) were among the first researchers to use the void fraction as the intrinsic flow feature for flow regime identification. The Probability Density Function (PDF) were obtained from the statistical analysis of this intrinsic flow feature and then employed for flow regime identification. They employed X-ray systems to determine the void fraction fluctuations and a lot of safety concerns arise when handling radiation sources during such operations. The peculiar features of statistical properties of differential pressure fluctuations were employed by Matsui (1984) for flow regime identification in a vertical pipe. Barnea et al., (1980) employed conductance probes to identify flow regimes in horizontal, near horizontal and upward flows. The technique is based on different conductivity between the gas and liquid phases (air and water respectively). Conductivity and capacitance are appropriate flow properties since they correlates the amount of material that constitutes the liquid phase. Another

advantage of using conductivity or capacitance (depending on the liquid phase) is the fact that instrumentation for collecting the data is easy to fabricate, cheap, simple to use, gives reasonable degree of accuracy and is non-intrusive. The next section details the methodology adopted for the objective flow regime identification technique developed as part of this study.

4.6.1 Experimental Procedure

Two pairs of ring-type conductance probes are designed and calibrated as detailed in Chapter 3 and utilized in this study for the objective identification of gas-liquid two-phase flow regimes. The probes are non-intrusive, flush mounted on the outer pipe of the annulus configuration and as such do not obstruct the flow in the annulus section. Air-water experiments are carried out over the entire test matrix developed for this study and voltage signals from the probes are recorded at a sampling rate of 100 Hz. Data is collected for each gas and liquid superficial velocity investigated and each data sample was collected over a 180 second period.

4.6.2 Methodology/Theory for Objective Flow Regime Identification

Flush-mounted conductance probes immersed in a two-phase flow media are utilized based on the potential field theory. A resistive behaviour is experienced when electrolytes are subject to alternating current (a.c.) electrical excitation at sufficiently high frequency (Devia and Fossa, 2003). The identification of flow regimes is done using the methodology proposed by Kelessidis & Dukler (1989). Probability Density Function (PDF) analysis of voltage-time $V(t)$ plots is conducted by dividing the observed voltage and time scales into equal increments of width w and Δt respectively. If the observed voltage during a given time period T is within the interval $(v - w/2, v + w/2)$ for a total of n_i times, the PDF, $p(v)$ is given as

$$p(v) = \lim_{w \rightarrow 0} \frac{P[v, w]}{w} = \lim_{w \rightarrow 0} \frac{1}{w} \left(\lim_{T \rightarrow \infty} \frac{T_x}{T} \right) \quad (4-7)$$

Where $T_x = n_i \Delta T$ and $P[v, w]$ is the probability distribution function. A plot of PDF values corresponding to voltage values versus the ratio of the voltage to

maximum voltage V/V_{max} , where V_{max} is the maximum voltage for which a non-zero PDF value is estimated. A high-level output of voltage (5.0 V) is obtained when the annulus section between the ring electrodes is filled completely with water and a low-level output voltage (0 V) is obtained when the annulus section between the ring electrodes is empty. The voltage-time trends and PDF plots are then employed to classify the flow regimes. However, according to Wu et al.,(2017) the researcher is still saddled with the responsibility of defining the rules for flow regime identification using statistical parameters and as such these method may still be limited by subjective bias of the researcher as well as challenges when comparing studies from different studies.

To eliminate any subjectivity, kernel methods are employed to analyse the conductance data. The method involves projecting the Probability Density Function (PDF) features from the voltage-time data onto a reduced space of 2 dimensions, via Kernel Principal Components Analysis (KPCA). This step provides a means to effectively visualise the voltage-time data in 2D space, without prior knowledge of the gas and liquid flow rates. A flow regime map is then developed where flow regime boundaries are established using Kernel Support Vector Machine (SVM). This step assigns every point in the map to a flow regime.

4.6.2.1 Kernel Principal Components Analysis

In this study, each bin of V/V_{max} in a PDF plot is treated as a dimension or “feature”. For a PDF curve with M bins, a *dimensionality reduction* method is used to reduce M features to 2 features, which are then made to comprise the coordinates of a flow regime map. This step is *unsupervised*, i.e. it proceeds with no knowledge of the flow regime labels yet. After this step, each PDF obtained from each data sample is represented as on a 2D map as a data point, which will be referred to as a virtual flow regime map. This flow regime map retains the properties of the actual flow regime map in that: (i) a clear separation exists between the different flow regime points when each data points are assigned a label; and (ii) a continuous path must be traceable for the points on the map by successively projecting incoming PDF curves from a moving time-window of

voltage signals when gas and liquid flowrates are increased or decreased gradually.

Principal Components Analysis (PCA) is a standard linear dimensionality reduction tool that aims to project input data onto a lower dimensional *latent space*, while preserving information in the form of variance of data. For instance, Wang & Zhang (2009) have used PCA for mapping electrical capacitance data prior to classification. Going further, Kernel PCA is a nonlinear extension of PCA that enhances the separation of dissimilar data in the latent space (Scholkopf et al. 1998). In this work, the following KPCA methodology is adopted.

Let $x_i \in \mathfrak{R}^M, i = 1, 2, \dots, N$ denote a training data set of N samples. As a pre-processing step, all features are normalized to zero mean and unit variance. KPCA then proceeds by forming an $N \times N$ kernel matrix $K = [K_{ij}] = [K(x_i, x_j)]$, using a suitable kernel function K , which roughly acts as a similarity measure between any pair of samples, x_i and x_j . Here, the widely used radial basis function (RBF) kernel is chosen, given by

$$K(x, x') = \exp\left(\frac{-\|x - x'\|^2}{k_w}\right) \quad (4-8)$$

Where k_w is the kernel width. Note that K tends to a value of 1.0 for similar data, otherwise it tends to zero. The kernel matrix, K is then centered as,

$$K_c = K - 1_N K - K 1_N + 1_N K 1_N \quad (4-9)$$

Where 1_N is an $N \times N$ matrix where $(1_N)_{ij} = 1/N$. The eigenvalue decomposition of K_c is

$$K_c/N = V \Lambda V^T \quad (4-10)$$

Where each column of V is an eigenvector and $\Lambda = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_N) \in \mathfrak{R}^{N \times N}$ is a diagonal matrix of decreasing eigenvalues. From Equation (4-11), the projection matrix is formed as

$$P = \Lambda^{-1/2} V^T \in \mathfrak{R}^{N \times N} \quad (4-11)$$

By extracting the first 2 columns of P , denoted as P_2 , only the top 2 projections are retained that capture the maximum variance in the data. These projections, also known as *latent variables* L , are the new features in the latent space:

$$L = P_2^T K_c \in \mathbb{R}^{2 \times N} \quad (4-12)$$

Together with their respective labels, $y_i, i = 1, 2, \dots, N$ from the set of observed flow regimes, L is inputted into SVM for subsequent flow regime classification. Although classification accuracy may improve by extracting more than 2 KPCA features, only 2 are chosen: (i) to prevent overfitting, as it occurs at too large number of features and small N ; and, (ii) because the *intrinsic* dimensionality of the data is known for a fact to be 2, corresponding to the gas and liquid flow rates. Thus, 2 dimensions is enough to contain the information from a PDF curve. Indeed, overfitting is prone to occur when all $M = 50$ features of the PDF curves are inputted to the SVM, without the dimensionality reduction (PCA or KPCA) step. In this case, the classifier may perform so well on the training data, but poorly for unseen test data.

4.6.2.2 Binary Kernel Support Vector Machine

After visualizing all the PDF data on a 2-dimensional space, a cluster of similar data points is expected. A multi-class SVM can be used to establish the boundaries between the different flow regime clusters. SVM offers two major advantages: (i) the method is based on the Structural Risk Minimization (SRM) principle, as opposed to the Empirical Risk Minimization (ERM) employed by classical least-squares methods, and as such, the SVM is a flexible learner which has good generalizability (Cristianini & Shawe-Taylor, 2014); (ii) training an SVM only involves solving a convex quadratic programming problem, which is known to have a unique solution. In contrast, Artificial Neural Networks (ANNs) are usually trained iteratively by stochastic gradient descent, wherein the solution might converge to local minima (Hastie et al., 2008).

Originally, Cortes & Vapnik (2000) proposed the SVM for classifying data into 2 classes (binary), which are labelled as $y \in \{+1, -1\}$. The idea is to search for a linear separating hyperplane that maximizes the margin between the positive and negative classes, as illustrated in Fig. 4-18. Nonlinear boundaries are enabled by

using kernels in a dual form of the SVM (Cristianini and Shawe-Taylor, 2014). In this study, the so-called 1-norm C-SVM which is posed as the quadratic programming problem is adopted:

$$\begin{aligned} \max \quad & \sum_{i=1}^N \alpha_i - \frac{1}{2} \sum_{i,j=1}^N y_i y_j \alpha_i \alpha_j K(x_i, x_j) \\ \text{subject to} \quad & \sum_{i=1}^N y_i \alpha_i = 0, \\ & 0 \leq \alpha_i \leq C, \quad i = 1, \dots, N \end{aligned} \tag{4-13}$$

Where x_i are the N training data set, α_i are Lagrange multipliers, $K(\cdot, \cdot)$ is a kernel function, y_i are the labels, and C is a regularization parameter called the *box constraint*. The theory and derivation of this form of SVM is found in Cristianini & Shawe-Taylor (2014).

Solving (4-14) gives the optimal values α_i^* , from which the decision function is obtained as

$$f(x) = \sum_{i \in SV} y_i \alpha_i^* K(x_i, x) + b^* \tag{4-14}$$

Where b^* is a bias term and SV is a subset of training samples that emerged as *support vectors*, i.e. the samples that define decision boundaries just as the ones highlighted in Fig. 4-18. The bias is chosen so that $y_i f(x_i) = 1$ for any i with $0 < \alpha_i^* < C$ (Cristianini & Shawe-Taylor, 2014).

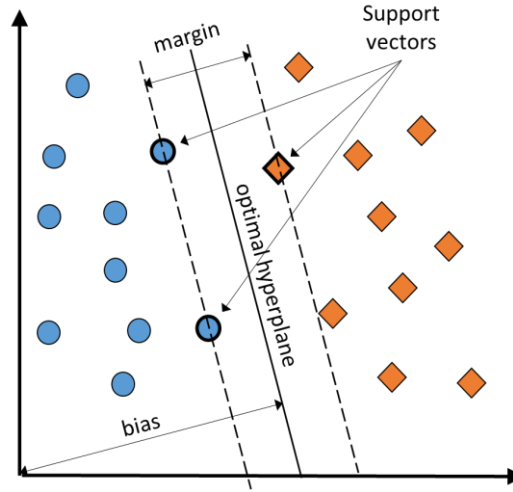


Figure 4-18: Illustration of optimal separating hyperplane in SVM

The SVM classifier is *trained* after obtaining $f(x)$. Hence, for any new sample x , the binary decision rule is given by $y = \text{sign}(f(x))$ which returns +1 or -1.

In this work, the RBF kernel in Equation (4-9) for $K(\cdot, \cdot)$ in Equation (4-14). Typically, a range of values of k_w and C are tried in order to find the best SVM performance for classification (Cristianini & Shawe-Taylor, 2014). Overfitting may occur at low values of k_w , while decision boundaries tend to be linear at too large k_w . The value of C also controls regularization: When $C = \infty$, a strict separation between classes is enforced (hard margin SVM) but decision boundaries become more tortuous as a result. Too large C may also produce non-contiguous regime regions. Otherwise for $0 < C < \infty$, decision boundaries are desirably less tortuous. However, misclassification rate increases as the value of C decreases (soft margin SVM).

4.6.2.3 Multi-class Support Vector Machine

Now, since there are more than 2 flow regimes, multi-class SVMs must be employed. This involves training many binary SVM classifiers according to either one-versus-one (1-v-1), one-versus-rest (1-v-r), or max-wins strategies. In this work, an efficient 1-v-1 algorithm called DAGSVM, proposed by Platt et al., (2000) is used.

In DAGSVM, $K(K - 1)/2$ binary SVM classifiers are trained between every possible pair of distinct classes, where K is the number of classes. Since all

classifiers are equally important, we use the same k_w and C parameters for all of them. The $K(K - 1)/2$ decision functions are placed in each node of a decision directed acyclic graph (DDAG), shown in Fig. 4-19 for $K = 8$. Each class is associated with a flow regime observed from the experimental setup. To use DAGSVM, any incoming sample is classified first in the root node, 1 vs. 8. From the current node, the DDAG is traversed either downwards or to the right. The sample is further classified successively on every node in the path, until a final decision is reached on a leaf node. This approach is proven to be efficient since any path from the root to any leaf has a length of $K - 1$. Thus, we only need to evaluate a sample 7 times before it is conclusively classified to a flow regime.

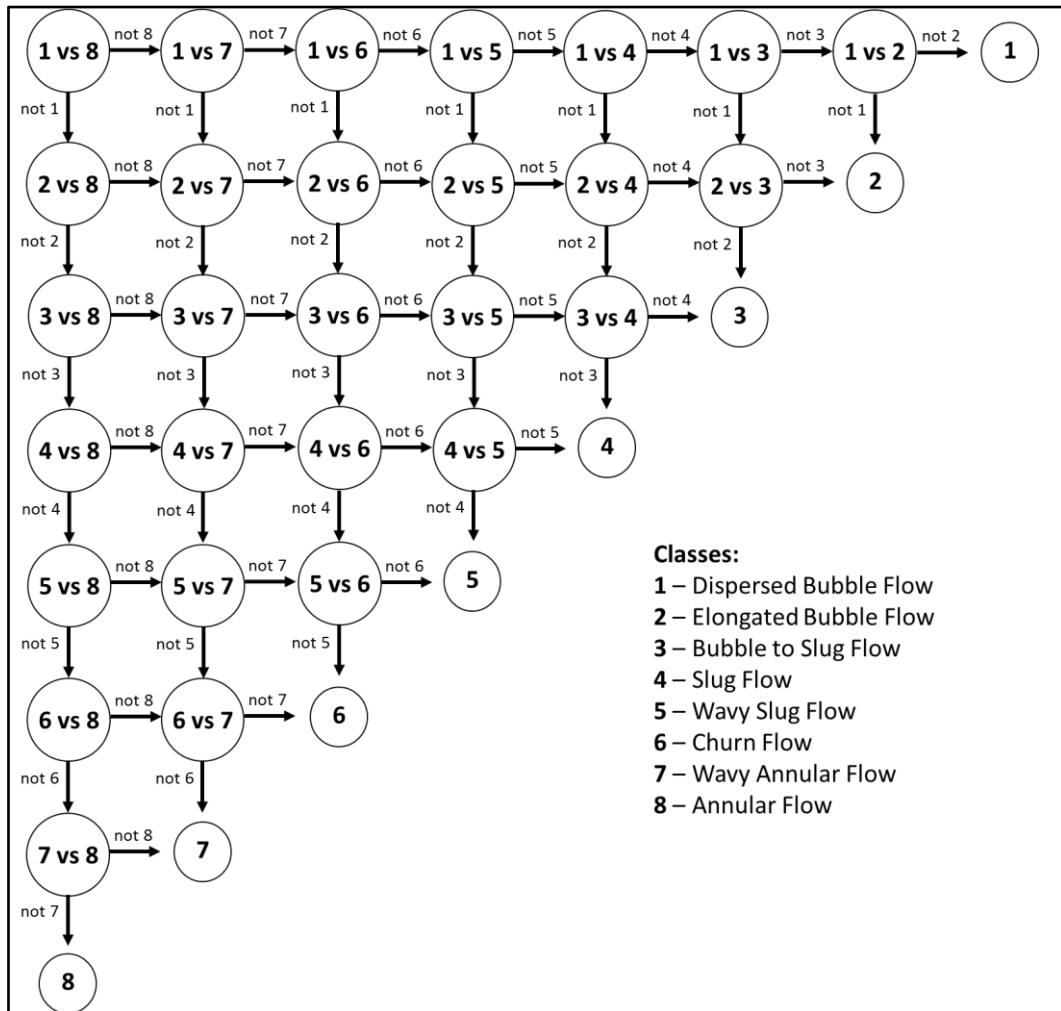


Figure 4-19: DAG of Binary SVM Classifiers for Flow Regime Classification

In summary, the methodology for objective flow regime identification using conductivity data is outlined in Fig. 4-20. In the end, a virtual flow regime map is sought from the data. “Virtual” means that the axes of this map have no physical meaning and the exact boundaries by the SVM have no physical basis as well. Rather, statistical machine learning principles are employed in place of a physical basis. In other words, a data driven approach is employed in this study. Nevertheless, the virtual flow regime map is a means for the objective flow regime identifier developed to explain its results. This feature of interpretability gives this approach an advantage over the Artificial Neural Network ANN-based data-driven approach (Cristianini & Shawe-Taylor, 2014). For static performance testing, 30% of the available data samples not employed for SVM training were used as test samples. Visual analysis of the resulting flow regime maps are done during static and dynamic tests.

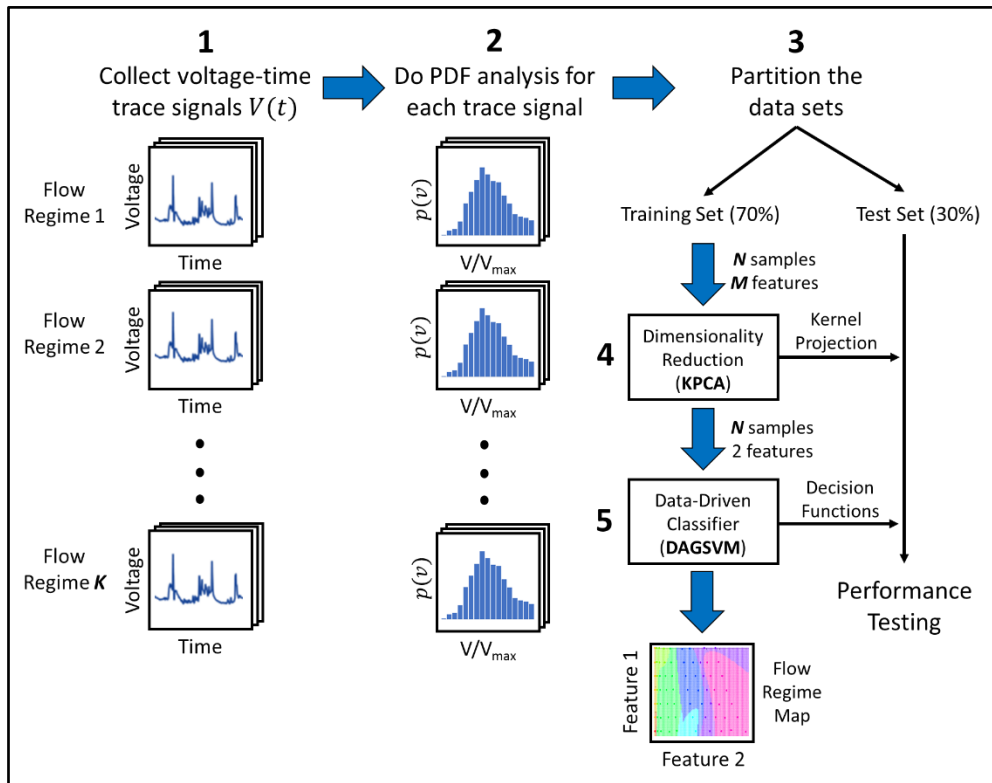


Figure 4-20: Methodology for Objective Flow Regime Classification

4.6.3 Results & Discussion

This section presents the results and discussion for the static performance of the KPCA-SVM based objective flow regime identification which would be followed by a real-time application afterwards.

4.6.3.1 Flow Regime Label Assignment

Figure 4-21 shows typical classification of flow regimes based on voltage-time trends and PDF plots of representative samples. The data interpretation is as follows:

4.6.3.1.1 Dispersed Bubble Flow

The dispersed bubble flow voltage signal shows a steady uniform oscillation at maximum voltage, which gives an indication of the presence of spherical bubbles dispersed in a continuous liquid phase. The PDF plot is unimodal having a peak at V/V_{max} close to 1.

4.6.3.1.2 Elongated Bubble Flow

During the elongated bubble flow regime, the probe signals fluctuates intermittent from maximum voltage corresponding to full liquid filling the annulus section between the ring electrodes to a lower voltage value as the gas plug travels past some part of the probe. The PDF feature of this flow regime indicates two peaks close to each other at high V/V_{max} values. The highest peak exist at V/V_{max} close to 1 while the lower peak is observed in the range $0.7 \leq V/V_{max} \leq 0.90$. This gives an indication of large gas bubbles traveling intermittently trapped in the liquid phase as it touches the probe electrodes.

4.6.3.1.3 Bubble to Slug Flow

This flow regime is the transition between the bubble and slug flow regimes. The PDF plots show a peak at V/V_{max} values close to 1, but with a long-tailed distribution of voltage values in the range $0.30 \leq V/V_{max} \leq 0.90$.

4.6.3.1.4 Slug Flow

Pulsating probe traces are observed the slug flow regime, which shows how the slug body and Taylor bubbles alternate in the annulus section between the ring electrodes. The PDF curve for slug flow is bimodal in nature, i.e. has two clearly distinguishable peaks. One peak exists in the lower V/V_{max} domain with the range between $0.30 \leq V/V_{max} \leq 0.50$, showing the Taylor bubbles passing in the annulus gap between the probes with some liquid flowing at the bottom of the annulus. The second peak has a range between $0.70 \leq V/V_{max} \leq 1.0$, which gives an indication of the liquid body travelling past the probe.

4.6.3.1.5 Wavy Slug Flow

The nature of the wavy slug flow regime is seen by the width and amplitude of the probe signals. At low V/V_{max} , small waves are observed represented by the zig zag spikes while a peak value is observed periodically at higher voltage values signifying a large wave that just touches the top of the annulus. Also, a unimodal PDF plot is obtained at lower V/V_{max} values, in which the second peak observed in the slug flow regime disappears.

4.6.3.1.6 Churn Flow

The rowdy nature of the churn flow regime is evident. Random peaks and troughs in the voltage signal which are not easily identifiable are observed. The PDF plot displays a single peak similar at low V/V_{max} values similar to what is observed in the wavy slug flow regime. However, the area under the curve is large cutting across a large range of V/V_{max} values. Also low but non-zero PDF values are observed at high voltage values. This shows the homogeneous nature of the flow.

4.6.3.1.7 Wavy Annular Flow

Wavy annular flow shows a probe trend which reflects the effect of aerated unstable waves passing through it, while most of the liquid flows at the bottom of annulus as a film. The PDF plot is unimodal located at low V/V_{max} with its maximum close to 0. It has a large area under the curve beyond the peak up to $V/V_{max} = 0.50$ showing a thick liquid film.

4.6.3.1.8 Annular Flow

Finally, the annular flow voltage trend show small spikes observed consistently about low voltage value indicating a wavy film interface. The film thickness is proportional to the mean voltage output. A single PDF peak is observed at low V/V_{max} values near zero. It has a smaller area under the curve and higher PDF values when compared to wavy annular flow.

The observed PDF trends detailed above for the different flow regimes is similar in some cases to similar trends observed by researches including Kelessidis & Dukler (1989) and Das et al.,(1999). A total of 110 data samples were obtained from the horizontal concentric experimental setup as detailed in Chapter 3. From this number, the voltage signals and flow regime labels was partitioned into $N = 77$ samples for training and 33 samples for testing.

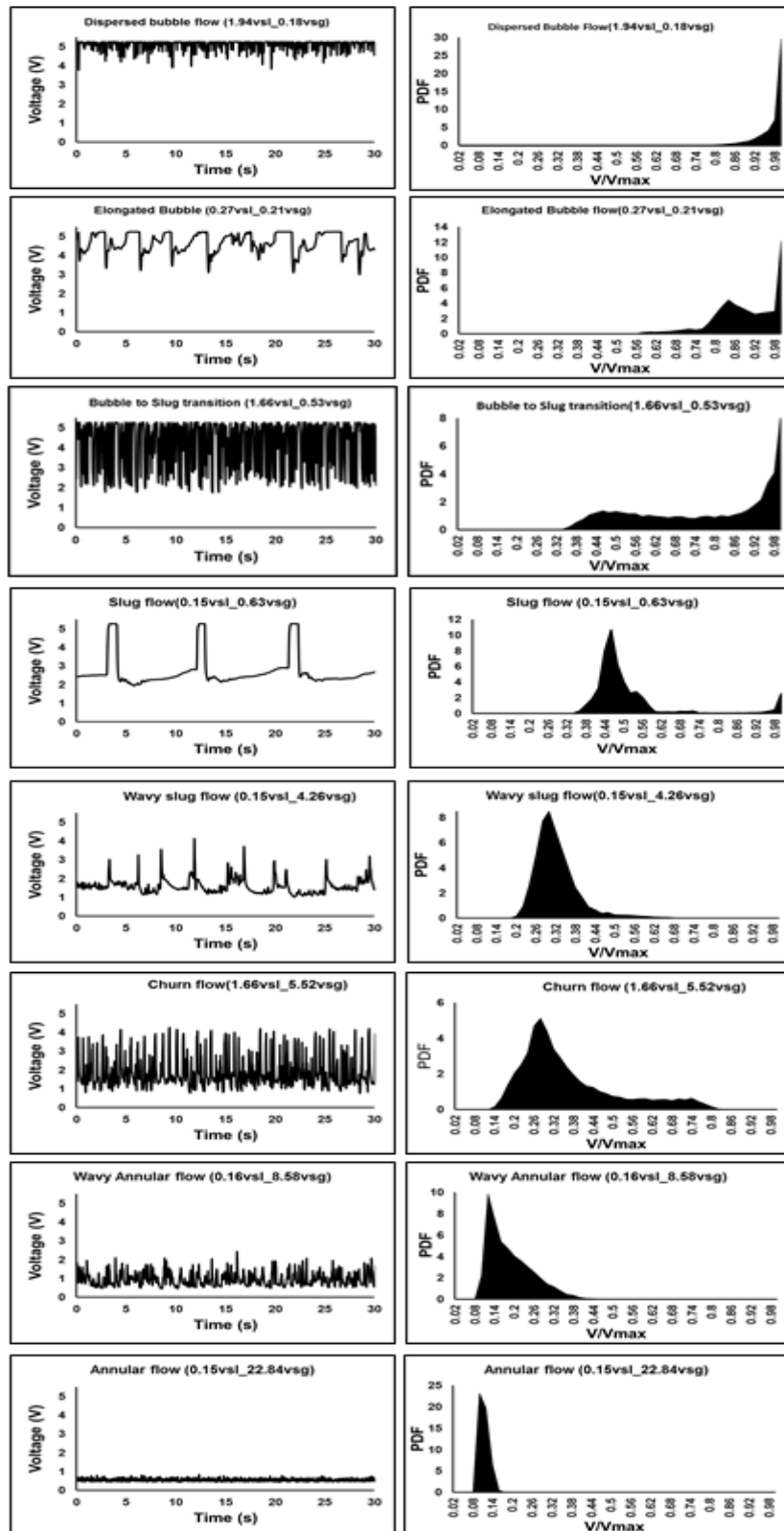


Figure 4-21: sample voltage-time plots and PDF curves for each flow regime

4.6.3.2 From PDF Curves to Latent Space

From the PDF plots, a 2-dimensional map is produced in the latent space using KPCA on the training samples, shown in Fig. 4-22a. The kernel width k_w was chosen as 0.8 quantile of the $\|x_i - x_j\|^2$ statistics (Karatzoglou et al., 2006). Linear PCA results are also shown in Fig. 4-22b for comparison. The advantage of KPCA over PCA is evident in that samples from different flow regimes are more clearly separated in KPCA. To build an intuition for the regions in the latent space, it is important to note that none of the points are located near the origin (0,0). The origin corresponds to a PDF plot where all $p(v)$ features lie on their respective means. The samples are found radially around the origin since their PDF features deviate from the mean values in a specific way. Slug, bubble, and annular flow samples are found on the lower-left, upper-left, and upper-right regions of the map, respectively. With these observations, the KPCA latent space is seen to be a reasonable visual representation of the various flow regimes. However, ambiguity between some churn flow, wavy slug flow, and slug flow samples occurs in the lower-right region of the map. Conferring with Fig. 4-21, the same ambiguity between the PDF plots of these flow regimes can be realized. These PDF plots all resemble a dominant peak between values of $0.2 \leq V/V_{\max} \leq 0.4$. Thus, for the lower-right region of the flow regime map, we allow for some misclassified samples using a soft margin SVM classifier.

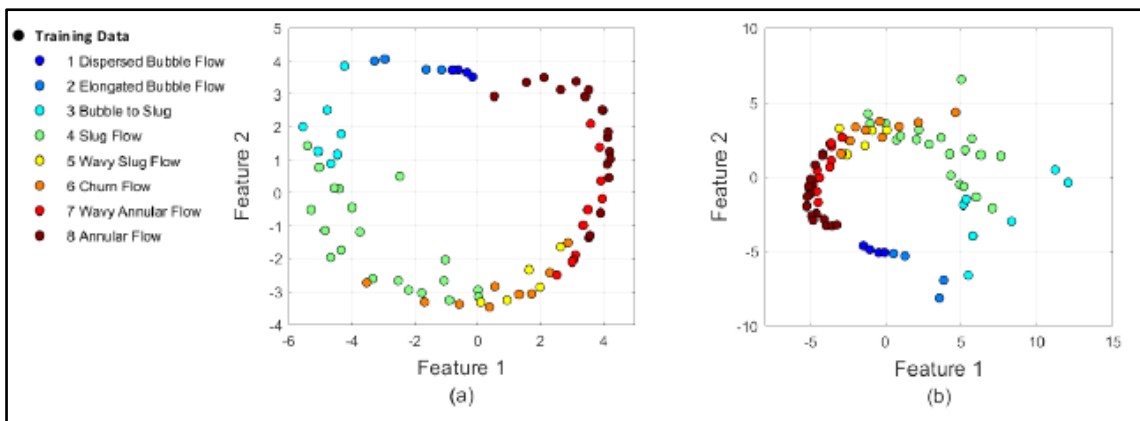


Figure 4-22: (a) KPCA and (b) PCA 2D visualization of training data of conductance PDF

4.6.3.3 From latent space to flow regime map

Multi-class DAGSVM was then used to establish the boundaries objectively between flow regimes in the latent space.

A sample flow regime map for $k_w = 3$ and $C = 100$ is shown in Fig. 4-23, where both training and test samples are superimposed. The classification accuracy for training and test data are 94.8% and 90.9%, respectively when compared with the visually observed flow regime map in Fig. 4-1. These results demonstrate the power of kernel methods for objective flow regime classification based on conductance data.

Basically, SVM assigned every point in the latent space to a flow regime according to the structural risk minimization principle. That is, all the decisions made by SVM minimizes the risk of making a wrong decision, given the labels and positions of the training samples. This logic, embodied by the structural risk minimization principle, applies to all decisions that the SVM made for all points in the latent space. In other words, this is the logic offered this our approach in place of human subjectivity in flow regime classification.

Table 4-5 then lists the data samples that were misclassified in Fig. 4-23. It can be seen that wavy slug flow samples are difficult to identify using our approach. Most wavy slug flow samples were identified as churn flow by the objective classifier. Nonetheless, wavy slug flow and churn flow samples have prominently different voltage-time trace signals (see Fig. 4-21). We attribute this misclassification problem to the fact that PDF curves simply account for the static locations of voltage values. Hence, one way to improve the identifiability of various slug flow conditions is to add features related to the *dynamics* in the voltage time series. With this, a clearer separation can be expected among different slugging conditions in the latent space.

Misclassification also raises the issue of the choice of parameters in the objective SVM classifier. As mentioned, different settings for k_w and C produce varying classification performance. The accuracy of SVM over a grid of parameter values, namely $k_w \in \{1, 3, \dots, 9\}$ and $C \in \{1, 10, \dots, 10^4\}$, is depicted in Fig. 4-24.

By adjusting k_w and C towards the direction of overfitting (lower k_w and higher C), the classifier becomes biased towards the visually observed flow regime

classification, giving a high accuracy of classification on the training data but lowering the accuracy of the test data. However, overfitting entails poor generalization to unseen test data, as illustrated by the flow regime map in Fig. 4-24a for $k_w = 1$ and $C = 10^4$. In this Figure, tighter and more tortuous boundaries are given to flow regimes represented by fewer samples. The wavy slug flow regime region also became non-contiguous. In short, overfitting makes the classification biased towards the training samples. In the other end, at high k_w and low C , under-fitting occurs as illustrated in Fig. 4-25b. In the case of under-fitting, the boundaries tend towards linearity at the expense of higher misclassification rates. In general, the only way to increase confidence with the resulting flow regime map is to validate it against as many unseen test data samples as possible. After evaluating the accuracy of the flow regime maps and their visual sensibility for each possible combination, the setting $k_w = 3$ and $C = 100$ were finally chosen as that which strikes a balance between overfitting and under-fitting. Thus, these settings were used in the objective classifier for real-time regime identification.

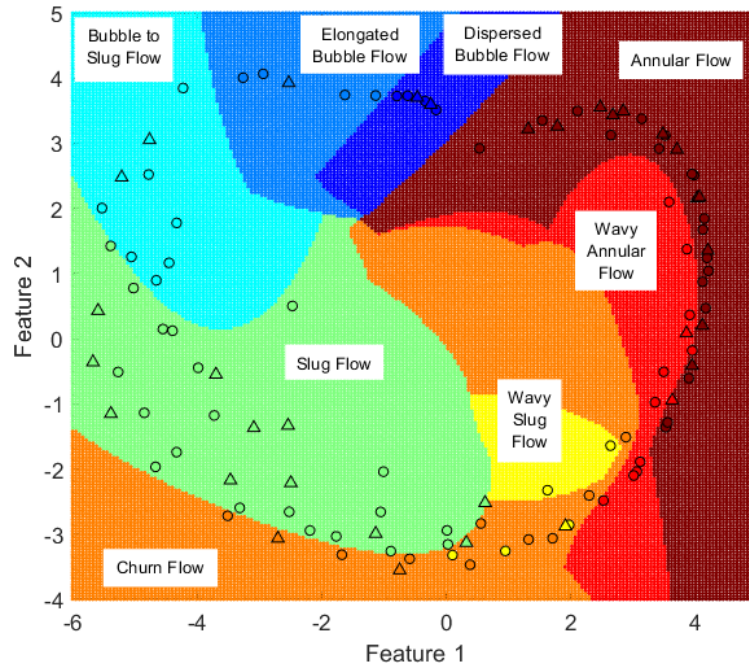


Figure 4-23: Virtual flow regime map from data using SVM ($k_w = 3; C = 100$).

Training samples are denoted by circles, while test samples are denoted by triangles

Table 4-5: Misclassified samples in the flow regime map in Fig. 4-23

A. Misclassified Training Samples (4 out of 77)			
V_{sg} (m/s)	V_{sl} (m/s)	SVM Classification	Actual Classification
3.69	0.83	Churn Flow	Wavy Slug Flow
3.90	0.56	Churn Flow	Wavy Slug Flow
4.26	0.15	Churn Flow	Wavy Slug Flow
8.65	1.67	Annular Flow	Wavy Annular Flow
B. Misclassified Test Samples (3 out of 33)			
V_{sg} (m/s)	V_{sl} (m/s)	SVM Classification	Actual Classification
1.23	0.16	Churn Flow	Slug Flow
4.15	0.28	Churn Flow	Wavy Slug Flow
8.05	1.94	Annular Flow	Wavy Annular Flow

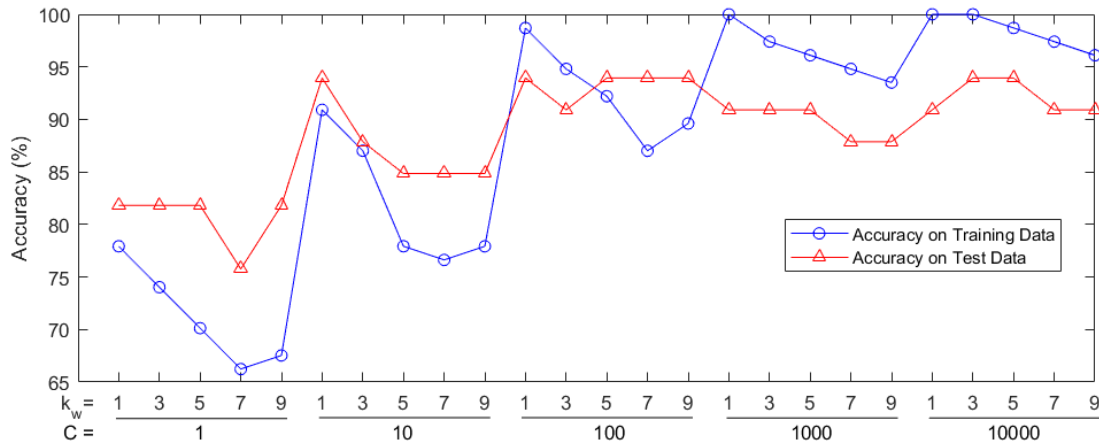


Figure 4-24: Accuracy of SVM classifiers at various $k_w = 3$ and C .

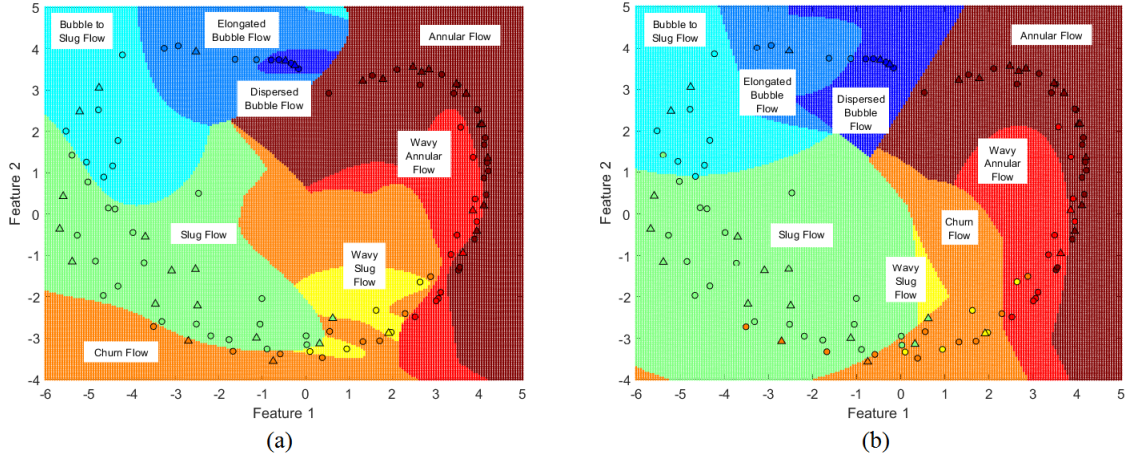


Figure 4-25: Flow regime maps from voltage-time data using SVM at: (a) $k_w = 1, C = 10^4$ (overfit); and (b) $k_w = 9, C = 10$ (underfit). Training samples are denoted by (o), while test samples are denoted by (Δ).

4.6.4 Application to Real-Time Flow Regime Identification

The trained objective flow regime identifier discussed in the preceding section, is adopted for real-time flow regime identification. The settings used in the SVM is the same as that used for static identification. New experiments are carried out at a fixed liquid superficial velocity (0.95 m/s) while the gas superficial velocity was increased steadily from 1.48 m/s to 26.17 m/s with increases taking place every 5 minutes. The trajectory of the gas-liquid superficial velocities is plotted in Fig. 4-26c where every 5 minutes is marked by a blue circle. The experiment duration was 30 minutes and voltage signals were collected at 100 Hz sampling rate and are presented in Fig.4-26a. Above the voltage-time plots, sample PDF plots at the representative time windows are depicted. The first PDF plot is from the first 180s time-window of the voltage signals. The PDF data from this is inputted into the KPCA-SVM identifier which gives an output of an identified flow regime. Successive movement of the time-window every second enables the flow regime to be identified at the end of every second. A summary of the identified flow regimes is depicted in the regime chart which is presented in Fig. 4-26a. This regime chart gives a list of all the possible flow regime classes on the y-axis per time plotted on the x-axis and in real-time application, the predominant flow regime in the horizontal concentric annulus is plotted against time. A comparison

is made between the trajectory in Fig. 4-26a and the flow regime map in Fig. 4-26c, which demonstrates the effectiveness of the developed method. The flow regimes at different gas and liquid superficial velocities were inferred accurately using only the knowledge of the flow regimes detected by the training samples, both within and beyond the borders of the training samples. For instance, the first flow regime identified is slug flow, and this results agrees with visually observed flow regimes and the fact that data points are located in the slug flow domain of the actual flow regime map. Similarly, traversing through the data points, various flow regimes must be crossed and this is reflected in the regime chart smoothly across time.

The data point trajectory is also plotted on the virtual flow regime map shown in Fig. 4-26b and is similar to the one in Fig. 4-22 but showing only the transition boundaries between the flow regimes. The virtual flow regime map is beneficial mainly because it explains why the objective identifier predicted a certain flow regime. For example, at 5 minutes, the identifier changed the flow regime from slug to churn flow because the trajectory had just crossed the exact boundary between the slug and churn flow regimes on the virtual map as computed by SVM. These results show that the constructed KPCA-based virtual flow regime map is useful for visualization of conductance data and as such the disadvantage of typical black-box pattern recognition models such as Artificial Neural Networks (ANNs) which give no visual aid and how they arrived at their decisions is eliminated.

Finally, the time window of 180 s for creating PDF plots from voltage data was chosen to try and pick up as much of the characteristics of each flow although Das et al.,(1999) concluded that 60 s was sufficient to develop PDF plots accurately. This time window was observed to improve flow regime identification performance. A time window which is too large may delay the response time of the identification while a too low time window may admit noise. Potentially, this could be used as a tuning parameter which could be called the *resolution*. Two objective identifiers can be trained: one having a higher resolution (smaller time-window length) than the other. When used together in the real-time tests, the

discrepancies between the outputs of each identifier can give more information about the multiphase flow.

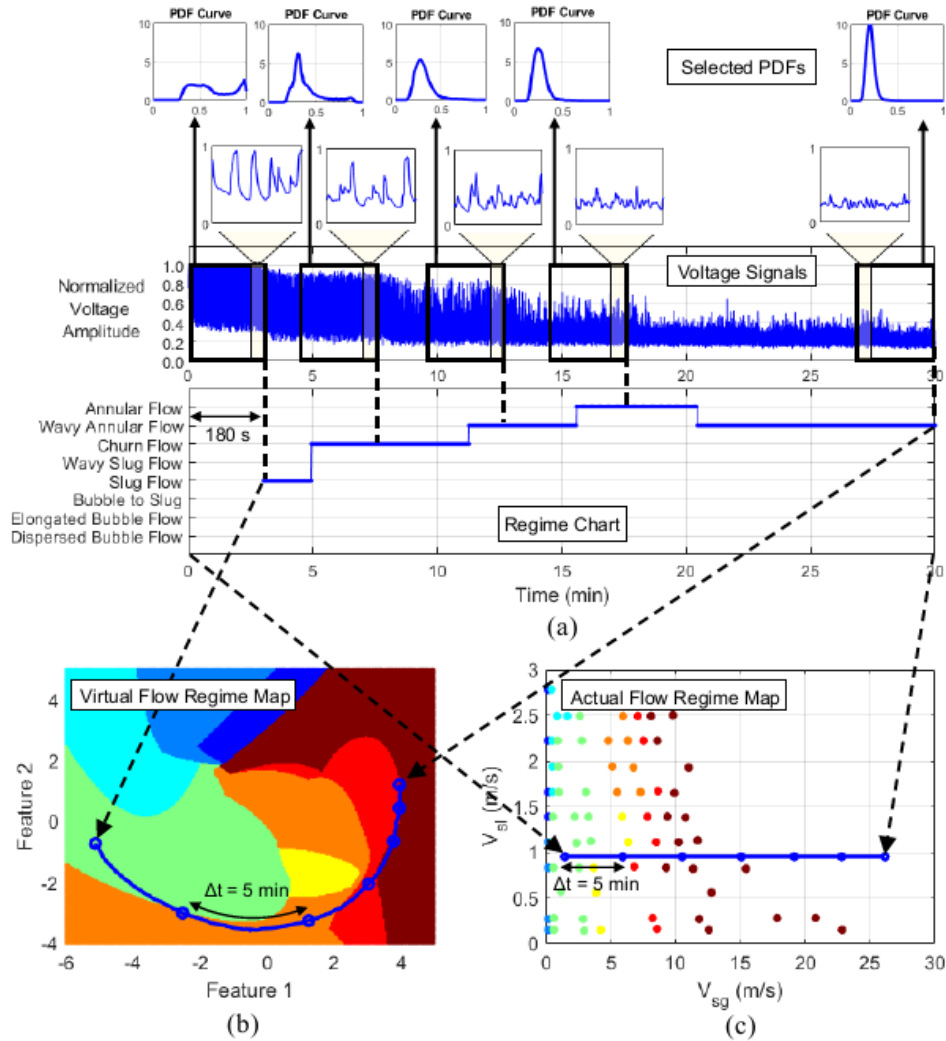


Figure 4-26: Results for real-time flow regime identification: (a) selected PDF plots, actual voltage-time signals, and regime chart; (b) trajectory of data points in the virtual flow regime map; (c) trajectory of data points in the actual flow regime map, along with training samples.

This technique could be adopted for objective flow regime identification in other conduits other than horizontal annuli configuration. Also, another potential application of this technique is switching of hybrid models for multiphase flow. That is the flow regime chart results can be used to switch between flow regime specific models for estimating properties of the flow or for model-based control.

Finally, further improvements can be made by paying more attention to the extraction of features and dimensionality reduction steps of this technique. In the future, it may be necessary to find feature extraction methods other than the use of KPCA of the PDF features, which would distinguish the flow regimes better particularly the intermittent flow region.

4.6.5 Conclusion

An objective flow regime identifier is proposed for gas-liquid two-phase flow in conduits in this section. Experimental studies were undertaken in a horizontal concentric annulus geometry, flush mounted with two pairs of conductance probes. By using kernel principal component analysis (KPCA) and multi-class kernel support vector machine (SVM), a virtual flow regime map is constructed completely using the PDF features of conductance data without any knowledge of the gas and liquid flow rates through the conduit. The chosen parameters avoid overfitting and underfitting and when compared with the visually observed flow regimes the training and test samples had accuracy of 94.8% and 90.9% respectively.

Also, for the first time, the proposed method has enabled an efficient real-time automatic flow regime identification tool based entirely on conductance data. However, improvements could still be made in terms of using more advanced feature extraction and dimensionality reduction techniques which could separate the data from different flow regimes better.

4.7 Chapter Summary

Flow regimes in horizontal annuli and their identification methods are studied. Experimental results for air-water tests carried out in two horizontal annulus configurations (concentric and fully eccentric) are presented. The experiments are conducted by varying a wide range of liquid and gas superficial velocities and in the first instance visually observing the flow regimes. For both annulus setups investigated, the observed flow regimes included; dispersed bubble, elongated bubble, slug, wavy slug, churn, wavy annular and annular flow regimes. The effect of annulus eccentricity on these two-phase flow regimes are then

investigated. Flow regime maps available in literature are compared with experimentally obtained maps and following from these comparisons, a robust flow regime map based on dimensionless parameters using over 1000 data points available in literature for two-phase gas-liquid flow in horizontal annuli is proposed. Finally, a novel objective real-time flow regime identification technique based on PDF of conductance data and kernel methods is developed. The main findings in this chapter are as enumerated below:

- A new flow regime is classified as wavy slug flow for this study. It was characterised using high speed camera images together with times series and PDF trends of the mean liquid holdup measured using conductance probes.
- The dominant flow regime in both annulus setups studied is the slug flow regime.
- The annulus eccentricity is observed to affect the observed flow regimes at low air and lowest water superficial velocities investigated in this study; where elongated bubble flow is encountered in the concentric annulus and slug flow in the fully eccentric annulus
- The bubble shape observed in the elongated bubble flow regime and the liquid film height during the wavy annular and annular flow regimes are affected by annulus eccentricity, visually observed difference were also confirmed from statistical PDF trends.
- The flow regime transitions observed to take place at higher liquid superficial velocities and lower gas superficial velocities in the fully eccentric annulus when compared to the concentric one.
- Both experimental flow regime maps were significantly different from maps available in literature for two-phase gas-liquid flow in pipes and annulus including those proposed by Beggs & Brill (1973), Mandhane et al., (1974), Taitel & Dukler (1976) (all developed for flow in circular pipes) and Osgouei et al., (2010) (developed for flow through horizontal annulus). The differences observed with circular pipe flow regime transitions may be due to less dominant gravitation factor in the annulus due to the uniqueness of

the geometry. The density difference in the annulus channel results in the suppression of the gas phase on the gas/liquid separation.

- Flow regime transition parameters developed for this study predicted experimental data with up to 86% accuracy but is not recommended for extension to other setups different from those used in developing it until further testing and improvement is done.
- Kernel Principal Component Analysis of PDF data from conductance probes can be used together with Support Vector Machine for objective real-time automatic flow regime identification in horizontal annulus and other conduits for that matter.

In conclusion, the flow regime have been identified and classified in horizontal annulus. The effect of annulus eccentricity on the flow regimes and their transitions can serve as a guide for drilling design engineers enabling them select optimum flowrates for the underbalanced drilling operation. The understanding provided by this study will lead to proper flow regime identification, leading to accurate selection of models for the design of equipment and or processes during gas-liquid flow in annulus. The developed flow regime transition criteria together with data provided will be also crucial to model developing physicist which can be incorporated into commercial software packages by simulation code developers. The development of real-time flow regime identification tool using SVM could potentially during real-time tests provide more information of the two-phase flow and also be applicable for switching between multiphase flow models using the flow regime charts developed. This could be beneficial to process control engineers who could use the technique to switch between flow regime based models for estimating specific flow properties and model based control. Measurement systems manufacturers and researchers working on heat exchangers and chemical reactor designs would potentially also be interested in the findings of this technique.

5 CHARACTERIZATION OF SLUG FLOW IN ANNULI

Chapter Highlights

- The annulus eccentricity results in a higher slug frequency in the fully eccentric annulus when compared to the concentric one.
- The annulus eccentricity is observed to have no effect on the slug translational velocity observed in horizontal annuli.
- The largest gap diameter concept is used to bring the dimensionless slug lengths in the concentric and fully eccentric annulus setups closer together. The approach reduces the difference between the average slug lengths of both annulus by 10%.
- The annulus eccentricity cause slug body holdup data to be higher in fully eccentric annulus when compared with the concentric annulus.

5.1 Overview

This chapter presents slug flow characteristics determined using non-intrusive conductivity measurements in concentric and fully eccentric annulus. For this study, two pairs of conductance probes flush mounted on a perspex pipe section of the outer pipe of the annulus cross section. Both probes were separated by a distance of 0.27 m and located a distance of 357 pipe diameters from the entrance of the annulus. The slug characteristics were computed from the analysis of the time series plots of the instantaneous liquid holdup values obtained from the probes.

During simultaneous gas-liquid two-phase flow operations, slug flow is the most predominant and complex flow regime in horizontal and near horizontal geometries. It is characterized by the intermittent flow of liquid slugs which bridge the entire conduit section followed by an elongated gas bubble flowing above a stratified liquid film layer (Wang et al., 2006; Al-Safran, 2009; Fan & Yan, 2014). The intermittency of the flow results in fluctuations in flow properties such as pressure and void fraction; which are important parameters to be considered for the design of pipelines and downstream facilities including slug catchers and separation systems (Fossa et al., 2003; Wang et al., 2006). The characterization

of slug parameters has seen significant efforts over the years with numerical simulations, theoretical analysis and experimental measurements all among the methods employed. Parameters measured include slug length, slug and film holdup, slug frequency, slug translational velocity and pressure gradient.

Most slug flow characterisation studies have been undertaken in circular pipes and as far back as the late 1960's and 1970's. Gregory et al., (1969; 1978) measured slug frequency and slug liquid holdup in three horizontal pipes with internal diameters of 0.019 m, 0.0258 m and 0.0512 m respectively. Carbon dioxide-water and Air-light refined oil were the testing fluids. A capacitance type volume fraction sensor was employed for slug flow parameters measurement. They developed empirical correlations for slug frequency and slug body holdup.

Experimental investigations were performed by Bendiksen (1984) to study the propagation of air bubbles in slug flow in pipes with diameters of 0.019 m and 0.05 m respectively. Inclination angles ranged from -30° to 90° . Based on their experimental investigations, they suggested a correlation of bubble and average liquid velocities based on least squares data fit.

Later Andreussi & Bendiksen (1989) determined the slug holdup for air-water flow in horizontal and near horizontal pipes using conductance probes. Experiments were conducted on a test section containing two transparent Plexiglas tubes with internal diameters of 0.05 m and 0.09 m respectively. They developed semi-empirical models for prediction of slug holdup which captured the effects of inclination, fluid properties and pipe diameter on this parameter.

Similarly, Fossa et al.,(2003), Wang et al.,(2006) and Fan & Yan (2014) all employed conductance probes for measurement of slug flow parameters in horizontal circular pipes. For their part, Fossa et al., (2003) measured slug frequency, slug translational velocity, slug holdup and slug length. Wang et al., (2006) on the other hand focused on slug length measurements using a single sensor conductance probe mounted at two different positions on the test section.

Fan & Yan (2014) extracted physical characteristic parameters such as slug holdup, slug length and slug translational velocity using two conductance probe

Al-Safran (2009, 2016) and Scott & Kouba (1990) studied phenomenologically slug flow characterization in pipelines. They developed new methods for predicting the existence of slug flow as well as new predictive models for some slug flow parameters.

Several experimental techniques have been adopted in the past to measure the slug flow characteristics in conduits including electrical impedance probes as utilized by Andreussi & Bendiksen (1989), Nydal et al.,(1992), Fossa et al.,(2003), Wang et al.,(2006) and Fan & Yan (2014); video methods were employed by Carneiro et al.,(2011) and Thaker & Banerjee (2015), Cook et al.,(1995) employed two impact tubes, while Al-Lababidi (2006) used ultrasonic measurement tools for slug flow characterization. Fan & Yan (2014) also reported the use of radiation attenuation and ultrasonic methods. All the studies highlighted here were undertaken for flow through circular pipes and from available literature, no studies have been undertaken to characterize slug flow in annuli.

The electrical impedance technique is based on the difference in the conductivities, permittivities and the electrical impedance across two electrodes immersed in a multiphase fluid observed in the individual phases. These properties are determined for each individual phase depending on the fraction of each phase in the conduit, the sensor configuration and flow regime. Conductance or capacitance techniques can be employed depending on whether the conducting phase is conductive or dielectric. Researchers have proposed different configurations of electrodes in order to reduce the dependence on flow regimes of the electrical impedance. Ring type conductance probes are employed in this study as described in chapter 3.

The slug flow regime is the predominant flow regime observed during two-phase gas-liquid flow in horizontal concentric and fully eccentric annuli as discussed in chapter 4 and although several studies exist of slug flow characteristics measurements in circular pipes, there are very few studies of slug flow characterization in horizontal annuli.

Ibarra & Nossen (2018) studied the bubble velocity in horizontal and low-inclination upward slug flow in concentric and fully eccentric annuli. Using gamma densitometers, they measured the instantaneous average cross-sectional holdup in two annuli geometries (concentric and fully eccentric) having D_o of 0.099 m and D_i of 0.050 m. The testing fluids used for their study were water and Exxsol D60 as liquid phase and sulphur hexafluoride (SF_6) as the gas phase. They however did not study other slug flow properties which are equally important for modelling of slug flow for the design of systems and processes. The slug parameters measured in this study are as follows:

- Slug frequency measurements in horizontal concentric and fully eccentric annuli using conductance methods and used to validate some correlations from literature.
- Slug translational velocity in horizontal concentric and fully eccentric annuli by conductance methods employed for validation of different correlations from literature.
- The coefficients distribution parameter C_0 , and drift velocity V_d are obtained based on experimental data of concentric annulus are also presented.
- Slug body and film length in horizontal concentric and fully eccentric annuli by conductance methods, used to validate correlations from literature.
- Slug body holdup in horizontal concentric and fully eccentric annuli by conductance methods, employed for validation of correlations in literature.

Finally, the effect of annulus eccentricity on slug flow parameters is investigated.

5.2 Slug Zone Classification

This section provides a classification of the slug flow zones in the annulus, which helps to identify the zones where the non-intrusive conductance probes can continue to function. According to Al-Lababidi (2006), slug flow could be defined as a mass of liquid travelling through a conduit, with a difference in dynamic pressure between the gas in front and behind it as the driving force, the liquid mass occupying the entire conduit. The slug regions are depicted in Fig 5-1 and

labelled A, B, C and D. The slug front is observed in (Zone A-B), the slug liquid body is seen in (Zone B-C), while the slug tail is seen in (Zone C-D).

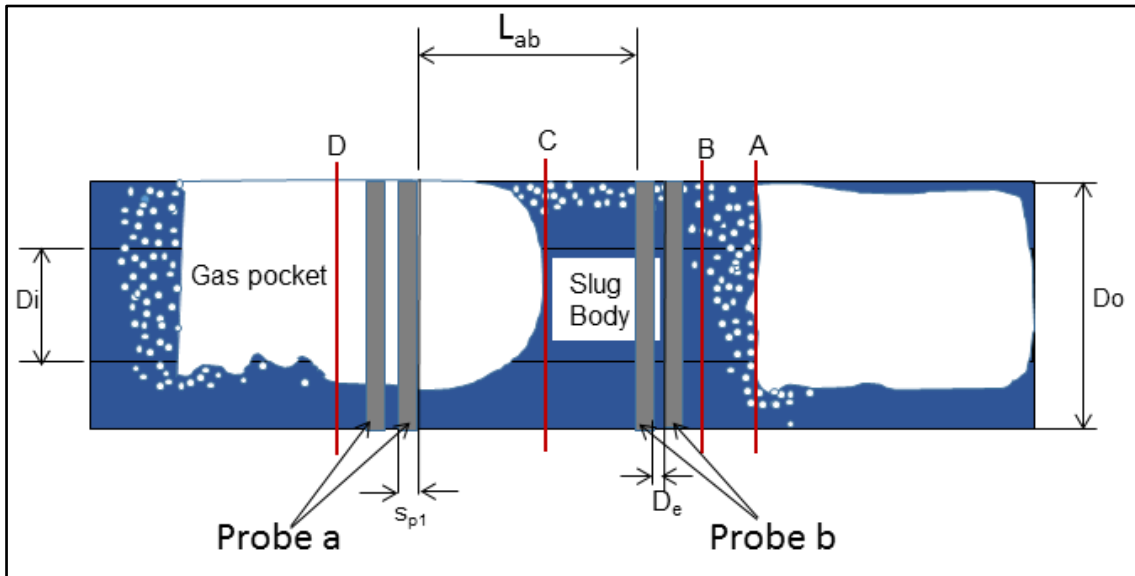


Figure 5-1: Slug flow regions in Horizontal concentric annulus

Also, the arrangement on the outer annulus pipe is depicted, in Fig. 5-1, where D_e is the spacing between each electrodes pair and is 26 mm, S_p is the width of the electrode and has value 6 mm and L_{ab} is the length separating the two probes with value of 270 mm. On the other hand, D_o and D_i are the outer and inner diameters of the annulus respectively.

5.3 Slug Frequency Measurements

In this study, slug frequency was measured by non-intrusive conductance probe technique in concentric and fully eccentric annulus and the measured frequency were used to validate the correlations by Gregory & Scott (1969), Fossa et al.,(2003) and Wang et al.,(2007). The slug frequency is defined as the number of slugs passing through a specific point (in this case through the conductance probes) in a conduit over a certain time frame. The slug frequency is an important variable during the design of slug catchers and separators and is a necessary input into mechanistic slug flow models used in predicting characteristics such as pressure drop and liquid holdup in pipelines (Al-Safran, 2009).

The approach of Al-Lababidi (2006) is employed practically to determine slug frequency for this study. The methodology involves obtaining the number of slugs counted in a given time interval after establishing a threshold value of the liquid holdup for which slug flow is encountered. Threshold values of 0.7 were reported by Nydal et al.,(1992), Fossa et al.,(2003), Al-Lababidi (2006) and Al-Safran . Liquid holdup values below 0.7 are considered as travelling waves and excluded from the slug count for frequency determination. For this study, after a sensitivity analysis was carried out, 0.7 was selected as the threshold value in agreement with suggestions made by the researchers listed above.

5.3.1 Slug Frequency in Horizontal Concentric Annulus

During air-water experiments conducted in the horizontal concentric annulus, conductance data is obtained for each of the test condition covered in the test matrix designed for the study where slug flow occurs. The liquid holdup is determined as a function of the dimensionless conductance of the conductance probes used for the study. A slug trace for the conductance probes is drawn for the conductance probes and a slug count is conducted for signals with threshold value above 0.7. Different tests were conducted at the liquid and gas superficial velocities presented in Table 5-1 and from the analysis of the time series plot of the varying liquid holdup, a ratio of the slug body peak counts above the threshold and the duration of each test point (30 s) for this study gave an estimate of the slug frequency for that test point as depicted in Fig. 5-2. Also, visual analysis of high speed camera recordings by counting the slugs passing through the test section viewing window over time were used to validate the observed results.

Table 5-1: Range of Liquid and gas Superficial velocities for slug flow in concentric annulus

V_{SL} (m/s)	V_{SG} (m/s)
0.15	0.63, 1.23, 2.97
0.27	0.62, 1.21, 2.89
0.56	0.61, 1.17, 2.73
0.83	0.59, 1.14, 2.57
1.11	0.57, 1.1, 2.4, 3.49

1.39	0.55, 1.06, 2.23, 3.29
1.66	0.53, 1.01, 2.08, 3.11
1.94	0.51, 0.97, 1.93, 2.94
2.22	0.49, 0.93, 1.79, 2.79
2.5	0.47, 0.88, 1.66, 2.63
2.77	0.45, 0.84, 1.55, 2.49

Slug frequency is plotted as a function of gas superficial velocity at different water superficial velocities as shown in Fig. 5-3. It is observed that there isn't a straightforward relationship between an increase in gas superficial velocity and the slug frequency. The observed trend includes in some cases, an increase in slug frequency initially as gas superficial velocities increases before reducing at the highest gas superficial velocity, while certain other conditions see a decrease of slug frequency as gas superficial velocity increases before increasing at higher gas superficial velocity values. This shows a weak dependence of frequency on gas superficial velocity for various liquid superficial velocities in horizontal concentric annulus and is consistent with what was observed by Wang et al., (2007) in their work.

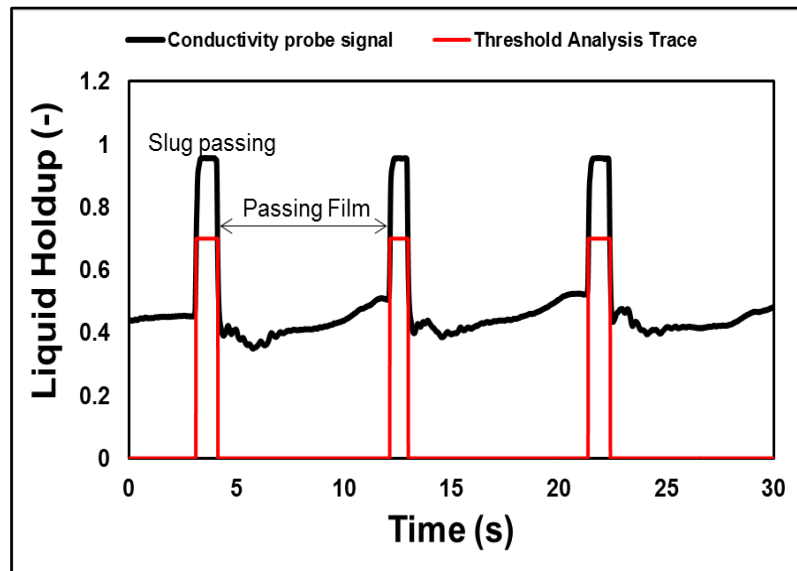


Figure 5-2: Threshold analysis applied on conductance probes

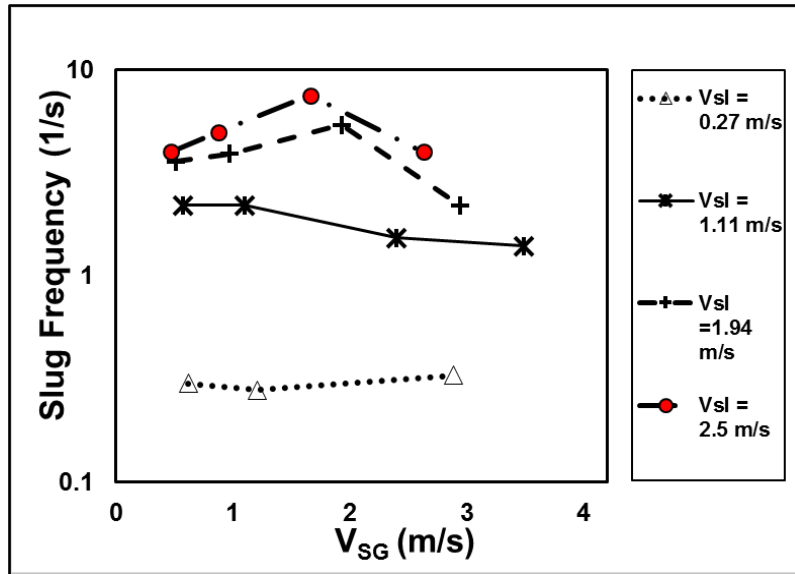


Figure 5-3: Slug Frequency as a function of gas superficial velocity at different liquid superficial velocities in horizontal concentric annulus

Similarly, Fig. 5-4 shows that an increase in liquid superficial velocity results in a corresponding increase in slug frequency. This implies that the slug frequency is strongly dependent on the liquid superficial velocity and is consistent with the observation of Al-Lababidi (2006) and Wang et al.,(2007).

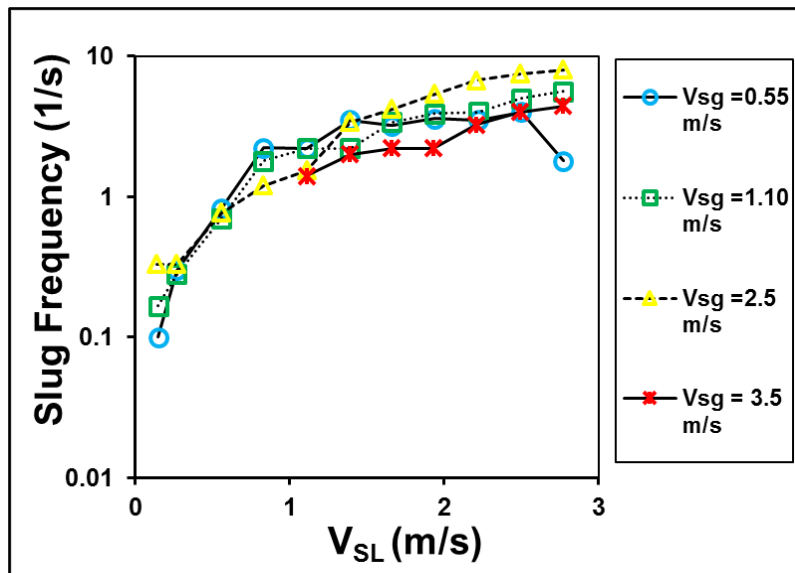


Figure 5-4: Slug frequency as a function of liquid superficial velocity at different gas superficial velocities in horizontal concentric annulus

In this study, the performance evaluation of slug frequency correlations in literature by Gregory & Scott (1969), Fossa et al., (2003), Wang et al.,(2007) and Al-Safran (2016) is carried out against the experimental data obtained. The approach involves validating the slug frequency based on modified Strouhal number given as:

$$St = \frac{\nu * D_H}{V_{SG}} \quad (5-1)$$

Where ν is frequency and D_H is hydraulic diameter. The slug frequency data in terms of Strouhal number is plotted against the liquid volume fraction computed as follows:

$$X_L = \frac{V_{SL}}{V_M} \quad (5-2)$$

In their study, Fossa et al., (2003) undertook air-water horizontal experimental studies in two different pipes having internal diameters of 0.06 m and 0.04 m respectively. Gas and liquid superficial velocities ranges explored were (0.3 - 4.0 m/s, and 0.6 - 3.0 m/s) respectively. An empirical correlation for Strouhal number was developed as follows:

$$St_{(Fossa)} = \frac{\nu * D}{V_{SG}} = \frac{A * X_L}{1 + B * X_L + C * (X_L)^2} \quad (5-3)$$

The constants of the correlation (A, B, and C) were inferred from slug frequency measurements and given as A= 0.044, B= -1.71, and C =0.70.

Wang et al.,(2007) carried out experimental studies in a horizontal pipe with internal diameter of 0.05 m. Air and water were the test fluids and the range of gas and liquid superficial velocities investigated were 1 – 20 m/s and 0.16 – 1.5 m/s respectively. They developed an empirical correlation similar to what Fossa et al., (2003) did as follows:

$$St_{(Wang et al.)} = \frac{\nu * D}{V_{SG}} = \frac{0.05X_L}{1 - 1.675X_L + 0.768(X_L)^2} \quad (5-4)$$

The measured slug frequency values were used to validate correlations and are presented in terms of Strouhal number in Table 5-2.

Figure 5-5 presents the comparison of Strouhal number obtained for this present work with those obtained from the correlations developed by Gregory & Scott (1969), Fossa et al. (2003), Wang et al. (2007) and Al-Safran (2016) and the following is inferred from the results:

- The slug frequency expressed as Strouhal number for flow in horizontal concentric annulus exhibits a similar trend as those obtained by Gregory & Scott (1969), Fossa et al. (2003), Wang et al. (2007) and Al-Safran (2016).
- Slug frequency is observed to increase with increasing superficial liquid velocity.
- The Gregory and Scott (1969) correlation matches the data in this study up to liquid volumetric fraction of 0.56. However, above this value, the frequency of this study is slightly higher than those of Gregory & Scott (1969) correlation.
- The correlation of Al-Safran (2016) provides marginally higher values of frequency than the data of this study.
- The correlations of Fossa et al. (2003) and Wang et al. (2007) show significantly higher Strouhal number values than those observed for this study. This is because the values developed for their constants were based on their own experimental data.

Generally, the observed differences in the correlations may be because they were developed for flow in circular pipes and have been extended to the annulus geometries using the hydraulic diameter concept.

Table 5-2: Slug frequency correlations and Strouhal number

Correlations	Slug frequency	Strouhal Number
Gregory & Scott (1969)	$v_{Gregory} = 0.0226 \left[\frac{V_{SL}}{gD_H} \left(\frac{19.75}{V_M} + V_M \right) \right]^1$	$St_{Gregory} = \frac{v * D_H}{V_{SG}}$
Fossa et al. (2003)	Experimental Data	$St_{(Fossa)} = \frac{A * X_L}{1 + B * X_L + C * (X_L)^2}$
Wang et al. (2007)	Experimental Data	$St_{(Wang)} = \frac{0.05X_L}{1 - 1.675X_L + 0.768(X_L)^2}$
Al-Safran (2016)	$v_{Al-Safran} = EXP[1.51 - 17.04(D_H) + 0.77Ln(V_{SL}) - 0.181Ln(S)]$ Where S is the Slip factor	$St_{Al-Safran} = \frac{v * D_H}{V_{SG}}$
This Study	Conductance measurements	$St_{Conductance} = \frac{v_{conductance} * D_H}{V_{SG}}$

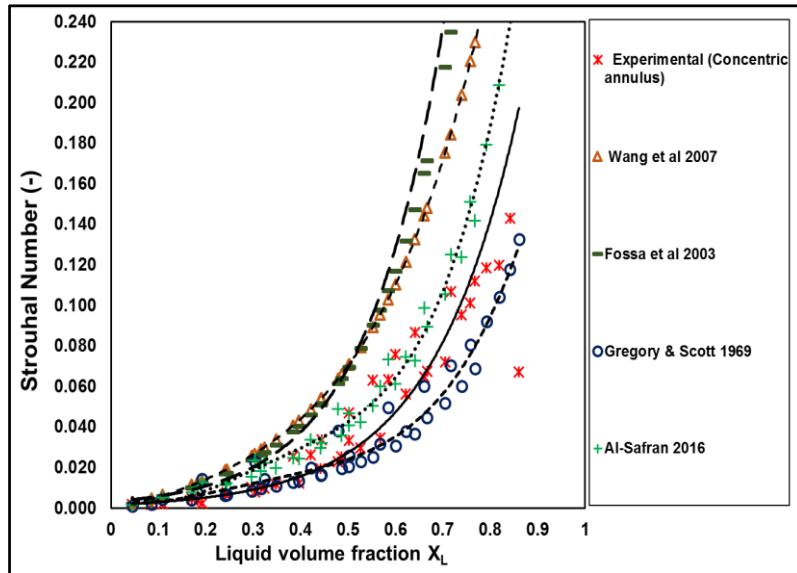


Figure 5-5: Validation of correlations using experimental slug frequency data in concentric annulus

5.3.2 Effect of Annulus Eccentricity on Slug Frequency

To understand the effect of annulus eccentricity on slug frequency observed during gas-liquid flow in horizontal annulus, experiments were conducted in a fully eccentric annulus with similar dimensions as the one presented in section 5.3.1. The experimental procedure was the same and the test conditions for which slug frequency were obtained in fully eccentric horizontal annulus are presented in Table 5-3.

The plot of slug frequency versus gas superficial velocity at different liquid superficial velocities shows a similar trend like observed in the concentric annulus. No particular effect of gas superficial velocity on slug frequency could be inferred as shown in Fig. 5-6. Similarly, the slug frequency in fully eccentric annulus is seen in Fig. 5-7 to be strongly dependent on the liquid superficial velocity.

Figure 5-8 shows a comparison between the observed slug frequency in concentric annulus and fully eccentric annulus. It can be noticed that at lower liquid superficial velocities, the slug frequency is higher in the fully eccentric annulus than the concentric annulus, however at higher liquid superficial velocities, the reverse is observed at some high gas superficial velocity.

Table 5-3: Range of Liquid and gas Superficial velocities for slug flow in fully eccentric annulus

V_{SL} (m/s)	V_{SG} (m/s)
0.15	0.21, 0.63, 1.23
0.27	0.21, 0.62, 1.22, 2.93
0.56	0.61, 1.17, 1.74, 2.73
0.83	0.6, 1.15, 2.67, 3.72
1.11	0.58, 1.1, 2.55, 3.54
1.39	0.56, 1.08, 2.44, 3.35
1.66	0.55, 1.05, 2.22, 3.01
1.94	0.53, 0.97, 1.93, 2.94
2.22	0.51, 0.97, 2.12, 2.86
2.5	0.47, 0.93, 2.02, 2.71
2.77	1.92

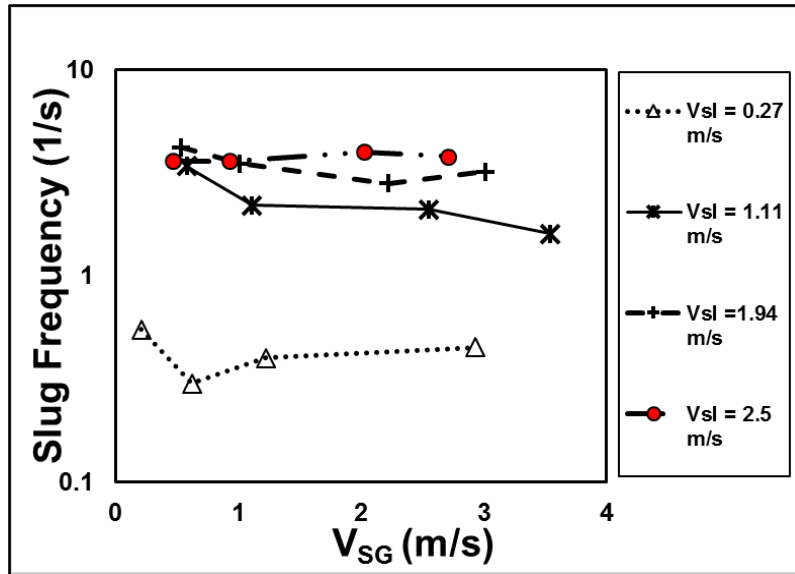


Figure 5-6: Slug Frequency as a function of gas superficial velocity at different liquid superficial velocities in horizontal fully eccentric annulus.

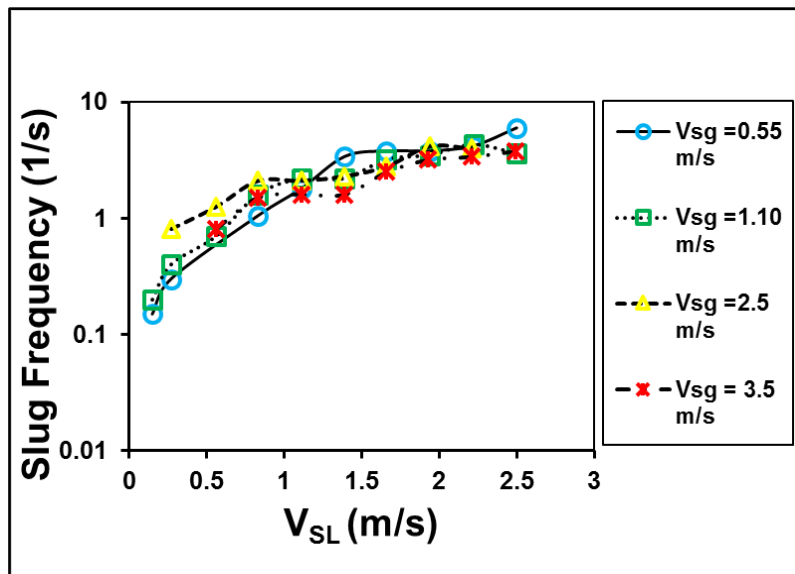


Figure 5-7: Slug frequency as a function of liquid superficial velocity at different gas superficial velocities in horizontal fully eccentric annulus.

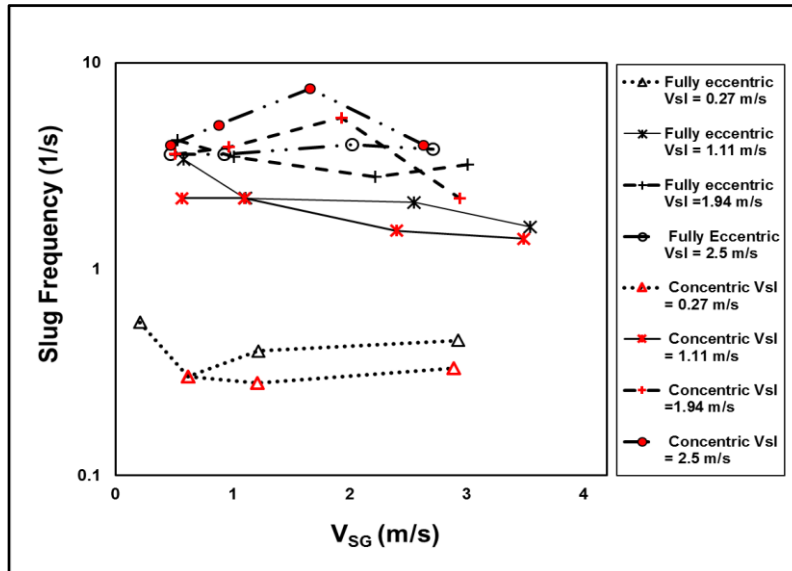


Figure 5-8: Effect of annulus eccentricity of slug frequency

The slug frequency data obtained from the fully eccentric annulus is compared with the correlations in Table 5-2 and the results are presented in Fig. 5-9. As observed previously in the concentric annulus data, the correlation of Gregory & Scott (1969) gives the best performance when compared with experimental frequency data up to liquid volumetric fraction of 0.72. Above this value, a higher experimental frequency is observed. Similarly, the Al-Safran (2016) correlation performs significantly better in the fully eccentric annulus when compared with the concentric one. On the other hand, the Fossa et al (2003) and Wang et al.(2007) perform badly when compared with experimental data.

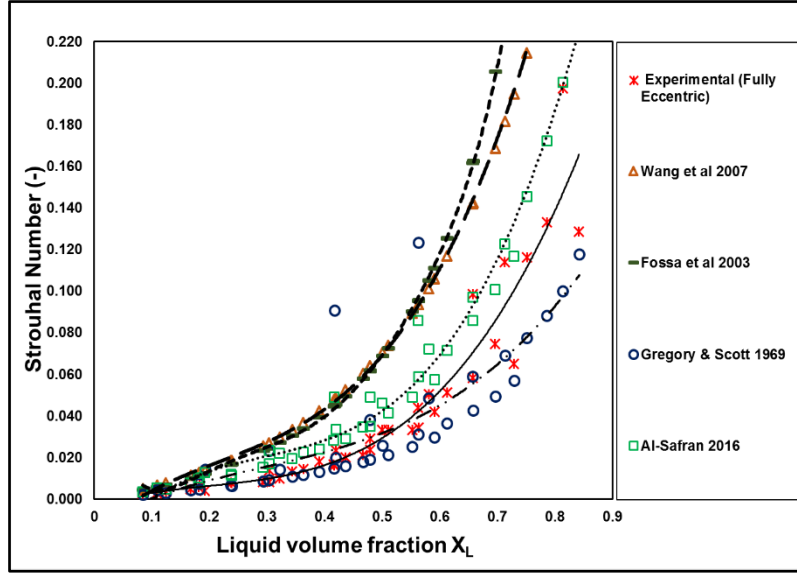


Figure 5-9: Validation of correlations using experimental slug frequency data in fully eccentric annulus

The annulus eccentricity is observed therefore to have some little effect on the slug frequency observed in horizontal annuli; and also there is a need to develop correlations for slug frequency determination in horizontal annuli as those available in literature were developed for flow in pipes and were just adapted for this study using the hydraulic diameter concept.

5.4 Slug Translational Velocity Measurements

The slug translational velocity for this study is determined by obtaining the time delay between two conductance probe signals using cross-correlation. The conductance probes are installed on the test section with a spacing $L = 0.308$ m between the centres of both probes and this spacing is used for slug translational velocity measurements. The conductance signals from both pairs of probes were cross-correlated based on the following equation:

$$R_{xy} = \frac{1}{T} \int_0^T x(t - \tau)y(t)dt \quad (5-5)$$

Where R_{xy} is the cross-correlation function, T is extraction duration, $x(t - \tau)$ and $y(t)$ are the two conductance probe signals at time $(t - \tau)$ and (t) respectively. The slug translational velocity is obtained as follows:

$$V_T = \frac{L}{\tau} \quad (5-6)$$

Where L is the known separated distance between centres of the conductance probes, τ is the time delay obtained by cross-correlation technique between the two conductance probe signals and V_T is the slug translational velocity measured using conductance probes. The arrangement of the probes is as presented in Fig. 5-10.

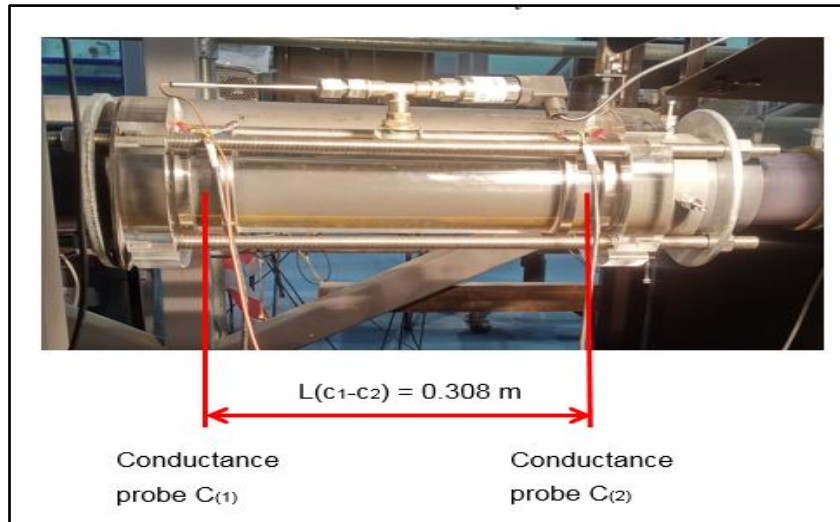


Figure 5-10: Arrangement of conductance probes for slug translational velocity measurements.

In order to cross-correlate the upstream and downstream conductance signals using the “xcorrel” subroutine of the MATLAB programming software version 2016a, the conductance signals must be extracted as shown in Figures 5-11 and 5-12 for slug flow in horizontal concentric annulus and Figures 5-13 and 5-14 for slug flow in horizontal fully eccentric annulus.

The extraction of the conductance signals causes the signal edge for each slug to become clearer and as such, the cross-correlation technique can be applied successfully (Al-Lababidi, 2006). The upstream and downstream conductance signals at different flow conditions as shown in Figures 5-11, 5-12, 5-13 and 5-14 follow the same trend, duplicating the slug shape.

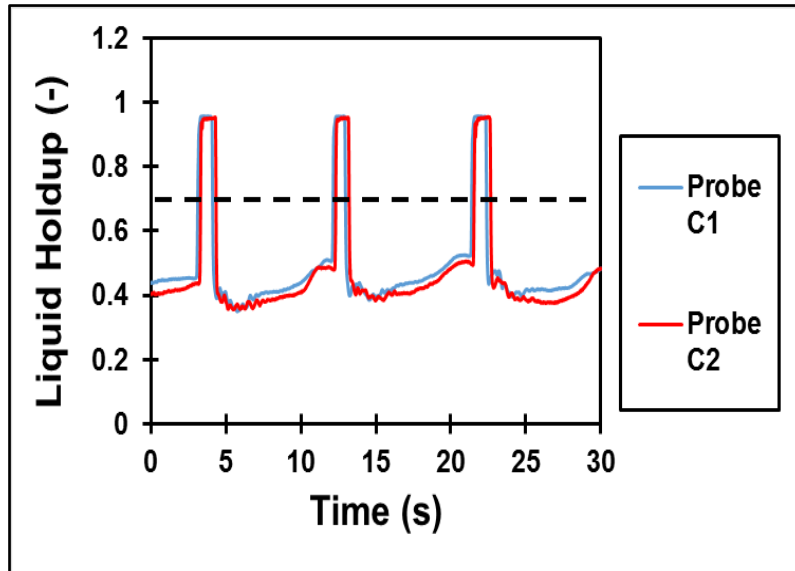


Figure 5-11: Conductance probes signals C1 and C2 from concentric annulus
($V_{SL} = 0.15$ m/s, $V_{SG} = 0.63$)

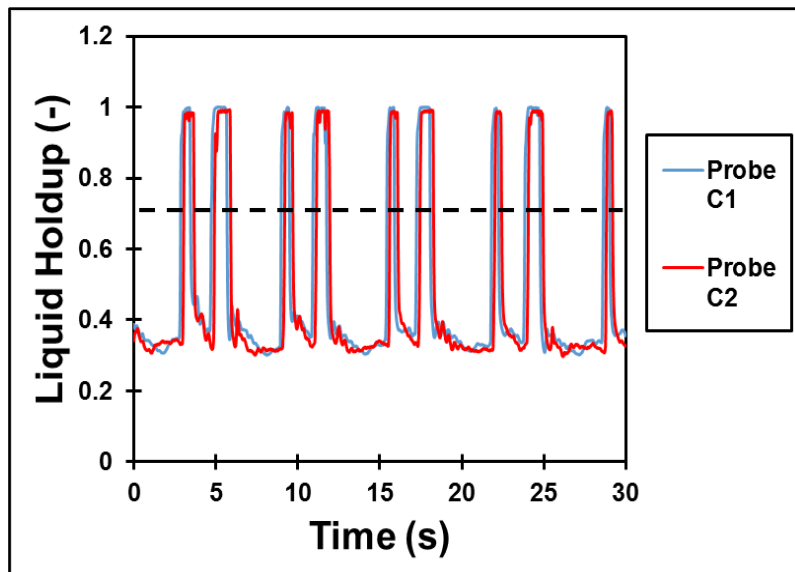


Figure 5-12: Conductance probes signals C1 and C2 from concentric annulus
($V_{SL} = 0.27$ m/s, $V_{SG} = 0.62$)

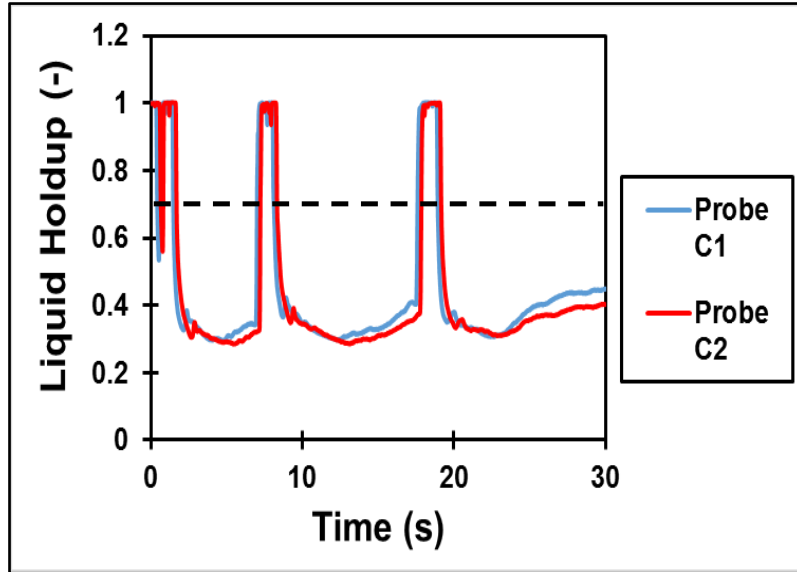


Figure 5-13: Conductance probes signals C1 and C2 from fully eccentric annulus ($V_{SL} = 0.15$ m/s, $V_{SG} = 0.63$ m/s)

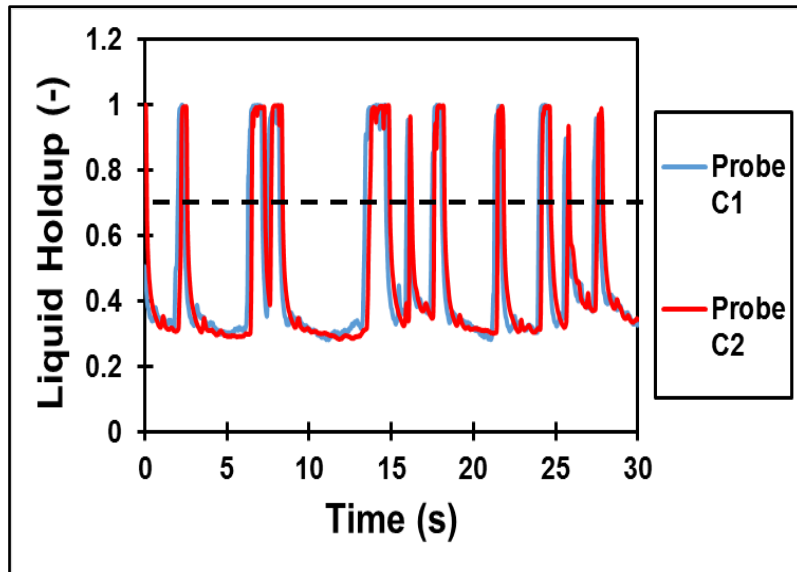


Figure 5-14: Conductance probes signals C1 and C2 from fully eccentric annulus ($V_{SL} = 0.27$ m/s, $V_{SG} = 0.62$)

5.4.1 Slug Translational Velocity in Concentric Annulus

The slug translational velocity in horizontal concentric annulus is measured based on the same conditions detailed in section 5.3.1 by using the cross-correlation technique. The observed translational velocity is plotted against the

gas superficial velocity as depicted in Fig 5-15 at different liquid superficial velocities.

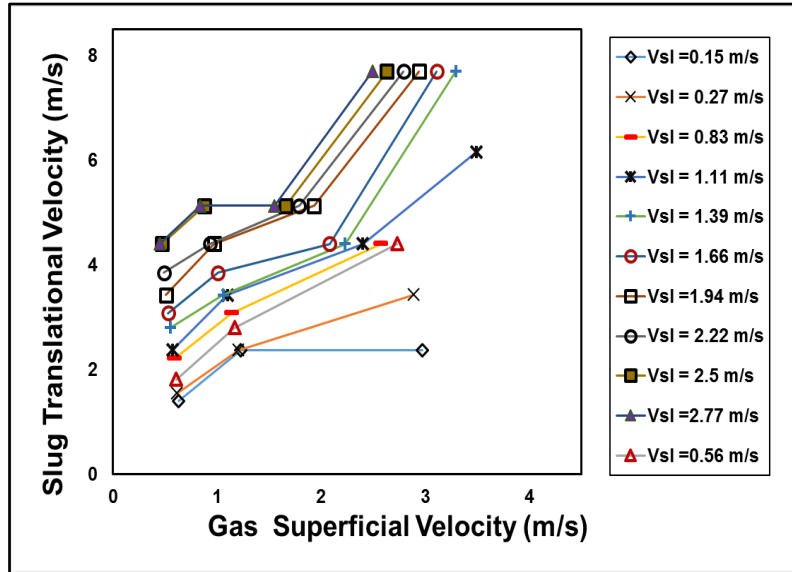


Figure 5-15: Slug velocity as a function of gas superficial velocity in horizontal concentric annulus.

The translational velocity is observed to increase with increase in gas and liquid superficial velocities.

Several different researchers including Bendiksen (1984) have found the slug translational velocity to be related strongly to the mixture velocity of the flow in the conduit. Nicklin et al (1962) as cited in Wang et al. (2006), Nicholson (1978) and Bendiksen (1984) all suggest that a linear relationship can be expressed between the slug translational velocity, the mixture velocity and the drift velocity, such that;

$$V_T = C_0 V_M + V_D \quad (5-7)$$

Where C_0 is a distribution parameter which is related to the velocity profile of dispersed systems, V_M is the mixture velocity and V_D is the drift velocity. Following a literature search, the coefficients C_0 and V_d could be expressed to be functions of the general expression:

$$C_0 = C_0(Fr_M, Re_s, \sigma, \varphi) \quad (5-8)$$

$$V_D = V_D(Fr_M, Re_S, \sigma, \varphi) \quad (5-9)$$

Where Fr_M is mixture Froude number defined by:

$$Fr_M = \frac{V_M}{\sqrt{gD_H}}, \text{ Where } D_H \text{ is the hydraulic diameter} \quad (5-10)$$

And Re_S is the slug Reynolds number given as:

$$Re_S = \frac{\rho_L V_M D_H}{\mu_L} \quad (5-11)$$

Where φ is the inclination angle and is zero for a horizontal system. A correlation for the motion of elongated gas bubble in horizontal concentric annulus based on a linear fit to experimental data is extracted for this study. The slug translational velocity measured using conductance probes employed for this study is plotted against mixture velocity as shown in Fig. 5-16. An increase in mixture velocity results in a corresponding increase in slug translational velocity up to 3.85 m/s; above this slug translational velocity, an increase in mixture velocity doesn't produce a corresponding increase in translational velocity.

Bendiksen (1984) and Al-Lababidi (2006) plotted mixture Froude number for mixture velocity versus slug translational velocity in order to derive the coefficients C_0 and V_D . Two data groups are distinguished in this study based on the mixture Froude number values as shown in Table 5-4 as suggested by Al-Lababidi (2006).

Table 5-4: Froude number groupings for determination of coefficients

Group	Mixture Froude number range
Group 1	$Fr_M \leq 3.5$
Group 2	$Fr_M > 3.5$

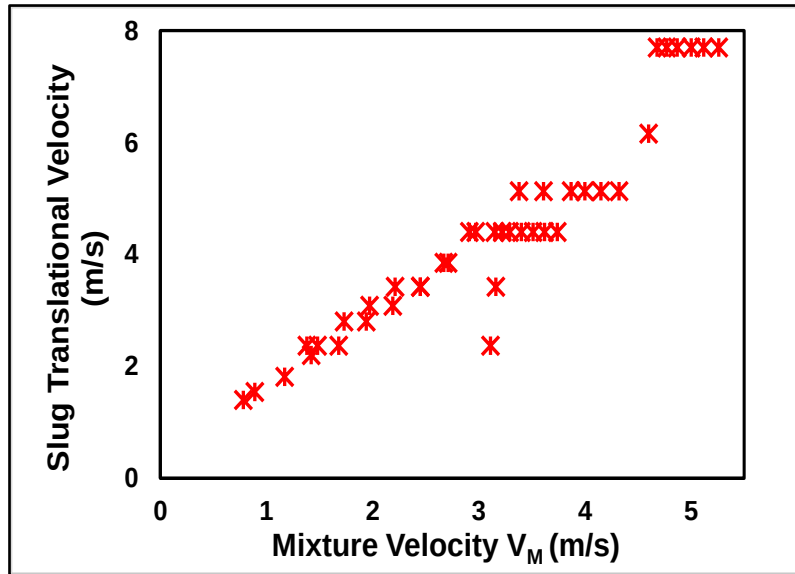


Figure 5-16: Slug translation velocity as a function of mixture velocity for horizontal concentric annulus

Analysis of the mixture Froude number is undertaken as shown in Fig 5-17 and the coefficients C_0 and V_D for each group is obtained based on a linear fit to the group data as seen in Fig. 5-18.

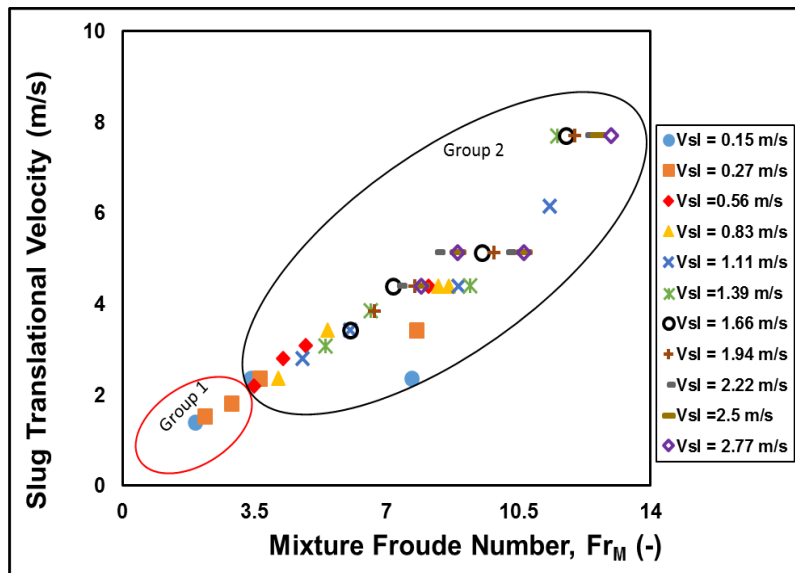


Figure 5-17: Slug translational velocity as a function of mixture Froude number in concentric annulus.

From Fig. 5-18, the following correlation for slug translational velocity of each group is defined as follows:

$$\text{Group 1: } V_T = 1.4072V_M + 0.2767 \quad (5-12)$$

$$\text{Group 2: } V_T = 1.4643V_M - 0.2461$$

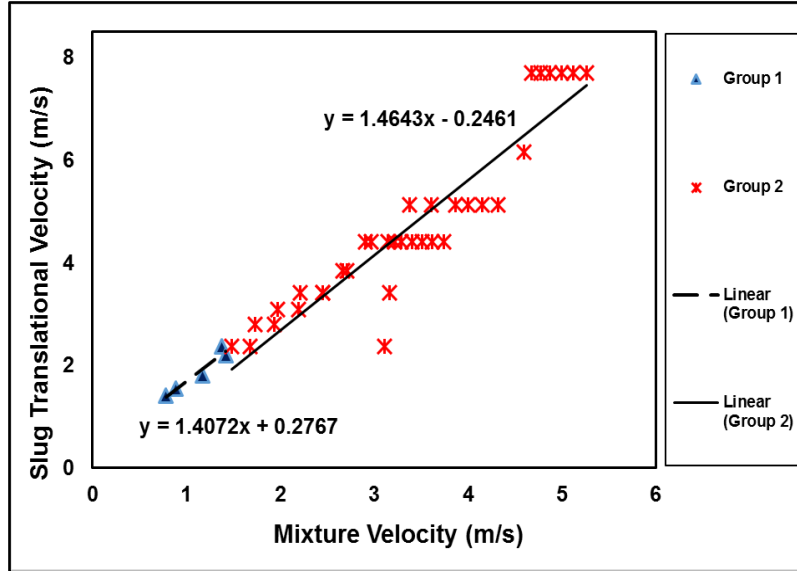


Figure 5-18: Extraction of linear coefficients C_0 and V_D in concentric annulus

The values of the distribution parameter C_0 and drift velocity V_d are given in Table 5-5 below:

Table 5-5: Extracted coefficients for slug translational velocity in horizontal concentric annuli

Distribution Parameter C_0	Drift Velocity V_D
1.4072	0.2767 when $Fr_M \leq 3.5$
1.4643	0.2461 when $Fr_M > 3.5$

In their work, Ibarra & Nossen (2018) obtained distribution parameters and drift velocity for the mean slug translational velocity for concentric and fully eccentric annuli in horizontal and slightly inclined geometries. Similarly, the relationship between the slug translational velocity and the mixture velocity was predicted using a uniform correlation. The parameters were based on two mixture Froude number groupings; $Fr_M < 3.3$ and $Fr_M \geq 3.3$ and the results for gas-water horizontal concentric annulus was as presented on Table 5.6 overleaf.

Table 5-6: Extracted coefficients in horizontal annulus by Ibarra & Nossen (2018)

Distribution Parameter C_0	Drift Velocity V_D
1.19	0.39 when $Fr_M < 3.3$
1.74	0.91 when $Fr_M \geq 3.3$

The observed values of C_0 and V_D is quite similar from their study and that presented here. However, the small difference observed is probably due to the difference in annular gap between both setup where they were obtained.

5.4.2 Effect of Annulus Eccentricity on Slug Translational Velocity

To study the effect of annulus eccentricity on slug translational velocity, the conductance probes are implemented on the fully eccentric annulus and the slug translational velocity is measured as discussed in Section 5.4. The results of slug translational velocity as a function of gas superficial velocity is shown in Fig. 5-19. The translational velocity is observed to increase with increasing gas and liquid superficial velocities similar to what was observed in the concentric annulus setup. This implies that the annulus eccentricity has little influence on the slug translational velocities observed in horizontal annuli.

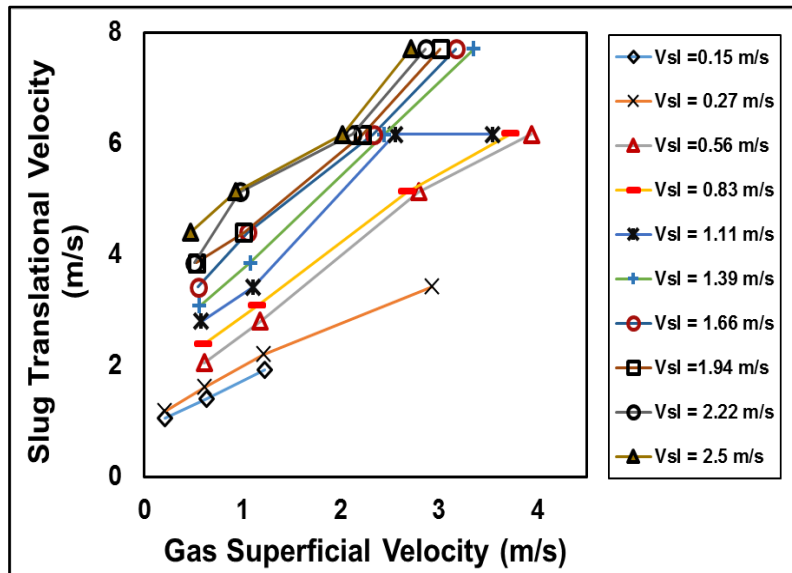


Figure 5-19: Slug velocity as a function of gas superficial velocity in horizontal fully Extraction eccentric annulus.

5.5 Slug Body Length and Film Region Length Measurements

Slug body length is a requirement in most slug flow models and its prediction is quite difficult. It is strongly dependent on the pipe diameter but some challenges have been observed with estimating the slug length for smaller pipe diameters. Furthermore, no study has been undertaken to determine the slug length in annulus.

A statistical approach is adopted for the study of the slug body length distribution presented in this section. The time of slug (t_{slug}) and film (t_{film}) are measured by applying the threshold level and assessing the width of the conductance probe signals as shown in Fig. 5-2. The threshold value was chosen as 0.7 for this study and based on that value, the slug body is successfully discriminated against the film region in the entire slug unit.

The slug and film lengths are computed based on the Equation below:

$$L_{(S)} = t_{slug} * \bar{V}_T, L_F = t_{Film} * \bar{V}_T \quad (5-13)$$

Where $L_{(S)}$ is the slug length, t_{slug} is the slug body passing time, L_F is the film region length, t_{Film} is the film region passing time and $\bar{V}_T$ is the averaged slug translational velocity measured using conductance probes.

5.5.1 Slug and Film Region Lengths in Concentric Annulus

Different slug length data for experiments conducted in concentric annulus are presented in Fig. 5-20. The average slug body lengths are plotted as a function of gas superficial velocities for different liquid superficial velocity. Similar to what was reported by Nydal (1992) and Al-Lababidi (2006), the slug length data observed for horizontal concentric annulus is to a large extent independent of gas superficial velocities.

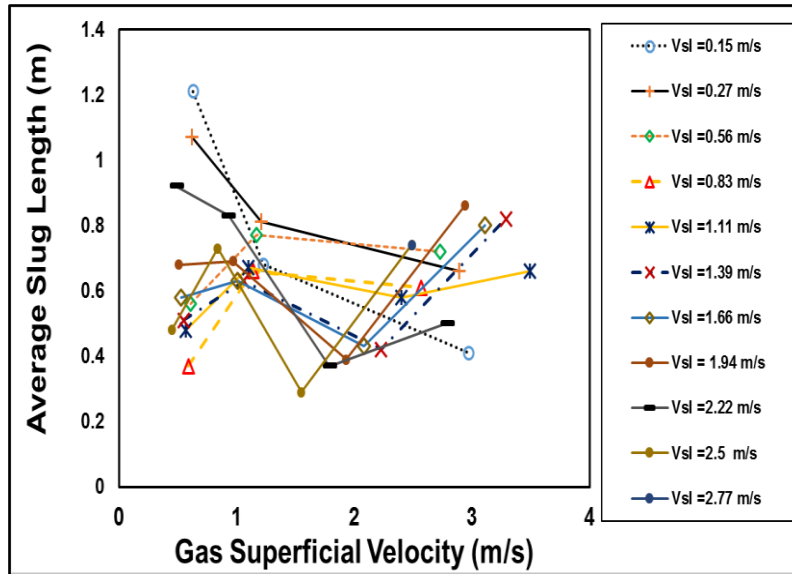


Figure 5-20: Slug length measured with conductance probes as a function of gas superficial velocity in concentric annulus

Different researchers reported constant slug lengths for a large range of mixture velocities during air-water flow in horizontal pipes. Dukler & Hubbard (1975) and Andreussi & Bendiksen (1989) reported slug lengths of $(2D - 24D)$, Nicholson et al. (1978) and Al-Lababidi (2006) observed $L_s = 12D - 30D$, while Wang et al. (2006) reported two ranges of slug length which were $(15D - 27D)$ and $(23D - 40D)$, where the first range was obtained at a shorter measurement distance on their setup than the second one. All these were reported for studies undertaken carried out in horizontal circular pipes.

Figure 5-21 shows that the range of slug length L_s obtained during this study in concentric annulus was between $(13D - 72D)$. The average slug length obtained using conductance probes in horizontal concentric annulus is approximately $(37D)$. It is higher than the value of slug length used by Lage et al., (2000) used as the closure for the intermittent flow model which was $30D$ and would result in huge errors in the pressure drop estimates. This is so because those values were based on air-water flow through horizontal circular pipes.

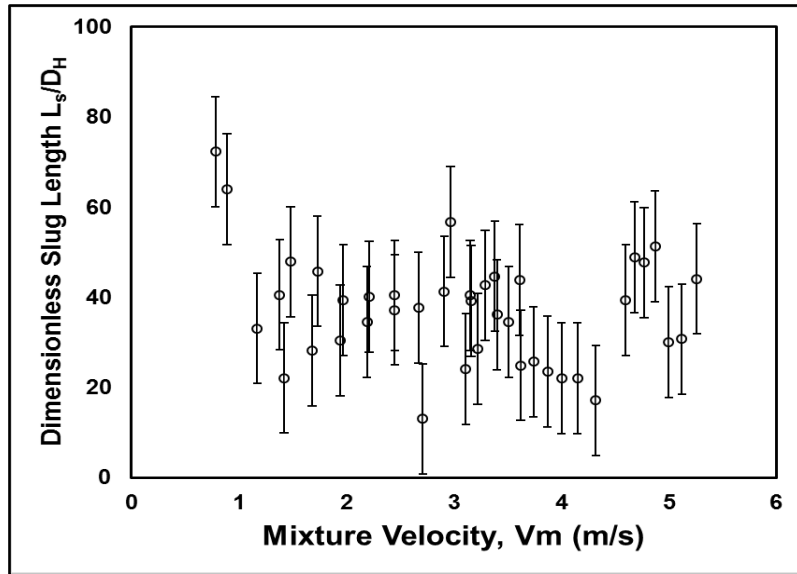


Figure 5-21: Dimensionless mean slug length as a function of mixture velocity in horizontal concentric annulus (The error bars represents the standard deviation from the mean value)

Regarding the film region length measured using conductance probes in the horizontal concentric annulus setup, a plot of film region length as a function of gas superficial velocities at different liquid superficial velocities in Fig. 5-22, shows that the film region length L_F increases with increase in gas superficial velocity, while increase in liquid superficial velocity results in a reduction in the film region length. This is in line with what was observed by Al-Lababidi (2006) during their study.

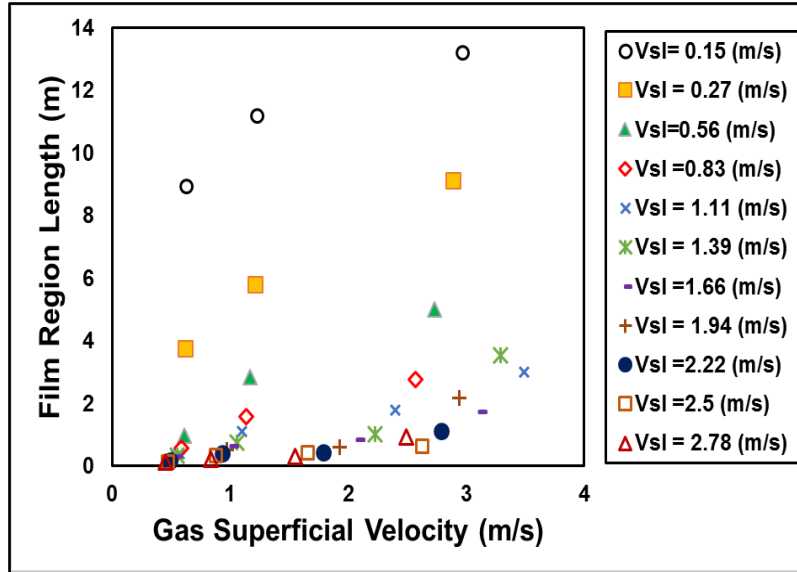


Figure 5-22: Film Region Length as a function of gas superficial velocity in horizontal concentric annulus.

5.5.2 Effect of Annulus Eccentricity on Slug and Film Region Lengths

The effect of annulus eccentricity on slug length and film region in horizontal annulus is studied in the fully eccentric annulus of this study. Fig. 5-23 shows a plot of the average slug length as a function of the gas superficial velocity at different liquid superficial velocities.

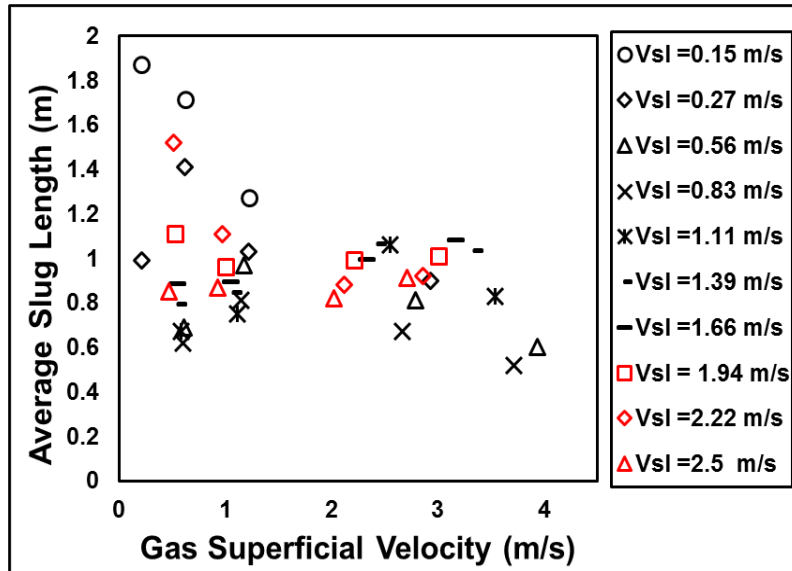


Figure 5-23: Slug length measured with conductance probes as a function of gas superficial velocity in fully eccentric annulus

It can be observed that as was stated in the concentric annulus, the slug length values are almost independent of the gas and liquid superficial velocities.

The annulus eccentricity affects the slug length observed in horizontal annulus. Longer slug lengths are observed in the fully eccentric annulus at similar gas and liquid superficial velocities when compared with those measured in the concentric one. Studies carried out by Mitsuishi & Aoyagi (1973) who measured point velocities of non-Newtonian solutions in eccentric annuli and Hacılamoglu & Langlinais (1990) who developed numerical methods to compute the velocity profile in concentric and eccentric annuli, show that point velocities are reduced in the reduced section of the eccentric annulus and depends on the diameter ratios as well as the annulus eccentricity. It is envisaged that this reduction in the velocities will particularly affect the liquid phase which flows at the bottom of the horizontal system, resulting in a reduction in its average velocity. This would in turn affect the slippage in the fully eccentric annulus making it higher than in the concentric one.

The dimensionless slug length L_s observed during this study in fully eccentric annulus is (31D – 111D) as presented in Fig. 5-24. Comparing Fig. 5-24 with Fig. 5-21, it can be seen that the dimensionless slug lengths of the fully eccentric

annulus are 2.4 and 1.5 times respectively those observed in concentric annulus in the higher and lower slug length ranges. This is quite a significant impact of the annulus eccentricity effect. The average dimensionless slug length observed in the fully eccentric annulus is 57D.

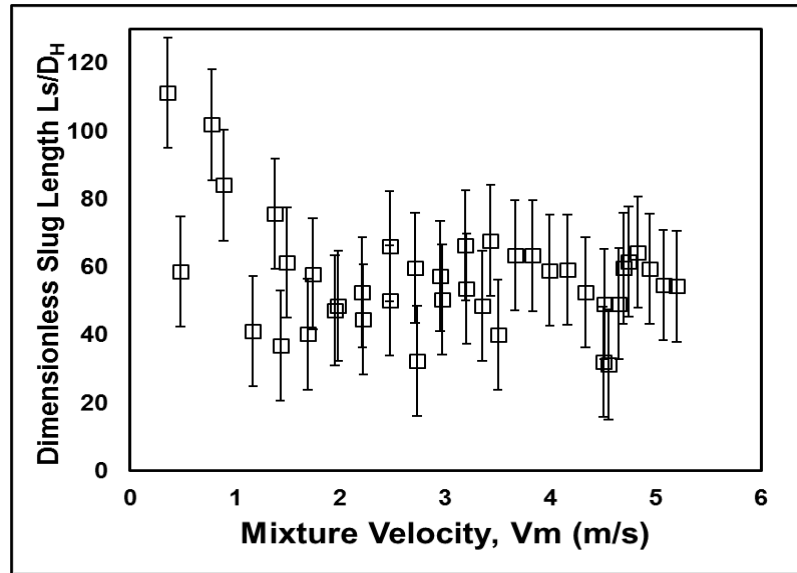


Figure 5-24: Dimensionless mean slug length as a function of mixture velocity in horizontal fully eccentric annulus (The error bars represents the standard deviation from the mean value)

The dimensionless slug length in both annuli is based on the standard hydraulic diameter concept. A 33% difference is observed between the average dimensionless slug lengths of both annuli and this is due to the diameter concept used. It is possible to improve the observed difference in this parameter by implementing a new diameter concept. The largest gap definition presented in chapter 2 is proposed as an appropriate definition for the concentric annulus, while the fully eccentric annulus, the largest gap is the difference of the outer and inner diameters, hence is identical to the conventional definition of hydraulic diameter in such channels. Using the new proposed diameter concepts and the experimental results, a comparison of the dimensionless slug length in concentric and fully eccentric annulus setups have been brought closer together as can be seen in Fig. 5-25. The observed difference in average slug lengths is reduced to 23%.

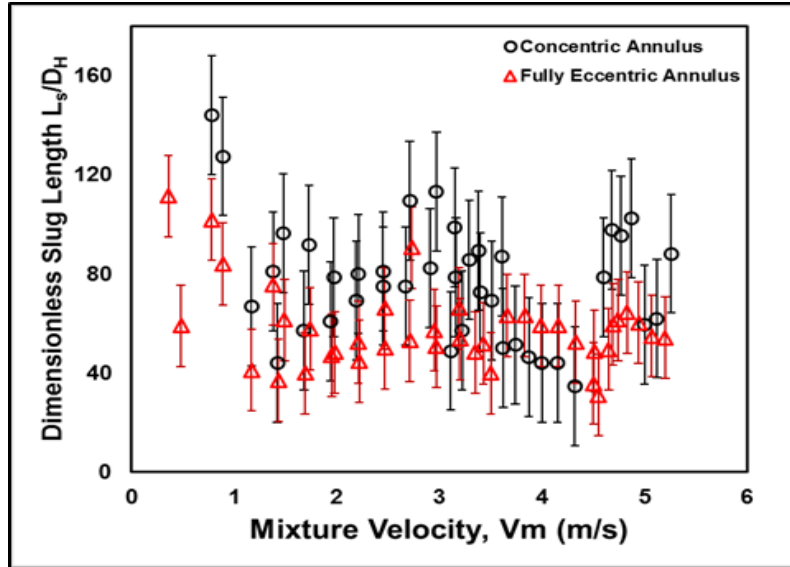


Figure 5-25: Dimensionless mean slug length as a function of mixture velocity in horizontal annulus based on largest gap diameter concept. (Error bars represent the standard deviation from the mean value).

The film region length measured in fully eccentric annulus is as depicted in Fig. 5-26. A similar trend is to what was obtained in concentric annulus where the film region length increases with increase in gas superficial velocity and decreases with increase in liquid superficial velocity is observed. The annulus eccentricity doesn't seem to affect the film region length considerable as only a slight increase in the average film region length value is noticed when both annulus setups are compared.

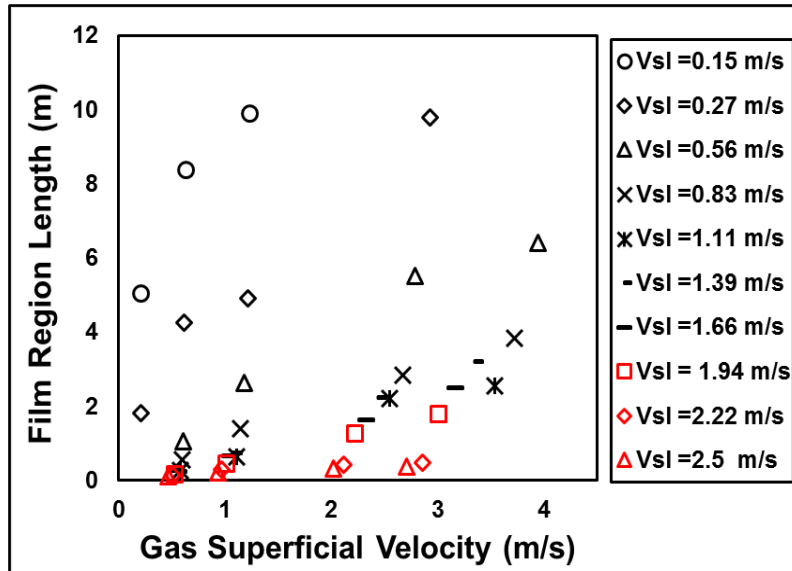


Figure 5-26: Film Region Length as a function of gas superficial velocity in horizontal fully eccentric annulus.

5.6 Slug Body Holdup Measurements

The liquid holdup in the slug body is an important parameter for slug flow modelling. Slug body holdup measurements in horizontal annuli were carried out using the conductance probes developed for this study. The liquid threshold value discussed in section 5.3 was adopted to discriminate adequately between the travelling waves and fully developed slugs detected by the conductance probes during experimental runs. Fig. 5-27 shows measurement of the slug body holdup by conductance probe techniques at slug flow conditions observed at ($V_{SL} = 0.15$ m/s, $V_{SG} = 0.63$ m/s). The slug body and film regions traces can be seen in the figure as detected by the conductance probe, after threshold analysis has been applied to distinguish the fully developed slugs from the travelling waves. The measured slug holdup obtained in this study were compared with prominent predictive models in literature. Gregory et al. (1978), Malnes (1979) as cited in Al-Lababidi (2006) and Paglianti et al. (1993) predictive models performances were evaluated.

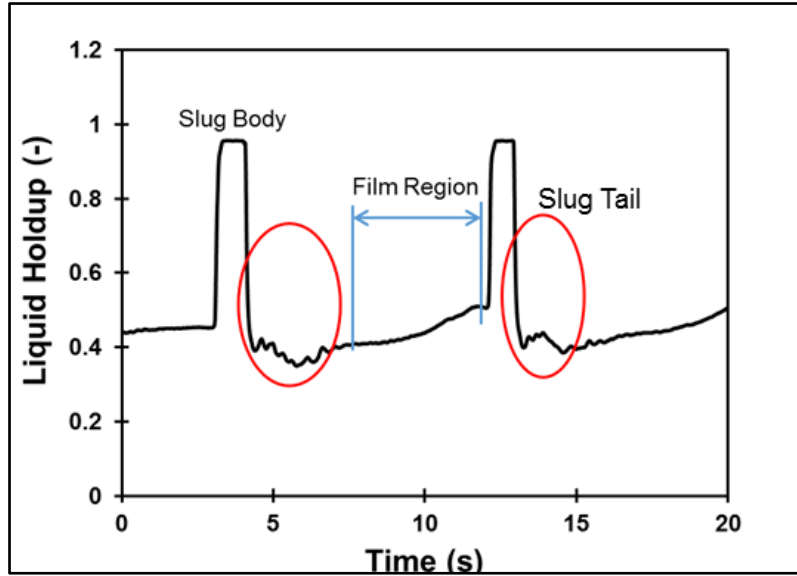


Figure 5-27: Slug Holdup measurements at ($V_{SL}=0.15$ m/s, $V_{SG}=0.63$ m/s)

These predictive models are as follows:

Gregory et al. (1978)

$$H_{LS} = \frac{1}{1 + \left(\frac{V_M}{8.66}\right)^{1.39}} \quad (5-14)$$

Malnes (1979)

$$H_{LS} = \frac{V_M}{C_M + V_M}, C_M = 83 \left(\frac{g\sigma}{\rho_L}\right)^{1/4} \quad (5-15)$$

Paglianti et al. (1993)

$$H_{LS} = \frac{1}{\left(1 + \frac{Fr^2 * Bo^{0.2}}{625}\right)^2} \quad (5-16)$$

Where Fr is the Froude number given as:

$$Fr = \frac{V_M}{\sqrt{gD_H}} \quad (5-17)$$

And Bo is the Bond number defined as:

$$Bo = \frac{\Delta\rho * g * D_H^2}{\sigma} \quad (5-18)$$

5.6.1 Slug Holdup Measurements in Concentric Annulus

In Fig. 5-28, the slug body holdup measured in the concentric annulus using conductance probes are presented. Generally, the slug holdup decreased with an increase in the gas superficial velocity. Also, a slight decrease is noticed with increase in liquid superficial velocities above 1.39 m/s.

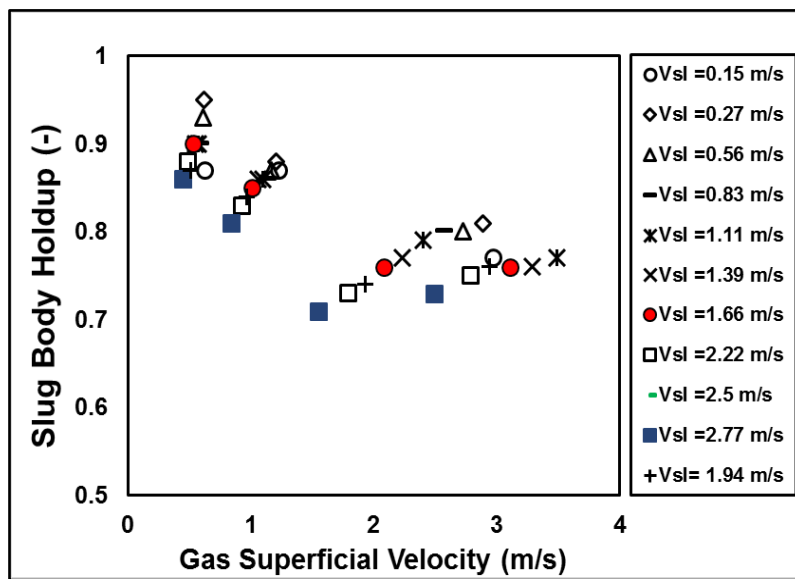


Figure 5-28: Measured slug holdup as a function of gas superficial velocity in concentric annulus

The predictive models described in section 5.6 are compared with measured slug body holdup values obtained in concentric annulus using conductance probes.

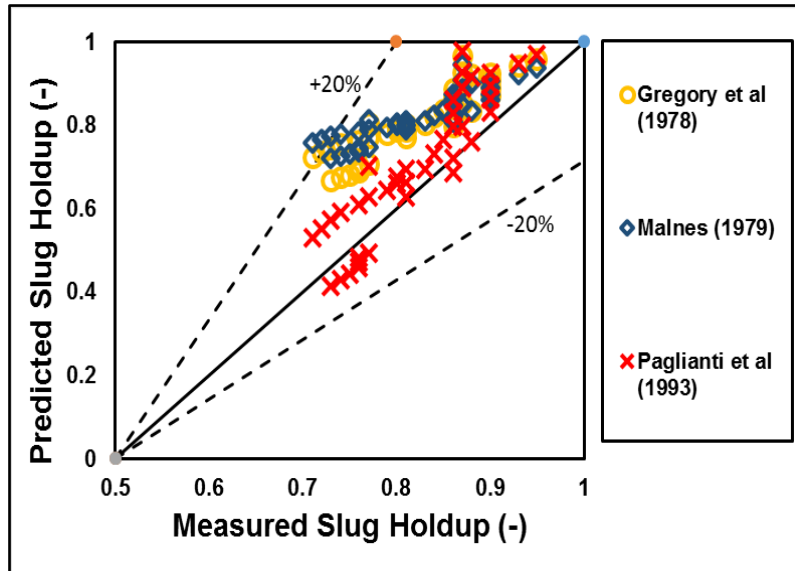


Figure 5-29: Comparison of slug bodyholdup values with predictive models in concentric annulus

The results are as presented in Fig. 5-29 and the statistical results of the conductance slug bodyholdup measurements performance are as shown in Table 5-6. It can be seen that the predictive model of Malnes (1979) performs best based on statistically analysis when compared with slug holdup data from concentric annulus although all the models tested have comparable results. The Gregory et al. (1978) model performs equally very well with the experimental data set but the Malnes model performed slightly better because it was based on modified representation of the former model. On the other hand, the model proposed by Paglianti et al. (1993) has the worst statistical performance with absolute average percentage error (AAPE) OF 15.3 % and a standard deviation of 14%. It is worth noting however, that none of these predictive models were developed for flow in horizontal annuli but rather for flow through circular pipes and have been extended to the annulus geometry using the hydraulic diameter concept. The errors may be a result of the geometry effect which may not be adequately captured with the hydraulic diameter.

Table 5-7: Statistical results of slug body holdup performance in concentric annulus

Predictive Model	E_1	E_2	E_3
Gregory et al. (1978)	-0.016	0.039	0.049
Malnes (1979)	0.000019	0.002	0.035
Paglianti et al.(1993)	-0.153	0.168	0.14

The mean error, E_1 , gives an indication of the magnitude of error and indicates the dispersion of the predicted value around the ideal prediction; the absolute mean error, E_2 gives the magnitude of the average absolute error. Finally, the standard deviation, E_3 , shows the degree of dispersion of the errors around their mean value. The errors used in this study are defined in Appendix B.

5.6.2 Effect of Annulus Eccentricity on Slug Body Holdup

The effect of annulus eccentricity on the slug body holdup in horizontal annuli is studied by measuring the slug body holdup using conductance probes in a fully eccentric annulus geometry. Fig. 5-30 shows the slug body holdup as a function of gas superficial velocity in this geometry. The trend observed is similar to what was seen with the concentric annulus, where the slug body holdup is observed to decrease with increase in gas superficial velocity. At lower liquid superficial velocities, a slight decrease is also noticed with increased liquid superficial velocities, but at V_{SL} above 0.56 m/s, there is little or no observed decrease in slug holdup with increase in liquid superficial velocity.

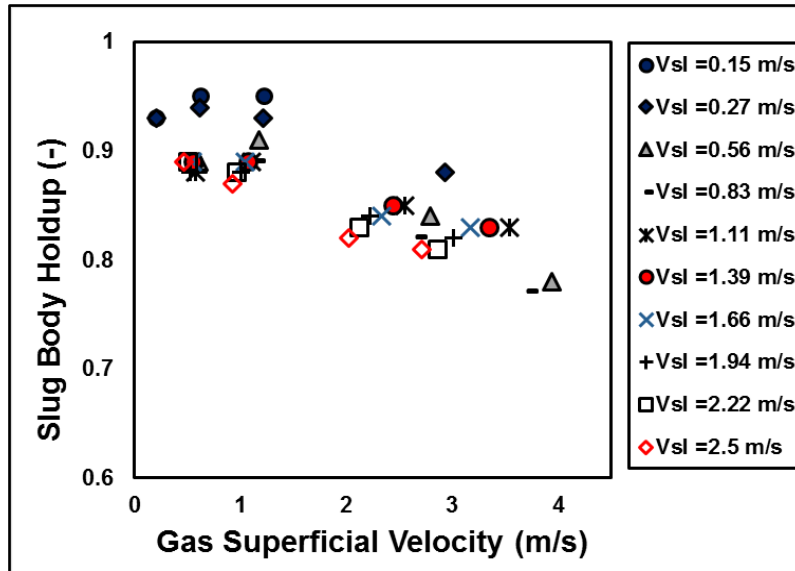


Figure 5-30: Measured slug body holdup as a function of gas superficial velocity in fully eccentric annulus

The annulus eccentricity causes the observed slug body holdup to be higher in fully eccentric annulus setup when compared with the concentric one. The slippage effect already highlighted probably plays a role in the observed trend. Also, it is possible the concentric annulus disrupts gas entrainment in the slug front. Figure 5-31 shows a plot of the slug body holdup for both annulus setup as a function of gas superficial velocity.

Also, the experimental data obtained in the fully eccentric annulus for slug body holdup is compared with the predictive models by Gregory et al. (1978), Malnes (1979) and Paglianti (1993) and the results are shown in Fig. 5-32. The experimental data is predicted fairly accurately by the Gregory et al. (1978) and Malnes (1979) models. On the other hand, the predictive model of Paglianti et al (1993) performs badly with the experimental data obtained in the fully eccentric annulus. Statistical results obtained from the models compared are presented in Table 5-7 and show that the Malnes (1979) model performs best.

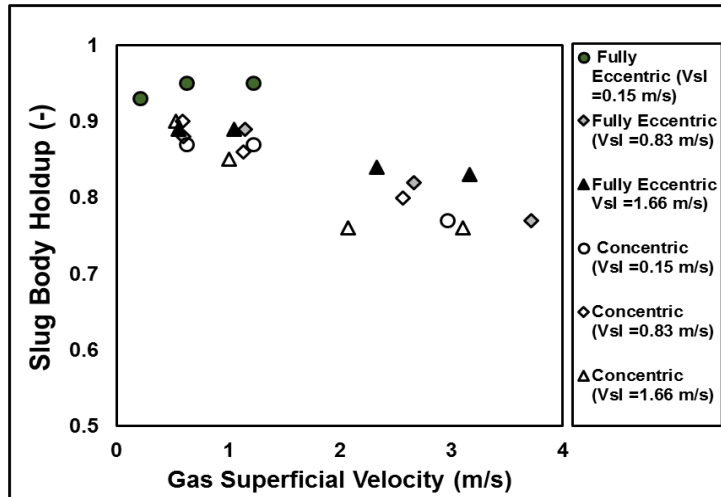


Figure 5-31: Effect of annulus eccentricity of slug body holdup

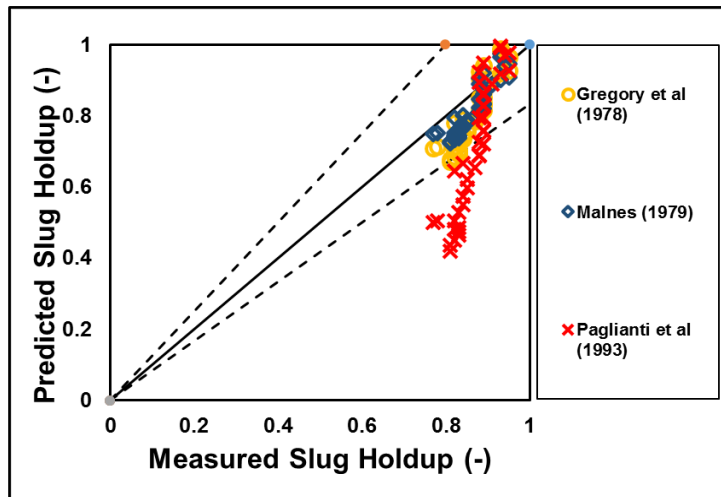


Figure 5-32: Comparison of slug body holdup values with predictive models in fully eccentric annulus

Table 5-8: Statistical results of slug body holdup performance in fully eccentric annulus

Predictive Model	E ₁	E ₂	E ₃
Gregory et al. (1978)	-0.063	0.078	0.069
Malnes (1979)	-0.050	0.058	0.044
Paglianti et al.(1993)	-0.192	0.208	0.17

5.7 Chapter Summary

This chapter covers measurements of the slug flow characteristics in horizontal concentric and fully eccentric annulus using conductance probes. Slug parameters investigated included slug frequency, translational velocity, slug and film region lengths and slug body holdup. The main findings of this chapter summarized thus:

- The slug frequency is found to be independent of the gas superficial velocities investigated. However, an increase in the slug frequency was observed as the liquid superficial velocity was increased. The annulus eccentricity results in a higher slug frequency being observed in the fully eccentric annulus when compared to the concentric one.
- Meanwhile, the annulus eccentricity is observed to have no effect on the slug translation velocity observed in horizontal annuli.
- The range of slug length observed in the concentric annulus was (15D-72D) with average length of 37D. On the other hand, the full eccentric annulus had slug lengths ranging between (31D – 111D) with average of 57D. This implies that the annulus eccentricity has an effect on the slug body length observed in horizontal annuli. However, the film region length seems unaffected by annulus eccentricity.
- The largest gap diameter concept is used to bring the dimensionless slug lengths in the concentric and fully eccentric annulus setups closer together. The approach reduces the difference between the average slug lengths of both annulus by 10%.
- Slug body holdup data obtained in both concentric and fully eccentric annulus indicates that the annulus eccentricity affects the slug body holdup measured using conductance probes in horizontal annuli.
- Predictive models in literature have been compared with the measured slug flow parameters with varying levels of success.

The main conclusion which can be drawn for this chapter are; the predictive models available in literature for two-phase slug flow characterization were mainly developed for flow in circular pipes and as such the discrepancies

observed during comparisons with experimental data maybe as a result of the different geometries. Irrespective of this fact, this a valuable first step in characterizing slug flow in annular geometries. The slug flow parameters measured will be suitable for equipment design engineers to design slug catchers, separators and pipe lines for the oil and gas industry. Also, process control engineers can find useful information for implementing slug control measures which may become necessary at certain conditions due to overall economics of the process.

6 LIQUID HOLDUP IN GAS-LIQUID FLOWS IN HORIZONTAL ANNULI

Chapter Highlights

- The annulus eccentricity causes higher liquid holdup values in concentric annulus at gas superficial velocities below 6.8 m/s when compared with the fully eccentric annulus. At gas superficial velocities above 6.8 m/s, the fully eccentric annulus has higher liquid holdup values than the concentric annulus.
- At low to intermittent mixture velocity ranges, the gravitational forces are observed to be more important due to the density difference in the concentric annulus when compared with the same flow conditions in the fully eccentric annulus.
- At higher mixture velocities, the frictional forces become more significant than the gravitational forces and the fully eccentric annulus seems to have higher frictional forces at the higher mixture velocities when compared with the concentric one
- A new liquid holdup correlation is proposed based on dimensionless numbers and is successfully utilized to predict integrated data from literature and experiments with a mean error of 13%.

6.1 Overview

In this section, the mean liquid holdup measured using conductance probes in horizontal concentric and fully eccentric annulus are presented. The effect of annulus eccentricity on the mean liquid holdup is investigated and performance evaluation of some existing models and correlations developed for flow in circular pipes and adapted to the annulus geometries based on different diameter concepts are presented. A new liquid holdup correlation is developed based on dimensionless parameters using an integration of data points from experiments and literature.

The liquid holdup refers to the part of the volume element during two-phase flow occupied by the liquid phase. Knowledge of the liquid holdup variations allows for

the calculation of the slippage between both phases. Energy transfer between the interfaces of the phases is as a result of the slippage between both phases, and as a result, the liquid holdup is an important parameter for determination of flow regimes and pressure drop during multiphase flows in conduits (Eaton et al., 1967)

Different modelling approaches have been adopted in the past for liquid holdup in conduits and the performance of some models from each of the groups are tested with experimental data. The modelling approaches include:

Homogeneous No-slip model: This modelling approach involves combining the two phases into a single fluid by averaging the velocity and average fluid properties while assuming no-slip conditions. Wallis (1969) defined the homogeneous liquid holdup as follows:

$$H_{Lhom} = 1 - \frac{1}{1 + \frac{1-x}{x} \cdot \frac{\rho_G}{\rho_L}} \quad (6-1)$$

Where x is the mass quality and from this, homogeneous liquid holdup can be computed by subtracting the void fraction from 1.

Separated Flow model: This modelling approach considers the fact that the two phases flowing through the conduit have different velocities and properties. The liquid holdup is determined based on the approach presented in Equation (6-2) where the slip ratio is S .

$$H_{Lseparated} = 1 - \frac{1}{1 + \frac{1-x}{x} \cdot \frac{\rho_G}{\rho_L} \cdot S} \quad (6-2)$$

Three different separated flow models are employed in this study to determine the void fraction and from there the liquid holdup. These are:

Chisholm (1967) basis for Lockhart & Martinelli (1949) correlation where the liquid holdup is computed as a function of the Lockhart & Martinelli parameter as given below:

$$H_L = 1 - (1 - X^{0.8})^{-0.378} \quad (6-3)$$

Chilsom (1973) for slip ratio:

$$S = \sqrt{1 - x \cdot \left(1 - \frac{\rho_L}{\rho_G}\right)} \quad (6-4)$$

Butterworth (1975) approximation of Lockhart & Martinelli (1949) velocity ratio:

$$S = 0.28 \cdot \left(\frac{1-x}{x}\right)^{-0.36} \cdot \left(\frac{\rho_G}{\rho_L}\right)^{-0.64} \cdot \left(\frac{\mu_L}{\mu_G}\right)^{0.07} \quad (6-5)$$

Drift Flux model: The drift flux model can give precise values of the void fraction if properly applied. This is because it accounts for the two most important factor which causes the slip between the phases; the direction of the gravity vector and the combined velocity-density distribution in the conduit. However, this modelling approach is difficult to implement and used only in complex systems (Gschnaidtner, 2014). The liquid holdup is computed using the drift flux model as given in Equation (6-6)

$$H_L = 1 - \frac{V_{SG}}{C_0 V_M + V_D} \quad (6-6)$$

Where C_0 is the distribution parameter and V_d is the drift velocity and represent the drift parameters. Several drift flux void fraction correlations are summarized by Bhagwat & Ghajar (2014). The drift flux parameters of Bonnecaze et al., (1971) cited in Bhagwat & Ghajar (2014), Fabre & Line (1992) and Wang et al., (2017) are used to obtain liquid holdup for this study based on the different diameter concepts utilized as highlighted in chapter 2.

Bonnecaze et al., (1971):

$$C_0 = 1.2 \quad (6-7)$$

$$V_d = 0.35 \sqrt{g D_H \Delta \rho / \rho} \text{ where } \Delta \rho = (\rho_L - \rho_G) \quad (6-8)$$

Fabre & Line (1992):

$$C_0 = \frac{2.27}{1 + \left(\frac{Re}{1000}\right)^2} + \frac{1.2}{1 + \left(\frac{1000}{Re}\right)^2} \quad (6-9)$$

$$V_d = 0.0246 \cos \theta + 1.606 \left(\frac{g \sigma \Delta \rho}{\rho_L^2} \right)^{1/4} \sin \theta \quad (6-10)$$

Wang et al., (2017):

$$C_0 = \frac{2}{1 + \left(\frac{Re_{TP}}{1000}\right)^2} + \frac{1.2 - 0.2\alpha^4}{1 + \left(\frac{1000}{Re_{TP}}\right)^2} \quad (6-11)$$

Where $Re_{TP} = \frac{V_M D_H \rho_L}{\mu_L}$ and α is the gas void fraction.

$$V_d = 1.53 \left(\frac{g \sigma (\rho_L - \rho_G)}{\rho_L^2} \right)^{0.25} + 0.35 \sqrt{\frac{g D_H (\rho_L - \rho_G)}{\rho_L}} \alpha (1 - \alpha)^{0.25} \quad (6-12)$$

Flow regime based models: These models consider the particular flow regimes when computing for the liquid holdup. They are usually referred to as mechanistic models and are based on fundamental laws, with the ability to model fluid properties and geometric variations more accurately than empirical models. A typical example of an empirical model which is flow regime dependent was proposed by Beggs and Brill (1973). This model accounts for three different flow regimes classifications namely: segregated flows, intermittent flows and distributed flows. Individual liquid holdup values can be estimated for each flow regime class based on the correlation that follow:

$$H_L = \frac{a \lambda_L^b}{(Fr_M^2)^c} \quad (6-13)$$

a, b and c are flow regime dependent coefficients and are provided in the Table for the three flow regime categories mentioned earlier.

Table 6-1: Liquid Holdup correlation coefficients

Flow Regimes	a	b	c
Segregated	0.98	0.4846	0.0868
Intermittent	0.845	0.5351	0.0173
Distributed	1.065	0.5824	0.0609

Also, the Petalas and Aziz (2000) model is modified for annulus geometry using different hydraulic diameter concepts and used to estimate the liquid holdup in the intermittent flow region. Their intermittent flow model used the slug and elongated bubble flow regimes. The liquid holdup for intermittent flow is determined by taking an overall liquid mass balance over the slug-bubble unit as given below:

$$H_L = \frac{H_{LS}V_T + V_{db}(1 - H_{LS}) - V_{SG}}{V_T} \quad (6-14)$$

Where velocity of dispersed bubbles is V_{db} , H_{LS} is the slug body holdup and are determined from empirical correlations. The elongated bubble translational velocity was computed from the model of Bendiksen (1984) as:

$$V_T = C_0 V_M + V_d \quad (6-15)$$

The distribution parameter C_0 is determined using the empirical correlation below:

$$C_0 = (1.64 + 0.12 \sin \theta) Re_{mL}^{-0.031} \quad (6-16)$$

The modified Reynolds number in Equation (6-14) based on the mixture velocities, liquid properties and hydraulic diameter computed as:

$$Re_{mL} = \frac{\rho_L V_M D_H}{\mu_L} \quad (6-17)$$

The elongated bubble drift velocity, V_d is computed using:

$$V_d = f_m V_{d\infty} \quad (6-18)$$

Where $f_m = 0.316 \sqrt{Re_{\infty}}$ for $f_m < 1$, else $f_m = 1$ and

$$Re_{\infty} = \frac{\rho_L V_{d\infty} D_H}{2\mu_L} \quad (6-19)$$

Drift velocity for elongated bubble at high Reynolds numbers is computed as:

$$V_{d\infty} = V_{dh\infty} \cos \theta \quad (6-20)$$

Where the elongated bubbles drift velocity in horizontal system is given as $V_{dh\infty}$ which is computed as:

$$V_{dh\infty} = \left[0.54 - \frac{1.76}{Bo^{0.56}} \right] \sqrt{\frac{g D_H (\rho_L - \rho_G)}{\rho_L}} \quad (6-21)$$

The Bond number, $Bo = \frac{(\rho_L - \rho_G)}{\sigma} g D_H^2$

Liquid holdup for intermittent flow can be computed from Equation (6-12) after the determination of the dispersed bubble rise velocity as:

$$V_b = 1.53 \left[\frac{g(\rho_L - \rho_G)\sigma}{\rho_L^2} \right]^{1/4} \sin \theta \quad (6-22)$$

The groups of models selected for evaluation were chosen for the predictive capabilities in gas-liquid two-phase flows and are generally accepted models in literature.

6.2 Mean Liquid Holdup in Horizontal Concentric Annulus

The mean liquid holdup for the horizontal concentric annulus test section was obtained from the time varying instantaneous liquid holdup measured with the conductance probes developed and calibrated for this study. If the instantaneous volumetric fraction of any phase (water or air) in the conductance probe's internal cross section is h_i , the average phase volume fractions (mean liquid holdup) can be determined over the entire time series recorded (T) for each flow condition. The number of data points recorded over the test period is given as N, then the mean volumetric phase fractions over the entire time series range, H_l can be determined as:

$$H_l = \frac{1}{T} \int_T^0 h_l dt = \frac{1}{N} \sum_{n=1}^N h_l \quad (6-23)$$

The representative mean liquid holdup measured as a function of the gas superficial velocities at different constant liquid superficial velocities is presented in Figure 6-1. From the results, it can be observed that generally, the liquid holdup reduces with increase in gas superficial velocity. This is because an increase in gas superficial velocity results in increase in the volume occupied by the gas phase in the concentric annulus, thereby reducing the liquid holdup. By the same token, an increase in the liquid superficial velocity results in a corresponding increase in the mean liquid holdup observed in the concentric annulus test section. This is similar to trends observed in circular pipes.

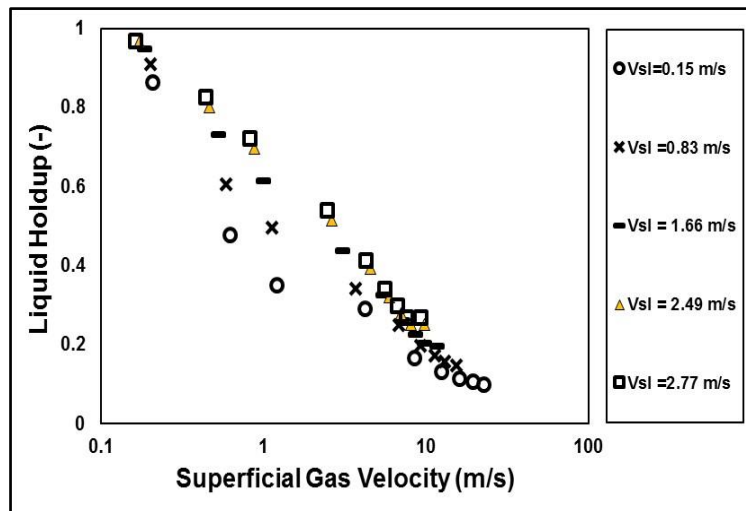


Figure 6-1: Mean liquid holdup as a function of gas superficial velocity at different liquid superficial velocities in horizontal concentric annulus

6.2.1 Mean Liquid Holdup Prediction in concentric Annulus

The four different modelling approaches discussed in section 6.1 namely The Homogeneous model, The Separated model (also known as Two Fluid model), The Drift Flux model and Flow Regime based models are evaluated in terms of their predictive ability in gas-liquid two-phase flows. Results are presented for the four model groups for flow in concentric annulus in the sub sections that follow.

6.2.1.1 Homogeneous Flow Modelling in Concentric Annulus

The homogeneous model generally considers both phases as a pseudo fluid which obeys the equations of single phase flow. To achieve this, average properties of both phases are obtained and pseudo properties which are weighted averages of both phases but are not necessarily properties of either phase. Since this model assumes that both phases travel with the same velocity (i.e. there is no slip between the phases), it has been used to predict the liquid holdup in the dispersed bubble flow regime of the concentric annulus. The results are presented in Figure 6-2 and show that the model predicts the conductance probe measured liquid holdup for all the test conditions evaluated pretty accurately.

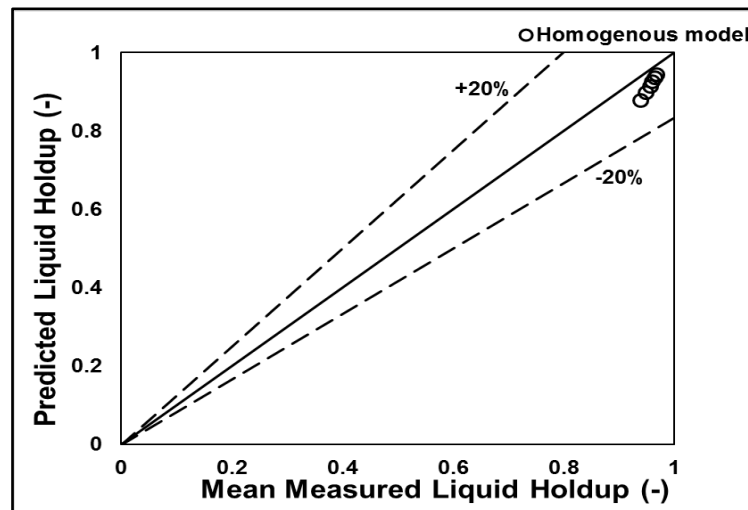


Figure 6-2: Predicted mean liquid holdup in dispersed bubble flow regime as a function of experimental data in the horizontal concentric annulus test facility.

6.2.1.2 Separated Flow Modelling in Concentric Annulus

The separated flow model considers both phases in the two-phase flow as flowing separately and models them as such. Under this category, the models evaluated include the Chisholm (1967) theoretical basis for the Lockhart & Martinelli (1949) model, the Chisholm (1973) model and the Butterworth (1975) approximation for Lockhart & Martinelli velocity ratio. Only the mean liquid holdup for the wavy annular and annular flow regimes are evaluated with this models and the result is presented in Figure 6-3. The models largely over predict the measured liquid holdup. The observed discrepancies maybe because these models were mainly

developed for flow in circular pipes and the geometry effect in the annulus were not considered in their models. The statistical error evaluators were used as shown in Table 6-2 and it shows that the Chisholm (1973) model for slip ratio determination performed best in two of the three statistical indices used for evaluation. The Butterworth (1975) correlation on the other hand had the best standard deviation result of the three models.

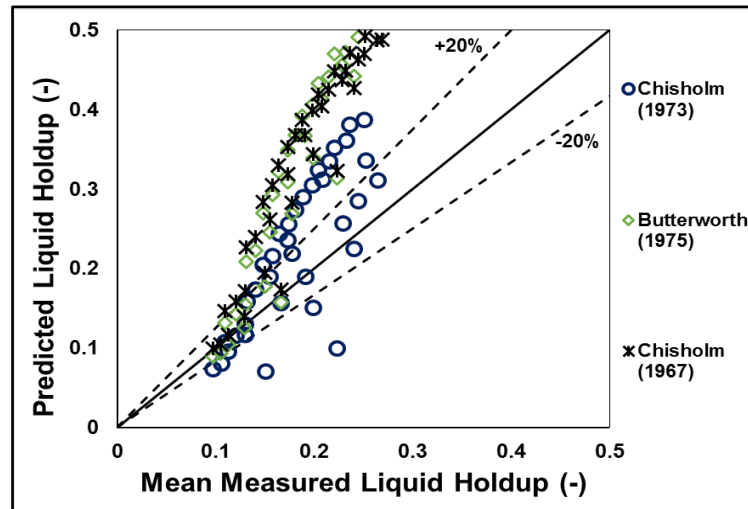


Figure 6-3: Predicted mean liquid holdup in the wavy annular and annular flow regimes as a function of experimental data in concentric annulus

Table 6-2: Statistical evaluation of the separated flow liquid holdup models in concentric annulus

Correlation	E ₁	E ₂	E ₃
Chisholm (1967)	0.38	0.38	0.17
Chisholm (1973)	0.11	0.25	0.25
Butterworth (1975)	0.36	0.38	0.21

6.2.1.3 Drift Flux Modelling in Concentric Annulus

Evaluation of drift flux models was carried out on the intermittent and dispersed bubble flow regimes in the horizontal concentric annulus based on different diameter concepts with the aim of accessing the predictive abilities of these

models. The closure relationships (distribution parameter and drift velocity) proposed by Bonnecaze et al.,(1971), Fabre & Line (1992) and Wang et al.,(2017) are evaluated for the intermittent and dispersed bubble flows liquid holdup measurements in the experiments. The observed results presented in Figure 6-4 and Table 6-3 overleaf shows the drift flux models tested generally perform reasonably accurately when compared with experimental liquid holdup measurements based on the hydraulic diameter concept. The performance of the other diameter concepts are presented in Appendix C1 and do not show any significant different from the hydraulic diameter results and as a result, the hydraulic diameter concept could be used to evaluate the liquid holdup in concentric annulus using the drift flux models compared in this study.

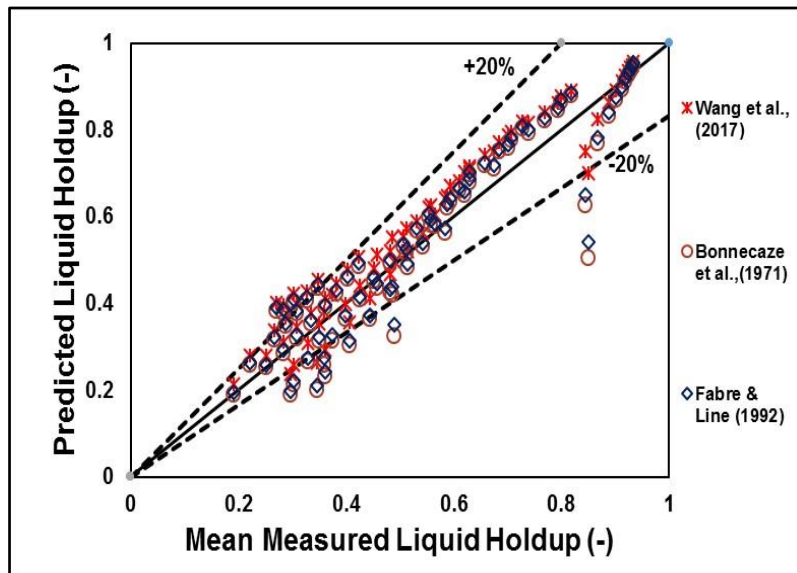


Figure 6-4: Drift flux models' predicted liquid holdup as a function of the measured liquid holdup for intermittent and dispersed bubble flow regimes in concentric annulus based on hydraulic diameter.

Table 6-3: Statistical analysis of drift flux model on experimental data in concentric annulus based on hydraulic diameter

Correlation	E ₁	E ₂	E ₃
Bonnecaze et al.,(1971)	-0.030	0.137	0.209

Fabre & Line (1992)	-0.008	0.131	0.189
Wang et al.,(2017)	0.087	0.126	0.134

The Wang et al., (2017) with E_2 and E_3 values of 0.126 and 0.134 respectively out-performs the other models in terms of the mean absolute error and the standard deviation. However, the Fabre & Line (1992) correlation performs best in terms of the mean error with value -0.008.

6.2.1.4 Flow Regime Dependent Modelling in Concentric Annulus

The flow regime dependent models evaluated for liquid holdup prediction based on different diameter concepts include the Beggs & Brill (1973) and the Petalas and Aziz (2000). Beggs & Brill (1973) developed parameters for flow regimes classes including segregated, intermittent and distributed flows. Figure 6-5 shows the result of the Beggs & Brill (1973) model as a function of mean measured liquid holdup based on the Omurlu diameter concept which performs best of all the diameter concepts for Beggs & Brill (1973) liquid holdup predictive model. The model largely over-predicts the liquid holdup in the wavy annular, annular flow and the dispersed bubble flow regimes irrespective of the diameter concept used. However, the intermittent flow region is predicted within a $\pm 20\%$ error margin. The coefficients developed by Beggs & Brill (1973) for the liquid holdup of the different flow regimes were developed based on experiments conducted for flow in circular pipes and the observed discrepancies maybe as a result of the geometry difference.

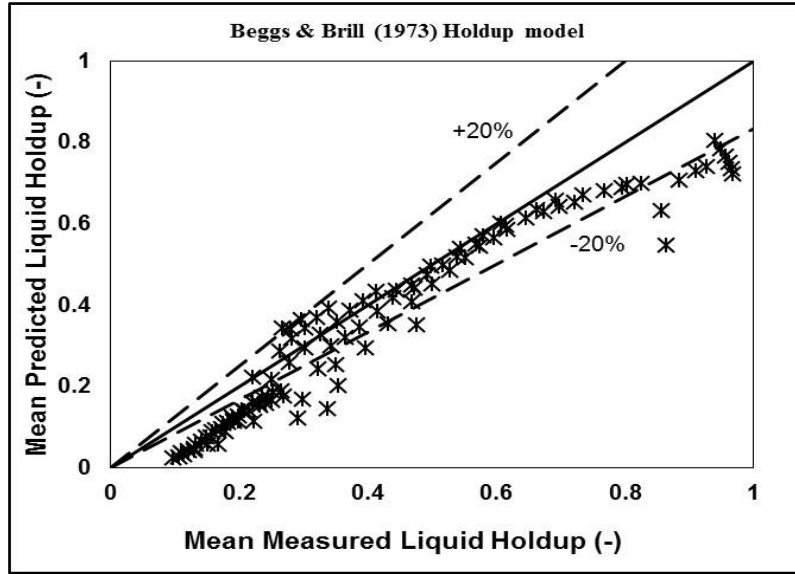


Figure 6-5: Beggs & Brill (1973) liquid holdup prediction model as a function of experimental measurements in concentric annulus based on Omurlu Diameter.

The performance of the other diameter concepts is as presented on Table 6-4. As highlighted earlier, the diameter concept proposed by Omurlu performs best with E_1 , E_2 and E_3 values of -0.065, 0.074 and 0.068 respectively.

Table 6-4: Performance of Beggs& Brill liquid holdup model based on different diameter concepts in concentric annulus

Diameter Concept	Mean Error (E_1)	Mean Absolute Error (E_2)	Standard Deviation (E_3)
Hydraulic Diameter	-0.086	0.092	0.078
Slot Diameter	-0.093	0.098	0.088
Lamb's Diameter	-0.093	0.098	0.088
Crittendon Diameter	-0.0793	0.086	0.074
Omurlu Diameter	-0.065	0.074	0.068
Largest Gap	-0.098	0.103	0.085

However, to use this model to determine liquid holdup in annulus, the coefficients will need to be modified to account for the geometry effect.

The Petalas & Aziz (2000) flow regime dependent liquid holdup model is modified using the different diameter concepts to determine the mean predicted liquid holdup for the intermittent flow regimes in concentric annulus.

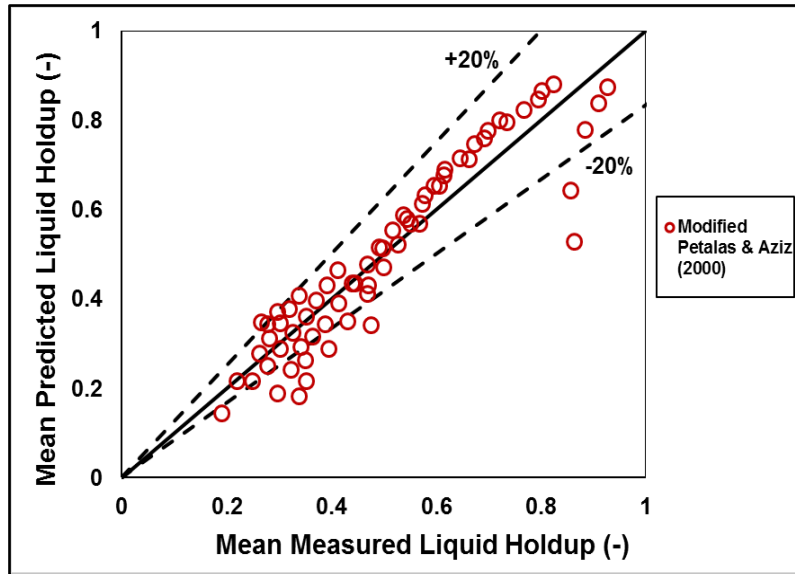


Figure 6-6: Modified Petalas & Aziz (2000) model for liquid holdup based on Omurlu diameter as a function of mean measured liquid holdup in concentric annulus.

Figure 6-6 shows the result obtained from the modelling approach of Petalas & Aziz (2000) modified using the Omurlu diameter when compared with experimentally measured liquid holdup in the intermittent flow region of the concentric annulus setup. The model largely predicts the experimental mean measured liquid holdup within a error margin of $\pm 20\%$ and the statistical analysis of the Omurlu diameter performed the best. This is true irrespective of the diameter concept used and the performance of the other diameter concepts are shown on Table 6-5 below

Table 6-5: Performance evaluation of Petalas & Aziz (2000) model based on different diameter concepts.

Diameter Concept	Mean Error (E_1)	Mean Absolute Error (E_2)	Standard Deviation (E_3)
Hydraulic Diameter	-0.0019	0.133	0.175
Slot Diameter	-0.002	0.134	0.175
Lamb's Diameter	-0.002	0.134	0.175
Crittendon Diameter	-0.0016	0.134	0.174
Omurlu Diameter	-0.0003	0.132	0.173
Largest Gap	-0.0021	0.134	0.175

6.3 Mean Liquid Holdup in Fully Eccentric Annulus

In order to study the effect of annulus eccentricity on mean liquid holdup in horizontal annulus, the mean liquid holdup in fully eccentric annulus is measured similarly as described for the concentric annulus in section 6.2. The experimental results are compared with the models highlighted in section 6.1 based on the different hydraulic diameter concepts and the results are presented in this section. The representative mean liquid holdup measured using conductance probes in the horizontal fully eccentric annulus are presented in Figure 6-7 as a function of gas superficial velocities at different liquid superficial velocities. It can be observed from the figure that the mean liquid holdup decreases with increase in gas superficial velocity and increases with increase in liquid superficial velocity. This is similar to the trend observed in the horizontal concentric annulus.

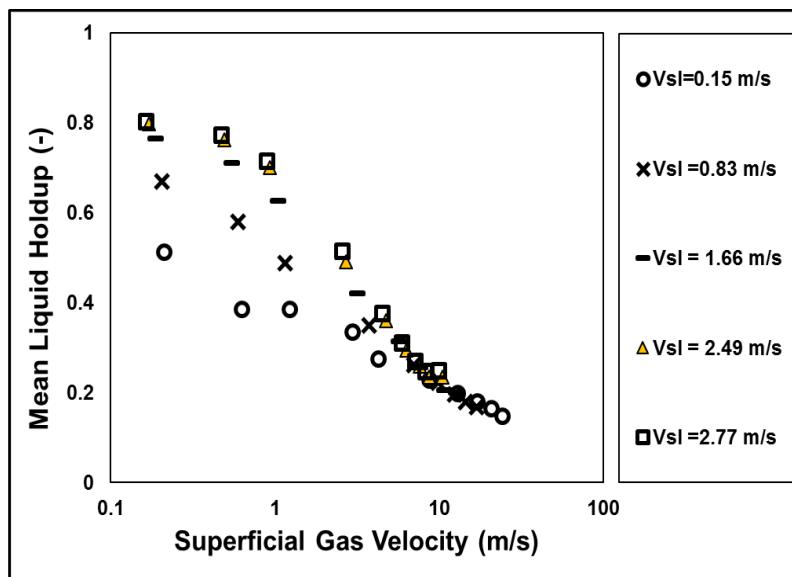


Figure 6-7: Mean liquid holdup as a function of gas superficial velocity at different liquid superficial velocities in horizontal eccentric annulus

6.3.1 Mean Liquid Holdup Prediction in Fully Eccentric Annulus

The mean liquid holdup in horizontal fully eccentric annulus is predicted using the models highlighted in section 6.1. The Homogeneous, Separated flow, Drift Flux and Flow regime based modelling techniques evaluated are evaluated against the experimentally measured mean liquid holdup obtained using conductance

probes in fully eccentric annulus and the results are as presented in the subsections that follow.

6.3.1.1 Homogeneous Modelling in Fully Eccentric Annulus

The result of the predictive ability of the homogenous flow model evaluated to predict the mean liquid holdup in the dispersed bubble flow regime is as shown in Figure 6-8. The model is observed to slightly over predict the mean measured liquid holdup in this conduit although within an error range not greater than 20%. The geometry effect was clearly not considered in the model and the discrepancies observed are probably as a result of this.

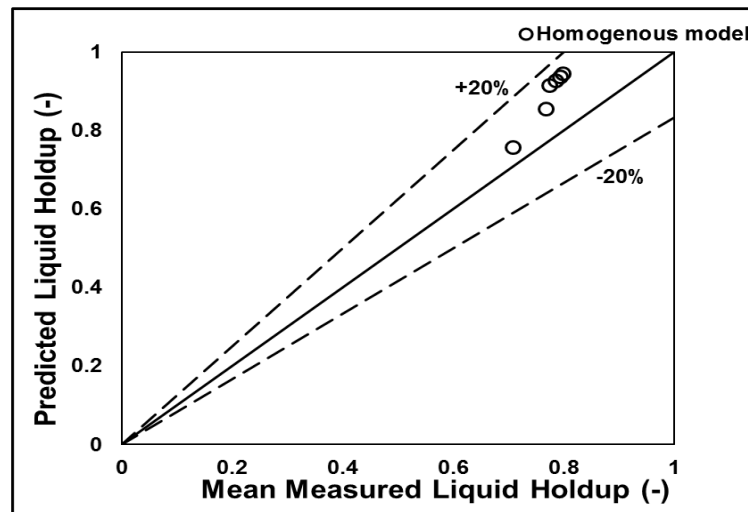


Figure 6-8: Predicted mean liquid holdup in dispersed bubble flow regime as a function of experimental data in the horizontal fully eccentric annulus test facility

6.3.1.2 Separated Flow Modelling in Fully Eccentric Annulus

The separated models of Chisholm (1967, 1973) and Butterworth (1975) are used to predict the mean liquid holdup observed in the fully eccentric annulus setup and the results are presented as a function of the mean measured liquid holdup for the wavy annular and annular flow regimes in Figure 6-9.

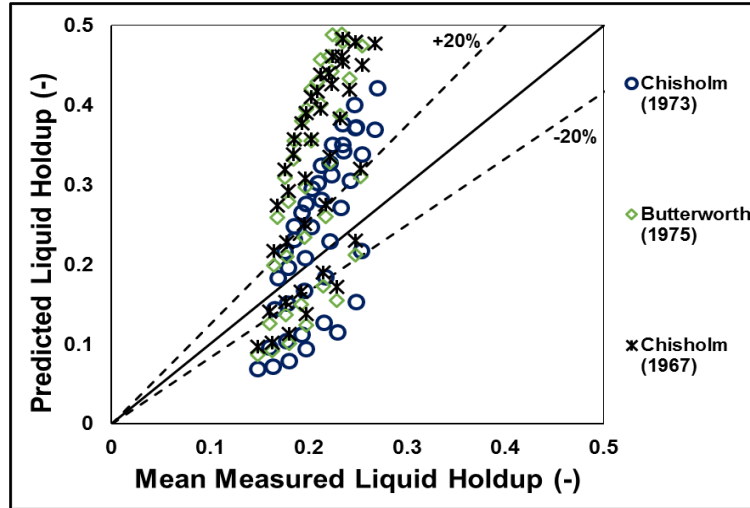


Figure 6-9: Predicted mean liquid holdup in the wavy annular and annular flow regimes as a function of experimental data in fully eccentric annulus.

Generally, the models over predict the experimental mean liquid holdup in fully eccentric annulus and the statistical analysis of the performance of each model is presented in Table 6-5. The model proposed by Chisholm (1973) performed best in terms of two statistical parameters E_1 and E_2 (mean error and absolute mean errors) while the Chisholm (1967) has the best standard deviation (E_3) value of 0.34.

Table 6-6: Statistical evaluation of the separated flow liquid holdup models in fully eccentric annulus

Correlation	E_1	E_2	E_3
Chisholm (1967)	0.25	0.40	0.34
Chisholm (1973)	-0.07	0.40	0.51
Butterworth (1975)	0.22	0.43	0.41

6.3.1.3 Drift Flux Modelling in Fully Eccentric Annulus

Similarly, the drift flux modelling approach is extended to the fully eccentric annulus liquid holdup prediction based on different diameter concepts. The closure relations of Bonnecaze et al., (1971), Fabre & Line (1992) and Wang et al., (2016) are applied on the intermittent and dispersed bubble flow regimes and the results are presented on Figure 6-10 and Table 6-7 based on the Omurlu

diameter concept which performs best of the diameter concepts evaluated in terms of statistical analysis.

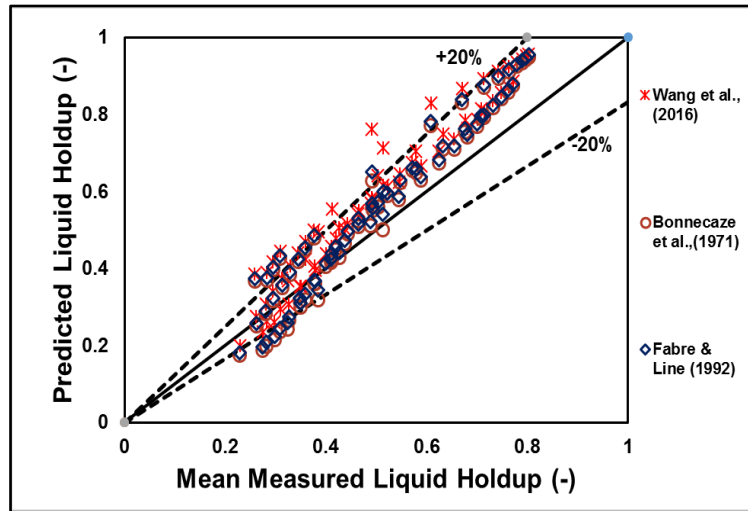


Figure 6-10: Drift flux models' predicted liquid holdup as a function of the measured liquid holdup for intermittent and dispersed bubble flow regimes in fully eccentric annulus based on Omurlu diameter.

All the models over-predict the mean measured liquid holdup in the fully eccentric although mainly around the +20% range. The statistical analysis however shows that the Bonnecaze et al., (1971) model performed best in terms of mean error and absolute mean error (E_1 and E_2 respectively) while the model of Wang et al., (2017) has the best standard deviation (E_3) value of 0.134. The performance of the different diameter concepts on the three models evaluated can be seen in Appendix C2

Table 6-7: Statistical analysis of drift flux models based on experimental data in fully eccentric annulus

Correlation	E_1	E_2	E_3
Bonnecaze et al.,(1971)	0.040	0.142	0.172
Fabre & Line (1992)	0.067	0.142	0.151
Wang et al.,(2017)	0.185	0.20	0.133

6.3.1.4 Flow Regime Dependent Modelling in Fully Eccentric Annulus

The Beggs & Brill (1973) and Petalas & Aziz (2000) flow regime dependent models for liquid holdup prediction are extended to the fully eccentric annulus using the different diameter concepts. The Beggs & Brill (1973) model was applied to the entire range of flow regimes encountered in the fully eccentric annulus based on their classification (segregated, intermittent and distributed) using their respective coefficients. Figure 6-11 shows the results obtained from the analysis of this model using the Omurlu diameter. It is observed that the model largely under-predicts the wavy annular and annular flow regimes, while the intermittent flow regime is predicted accurately with minor errors all within the $\pm 20\%$ error margin irrespective of the diameter concept utilized. The dispersed bubble flow regime on the hand is mainly under-predicted as well but not below the 20% error margin. The performance of the diameter concept used to predict the liquid holdup based on Beggs & Brill (1973) model is presented on Table 6-8.

Table 6-8: Performance of Beggs & Brill liquid holdup model based on different diameter concepts in fully eccentric annulus

Diameter Concept	Mean Error (E_1)	Mean Absolute Error (E_2)	Standard Deviation (E_3)
Hydraulic Diameter	-0.062	0.076	0.07
Slot Diameter	-0.063	0.079	0.08
Lamb's Diameter	-0.061	0.076	0.07
Crittendon Diameter	-0.05	0.069	0.07
Omurlu Diameter	-0.036	0.063	0.07

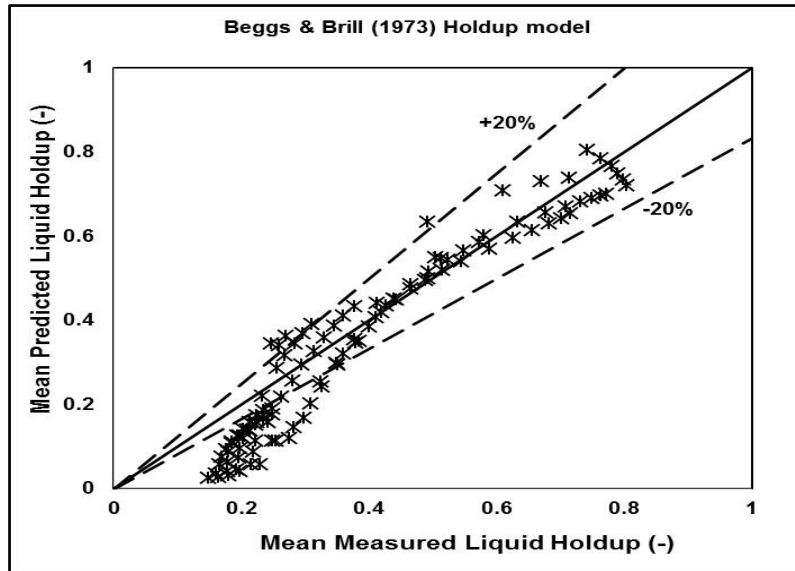


Figure 6-11: Beggs & Brill (1973) liquid holdup prediction model based on Omurlu diameter as a function of experimental measurements in fully eccentric annulus

Similarly, the results obtained from the Petalas & Aziz modelling approach when compared with experimental data is shown in Figure 6-12 based on the hydraulic diameter concept. The model under-predicts some of the data while over predicting some others. However, no significant difference is observed irrespective of the diameter concept utilized. Table 6-9 shows the performance evaluation of the different diameter concepts. Apart from the Omurlu and Crittendon diameter with lower mean error values, the hydraulic, slot and Lamb's diameter concepts have similar E_1 values. All the diameter concepts have very similar E_2 values.

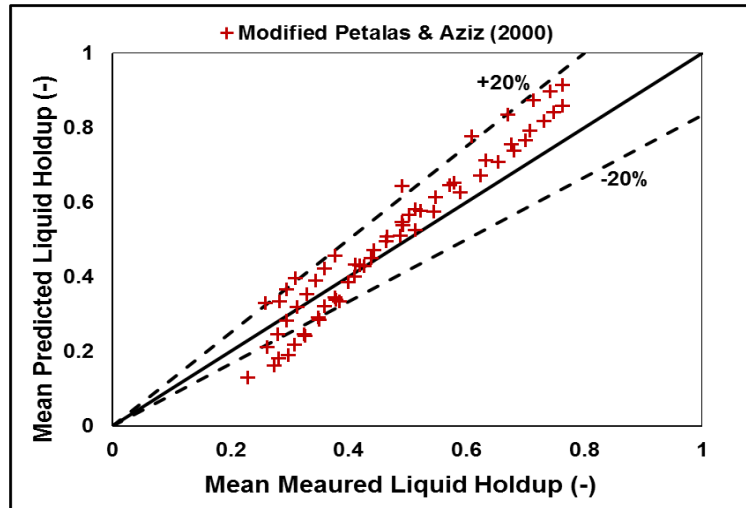


Figure 6-12: Modified Petalas & Aziz (2000) model for liquid holdup as a function of mean measured liquid holdup in fully eccentric annulus.

Table 6-9: Performance Petalas & Aziz (2000) liquid holdup model based on different diameter concepts in fully eccentric annulus

Diameter Concept	Mean Error (E ₁)	Mean Absolute Error (E ₂)	Standard Deviation (E ₃)
Hydraulic Diameter	0.040	0.143	0.168
Slot Diameter	0.048	0.143	0.164
Lamb's Diameter	0.048	0.143	0.164
Crittendon Diameter	0.0256	0.142	0.173
Omurlu Diameter	-0.0014	0.145	0.187

6.4 Effect of Annulus Eccentricity of Mean Liquid Holdup

In order to study the effect of annulus eccentricity on the mean liquid holdup measured using conductance probes in horizontal annulus, the mean measured liquid holdup plotted as a function of the gas superficial velocity for different liquid superficial velocities in the concentric annulus setup is compared with those from the fully eccentricity as presented in Figure 6-13.

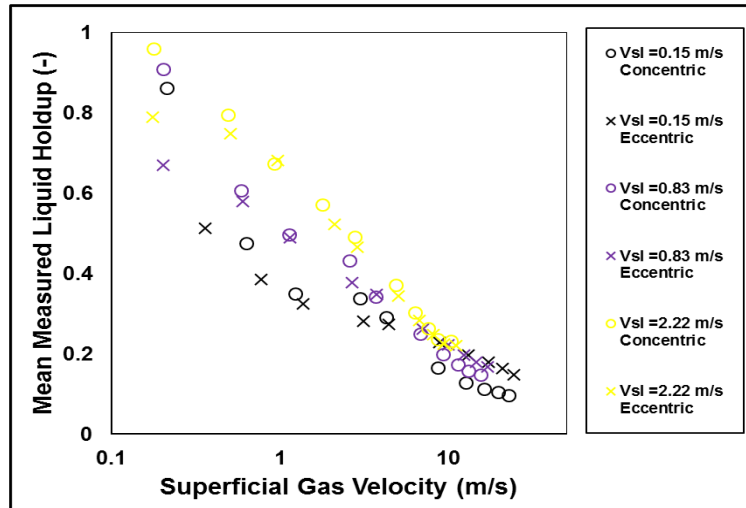


Figure 6-13: Effect of annulus eccentricity on mean measured liquid holdup as a function of gas superficial velocity.

It can be observed that at the lower to intermediate gas superficial velocity ranges investigated for this study (between 0.15 - 6.8 m/s), the mean liquid holdup is higher in the concentric annulus when compared with what is measured in the fully eccentric annulus, however, at gas superficial velocities above 6.8 m/s, the liquid holdup trend is observed to show higher values in the fully eccentric annulus than the concentric one. The reason for this is probably the slip velocity differences between both annulus setups. At lower gas superficial velocities, a higher slip velocity occurs in the concentric annulus between the gas and liquid phases, due to buoyancy and lower frictional forces. Also, a reduction in the cross sectional area available for gas phase flow is observed while the liquid flow area increases at this lower gas superficial velocities in the concentric annulus when compared to the fully eccentric one at the same conditions, which results in more liquid accumulation in the concentric annulus when compared with the fully eccentric one.

The observed point of cross over where the fully eccentric annulus is observed to have higher liquid holdup values occurs at the transition point to the annular flow region. At this point, the frictional forces are more significant and the fully eccentric annulus seems to endure higher frictional forces at this high gas superficial velocities.

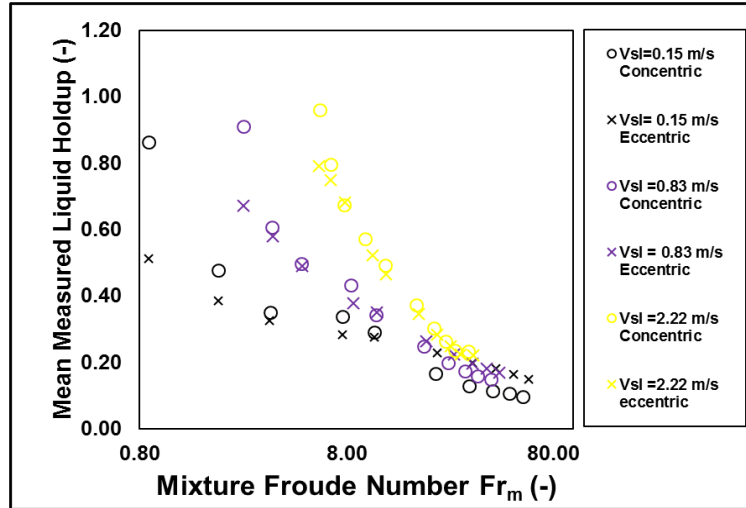


Figure 6-14: Effect of annulus eccentricity on mean liquid holdup as a function of mixture Froude number.

In order to further explain the observed phenomenon, the mean liquid holdup is plotted as function of the mixture Froude number (Fr_M) as presented in Figure 6-14. For the lower to intermittent mixture velocity ranges, the gravitational forces are observed to be more important due to the density difference in the concentric annulus when compared with the same flow conditions in the fully eccentric annulus. As a result, the Froude number would be the most important dimensionless group for liquid holdup determination in horizontal annulus. However, at higher mixture velocities, the frictional forces become more significant than the gravitational forces and the fully eccentric annulus seems to have higher frictional forces at the higher mixture velocities when compared with the concentric one.

6.5 Development of Liquid Holdup Correlation for Flow in Horizontal Annulus

The liquid holdup is very important parameter in sizing pipelines and separators and may cause discrepancies when used in pressure gradient prediction models. Most of the modelling approaches tested against experimental data were only effective for predicting liquid holdup for particular flow regimes. In this section, an empirical liquid holdup correlation is developed based on dimensionless groupings for all the flow regimes encountered in the horizontal annulus. The

liquid holdup is thought to be affected by the following dimensional variables in the horizontal annulus $\rho_L, \rho_G, V_{SG}, V_{SL}, V_M, \sigma, g, \mu_L, \mu_G$ and D_H . The relationship between the liquid holdup and these variables are represented in Equation (6-24)

$$H_L = f(\rho_L, \rho_G, V_{SG}, V_{SL}, V_M, \sigma, g, \mu_L, \mu_G, D_H) \quad (6-24)$$

Where ρ_L and ρ_G are the liquid and gas phase densities, V_{SG}, V_{SL} and V_M are the superficial gas, liquid and mixture velocities respectively, σ is the surface tension of the liquid phase, g is the acceleration due to gravity, μ_L, μ_G are the liquid and gas viscosities and D_H is the hydraulic diameter of the annulus.

The Buckingham Pi theorem was applied to the dimensional variables listed above in order to group them into dimensionless numbers. Five dimensionless groups were obtained initially as shown in Equation (6-25).

$$H_L = f\left(\frac{V_{SL}}{V_M}, \frac{\rho_L}{\rho_G}, \frac{V_M}{\sqrt{gD_H}}, \frac{V_M^2 D_H \rho_L}{\sigma}, \frac{\rho_L V_M D_H}{\mu_L}\right) \quad (6-25)$$

Equation (6-24) can be written in the form of well-known dimensionless numbers as:

$$H_L = f(\lambda_L, \rho_{ratio}, Fr_M, We, Re_M) \quad (6-26)$$

Where ρ_{ratio} , λ_L, Fr_M, We and Re_M are the density ratio, no-slip holdup, Webber number, mixture Froude number and mixture Reynolds number respectively.

A dataset comprising of data points from literature obtained from Osamusali (1988) and Gschnaidtner (2014) integrated with some experimental data points from the concentric and fully eccentric annulus were used in developing this correlation. The liquid superficial velocity ranged from 0.054 – 2.91 m/s while the gas superficial velocity ranged between 0.017 – 24 m/s. Also the data was obtained from both concentric and eccentric annulus setups having different hydraulic diameter values. The power law relationship was selected between the dimensionless groups and the liquid holdup is determined as follows:

$$H_L = \gamma \lambda_L^a \rho_{ratio}^b Fr_M^c Re_M^d We^e \quad (6-27)$$

Where γ, a, b, c, d and e are coefficient and exponents respectively which are obtained by data curve fitting. A multiple non-linear regression method applied for preliminary assessment of the effect of each dimensionless groups produced a zero coefficient on the Weber number showing that the contribution of the Weber number to prediction of liquid holdup in horizontal annulus is statistically insignificant. As such, it is removed from Equation (6-27) and the equation becomes:

$$H_L = \gamma \lambda_L^a \rho_{ratio}^b Fr_M^c Re_M^d \quad (6-28)$$

Regression of Equation (6-28) against database of the liquid holdup using GRG non-linear optimisation solver of a commercial software and the values of γ, a, b, c and d were obtained as 0.92, 0.62, -0.416, 0.19 and -0.291 respectively with a mean square error of 0.13. Therefore Equation (6-29) is proposed for liquid holdup prediction in horizontal annulus and it correlated well with the data set.

$$H_L = 0.92 \lambda_L^{0.62} \rho_{ratio}^{-0.416} Fr_M^{0.19} Re_M^{-0.291} \quad (6-29)$$

6.5.1 Performance of Proposed Correlation

The proposed correlation is validated with an independent data set not used in its development and the result is shown in Figure (6-15). The dataset also is a combination of the data of Osamusali (1988), Gschnaidtner (2013) and experimental data obtained from the concentric and fully eccentric annulus setups of this study. The results shows that the correlation predicts accurately the liquid holdup in the horizontal annulus for all the flow regimes within a $\pm 20\%$ error range with E_1 and E_2 values of 0.13 and 0.30 respectively. However, it is worth stating that the developed correlation has room for improvements and needs to be validated against a more diverse and wider dataset.

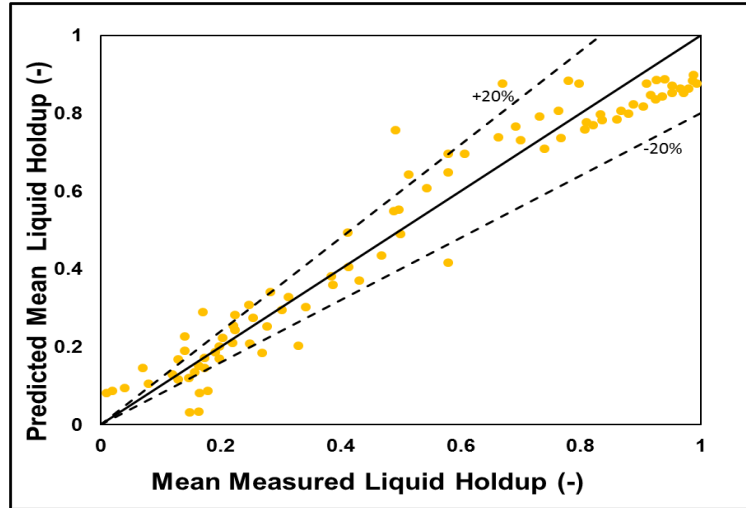


Figure 6-15: Validation of proposed liquid holdup correlation

6.6 Summary

Experimental results for air-water liquid holdup measured using electrical impedance probes (Conductance probes) in concentric and fully eccentric annulus are presented in this chapter. The mean liquid holdup in the annulus geometries investigated is determined from the time varying instantaneous liquid holdup plots. The main findings in this chapter are summarised as follows:

- The liquid holdup in horizontal (concentric and fully eccentric) annulus is observed to reduce with increase in the gas superficial velocity and increase with increase in the liquid superficial velocity.
- Four different modelling approaches (Homogeneous, Separated, Drift Flux and Flow Regime dependent models) are used to predict the mean liquid holdup in the concentric and fully eccentric annuli based on different diameter concepts.
- The Homogeneous modelling approach was applied to the dispersed bubble flow regimes in the concentric and fully eccentric annulus setups. The model performs well both in the concentric and fully eccentric annulus. However, it is slightly better in the concentric annulus.
- Different Separated flow modelling approaches are used to predict the experimental data and the Chisholm (1973) model performs the best in

terms of the mean error and absolute mean error in both concentric and fully eccentric annulus.

- The distribution parameter and drift velocity closure relationships proposed by Fabre & Line (1992) performs the best in terms of mean error of the Drift Flux modelling approaches evaluated in the concentric annulus while the Bonnecaze et al., (1971) closure relationships is the best in the fully eccentric annulus.
- The Beggs & Brill (1973) flow regime dependent model under-predicts the predicted mean liquid holdup at the low and very high liquid holdup values in both annulus setups investigated irrespective of the diameter concept utilized.
- The Petalas & Aziz (2000) is used to predict the intermittent flow regime in both annulus setups and mainly predicts the mean liquid holdup within an error range of $\pm 20\%$ irrespective of the diameter concept utilized.
- A higher mean liquid holdup is observed in the concentric annulus when compared to the fully eccentric annulus at the lower gas superficial velocities investigated. However, at gas superficial velocities above 6.8 m/s, the fully eccentric annulus is observed to have higher liquid holdup values when compared to the concentric one at the same conditions.
- The cross over point is observed to be the transition to the annular flow region. To explain the effect of the annulus eccentricity on mean measured liquid holdup, the Froude number is plotted as a function of liquid holdup.
- For the lower to intermittent mixture velocity ranges, the gravitational forces are observed to be more important due to the density difference in the concentric annulus when compared with the same flow conditions in the fully eccentric annulus.
- At higher mixture velocities, the frictional forces become more significant than the gravitational forces and the fully eccentric annulus seems to have higher frictional forces at the higher mixture velocities when compared with the concentric one.

- A new liquid holdup correlation is proposed based on dimensionless numbers as presented in Equation (6-29) and evaluated against data from literature integrated with experimental data.

In conclusion, the results of this chapter give an idea of the modelling approaches and diameter concepts that can be utilized in predicting liquid holdup in similar geometry. Also, the proposed correlation for liquid holdup prediction can be a useful tool for the design of applications in the petroleum and gas industry.

7 PRESSURE DROP IN GAS-LIQUID FLOWS IN HORIZONTAL ANNULI

Chapter Highlights

- Hydraulic diameter is the best concept for predicting homogeneous pressure drop in the concentric annulus while the Slot and Lamb's diameters are the best in fully eccentric annulus.
- The slot diameter is the best diameter concept and the Friedel (1979) is the best two-fluid model for predicting pressure drop in the concentric and fully eccentric annulus.
- The annulus eccentricity causes higher pressure drop in fully eccentric annulus when compared to the concentric which might be due to difference in the velocity profile, resulting in increased shear forces at the bottom of the fully eccentric annulus.

7.1 Overview

This chapter presents the results and discussion of the pressure drop in the horizontal (concentric and fully eccentric) annulus setups. Pressure transducer placed 4.91 m apart were used to measure the pressure drop in the annulus and the results compared with different models and correlations is reported. In order to benchmark the test facility against relatively established multiphase flows, the single-phase water analysis is presented in this chapter as well. The chapter begins with an overview which provides information about some of the models and predictions compared against experimental data, followed by single phase water test results and then two-phase air-water results in both the horizontal and fully eccentric annulus channels. The effect of annulus eccentricity of the measured pressure drop is also highlighted and different diameter concepts are used to test the performance of the modelling approaches utilized. Finally, a chapter summary of the key findings of this chapter is provided.

The pressure drop is a key parameter in the design of pipeline systems, underbalanced drilling operations as well as the design of heat exchanger. In this study, the pressure drop was measured by mean of static pressure transducers.

The specification of the instrumentation used is described in Chapter 3. Due to the importance of pressure gradients to many industrial applications, many studies have been undertaken extensively on the subject matter. As a result, many models and correlations were proposed to calculate the frictional pressure drop particularly in circular conduits. A detailed literature review is presented in Chapter 2 of the modelling approaches adopted for pressure gradient evaluation in annular channels but a summary of the pressure drop modelling approaches and correlations for common channels employed in this study for evaluation of experimental data are as described.

(1) Homogeneous model: The homogeneous no-slip flow model of Wallis (1969) is a simplified approach for treating two-phase flows. The technique involves averaging suitable properties of the flow and treating the fluid mixture as a pseudo-fluid which obeys single phase flow equations. Properties which are averaged include velocity, densities and viscosities.

The total pressure drop observed along a flow channel is expressed as the sum of frictional Δp_f , acceleration Δp_a and gravitation Δp_g pressure drop components expressed as follows

$$\Delta p = \Delta p_f + \Delta p_a + \Delta p_g \quad (7-1)$$

For flow through horizontal channels, the gravitational pressure drop component is dropped by definition and the pressure drop due to acceleration is ignored for unheated two-phase flows. Therefore, the frictional pressure drop component is the major contributor during adiabatic two-phase flows and the total pressure drop can be estimated primarily from it as follows:

$$\Delta p = -\Delta p_f \quad (7-2)$$

The homogeneous two-phase adiabatic flow pressure drop estimation approach is based on Equation (7-3) below:

$$\left(\frac{dp}{dl}\right)_{TP} = \frac{2f_{TP}G^2}{D_H\rho_{TP}} \quad (7-3)$$

The two-phase friction factor is computed from

$$f_{TP} = \frac{16}{Re_{TP}} \text{ for } Re_{TP} < 2000 \quad (7-4)$$

$$f_{TP} = 0.079 Re_{TP}^{-0.25} \text{ for } Re_{TP} > 2000 \quad (7-5)$$

Where the subscript TP represents the two-phase, G, ρ, f and D_H are mass flux, density, friction factor and hydraulic diameter concept of the flow channel. In order to extend the models to the horizontal annuli studied, different definitions of hydraulic diameter D_H have been adopted and their performances evaluated.

The two-phase Reynolds number is computed as follows:

$$Re_{TP} = \frac{\rho_{TP} V_M D_H}{\mu_{TP}} \quad (7-6)$$

The two-phase density is given by

$$\rho_{TP} = \left(\frac{x}{\rho_G} + \frac{1-x}{\rho_L} \right) \quad (7-7)$$

While the two-phase viscosity is computed using the Dukler et al., (1964) expression based on no-slip holdup as follows:

$$\mu_{TP} = \mu_L \lambda_L + \mu_G (1 - \lambda_L) \quad (7-8)$$

(2) Two-Fluid Model: This modelling approach designates two distinct phase. Every phase is treated uniquely as a separate fluid having its own governing equations. So generally, each phase has its own velocity, temperature and pressure. Lockhart and Martinelli (1949) proposed the following correlation for estimating two-phase frictional pressure drop:

$$\left(\frac{dp}{dl} \right)_{TP} = \phi_L^2 \left(\frac{dp}{dl} \right)_{L,G} \quad (7-9)$$

Where ϕ_L^2 is the two-phase multiplier and can be computed from the correlation of Chisholm (1967) as follows:

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (7-10)$$

The coefficient C is dependent on the flow regimes of the liquid and gas phase and the Martinelli parameter X is calculated as follows:

$$X^2 = \frac{\left(\frac{dp}{dl}\right)_L}{\left(\frac{dp}{dl}\right)_G} \text{ with } \left(\frac{dp}{dl}\right)_L = f_L \frac{2G^2(1-x)^2}{D\rho_L} \text{ and } \left(\frac{dp}{dl}\right)_G = f_G \frac{2G^2x^2}{D\rho_G} \quad (7-11)$$

Similarly, the correlation of Friedel (1979) which was developed after the Lockhart & Martinelli (1949) correlation but with a different definition of the two-phase multiplier. The two-phase frictional pressure drop is computed from Equation (7-9) but the two-phase multiplier is as given below

$$\phi_{Lo}^2 = E + \frac{3.24FX}{Fr^{0.045}We^{0.035}} \quad (7-12)$$

Where

$$Fr = \frac{G^2}{gD_H\rho_{TP}^2}, F = x^{0.78}(1-x)^{0.224}, We = \frac{G^2D_H}{\sigma\rho_L} \quad (7-13)$$

$$E = (1-x)^2 + x^2 \frac{\rho_L f_{Go}}{\rho_G f_{Lo}} \quad (7-14)$$

$$X = \left(\frac{\rho_L}{\rho_G}\right)^{0.91} \left(\frac{\mu_G}{\mu_L}\right)^{0.19} \left(1 - \frac{\mu_G}{\mu_L}\right)^{0.7} \quad (7-15)$$

Also, the correlation of Muller-Steinhagen and Heck (1986) is evaluated in this study. The two-phase frictional pressure drop of this model is computed as follows:

$$\left(\frac{dp}{dl}\right)_{TP} = \left(\left(\frac{dp}{dl}\right)_{Lo} + 2x \left(\left(\frac{dp}{dl}\right)_{Go} - \left(\frac{dp}{dl}\right)_{Lo} \right) \right) \cdot (1-x)^{\frac{1}{3}} + \left(\frac{dp}{dl}\right)_{Go} x^3 \quad (7-16)$$

They defined Reynolds number for computing friction factors and flow regimes as follows:

$$Re_{M-SL} = \frac{GD_H}{\mu_L} \quad (7-17)$$

$$Re_{M-SG} = \frac{GD_H}{\mu_G} \quad (7-18)$$

For $Re_{M-SL}, Re_{M-SG} \leq 1187$, the friction factor is calculated as follows:

$$f_{L,G} = \frac{64}{Re_{(M-S)L,G}} \quad (7-19)$$

And for $Re_{M-SL}, Re_{M-SG} > 1187$, the friction factor is given as

$$f_{L,G} = \frac{0.3164}{Re_{(M-S)L,G}^{\frac{1}{4}}} \quad (7-20)$$

Therefore, using Equation (7-19) – (7-20) the frictional pressure loss for each phase can be computed and then the two-phase frictional pressure drop of the correlation can be estimated.

Finally, the last correlation considered of the two-fluid modelling approach is the Sun & Mishima (2009) correlation. In their method, the frictional pressure drop of the liquid and gas phases are calculated using Equation (7-11) but they proposed the modification of the Lockhart & Martinelli two-phase multiplier depending on whether the flow regime of the phases were laminar or turbulent (where laminar flow had Reynold number values less than 2000 and turbulent flows had Reynolds number above 2000). The value of C in Equation (7-10) was modified for laminar flow as follows:

$$C = 26 \left(1 + \frac{Re_{L,G}}{1000} \right) \left[1 - \exp \left(\frac{-0.153}{0.27 \cdot La + 0.8} \right) \right] \quad (7-21)$$

Where La is Laplace number and is given by

$$La = \frac{\left(\frac{\sigma}{g(\rho_L - \rho_G)} \right)^{0.5}}{D_H} \quad (7-22)$$

For the turbulent flow, C is computed based on the following

$$C = 1.79 \left(\frac{Re_G}{Re_L} \right)^{0.4} \left(\frac{1-x}{x} \right)^{0.5} \quad (7-23)$$

Once the two-phase multiplier has been modified, the total frictional pressure drop can be calculated using Equation (7-9). In this study, different definitions of hydraulic diameter as highlighted in Table 2-4 have been utilized in the models to define the diameter of the annulus geometry wherever the diameter term is encountered and the performance of the modelling approaches and diameter concepts are evaluated.

(3) Mechanistic model: The mechanistic model of Petalas & Aziz (2000) is modified based on different hydraulic diameter concepts and used to compute the frictional pressure drop within the intermittent flow region of this study. The pressure drop of the intermittent flow region in the mechanistic model could be obtained by taking a momentum balance over a slug unit as follows:

$$-\left(\frac{dp}{dL}\right) = \frac{1}{L_U} \left[L_S \left(\frac{\tau_{LS} \pi D_H}{A} \right) + L_f \left(\frac{\tau_{Lf} S_{Lf} + \tau_{Gdb} S_{Gdb}}{A} \right) \right] \quad (7-24)$$

However, due to unreliable methods of determining the slug length, L_S or the length of the bubble region, L_f , they proposed a simple model to predict the two-phase frictional pressure drop of the slug unit thus

$$-\left(\frac{dp}{dL}\right) = \eta \left[\left(\frac{dp}{dL}\right)_{frSL} + (1 - \eta) \left(\frac{dp}{dL}\right)_{frAM} \right] \quad (7-25)$$

Where η is the weighting function, a function of the ratio of the slug length to the slug unit length $\left(\frac{L_S}{L_U}\right)$ determined empirically. It can be calculated as follows;

$$\eta = \lambda_L^{(0.75-H_L)} \quad (7-26)$$

With $\eta \leq 1.0$ and the average liquid volume fraction H_L in the slug unit can be computed using Equation (6-14) to (6-22). After the determination of these parameter, Petalas & Aziz (2000) proposed a correlation for the entrainment fraction, FE as follows:

$$\frac{FE}{1 - FE} = 0.735 N_B^{0.074} \left(\frac{V_{SG}}{V_{SL}} \right)^{0.2} \quad (7-27)$$

Where

$$N_B = \frac{\mu_L^2 V_{SG}^2 \rho_G}{\sigma^2 \rho_L} \quad (7-28)$$

Dimensionless liquid film thickness is determined from Equation (7-29) as follows:

$$\bar{\delta} = \frac{1}{2} \left[1 - \sqrt{(1 - H_L) \left(\frac{(FE)V_{SL} + V_{SG}}{V_{SG}} \right)} \right] \quad (7-29)$$

The mixture density and viscosity are computed from Equation (7-30) and (7-31) respectively:

$$\rho_M = H_L \rho_L + (1 - H_L) \rho_G \quad (7-30)$$

$$\mu_M = H_L \mu_L + (1 - H_L) \mu_G \quad (7-31)$$

After the determination of all these parameters, the frictional pressure drop of the slug unit can be computed from Equation (7-27).

$$\left(\frac{dp}{dL} \right)_{f_{rSL}} = \frac{2 f_{mL} V_M^2 \rho_M}{g D_H} \quad (7-32)$$

Where f_{mL} is computed from the mixture Reynolds number Re_{mL}

$$Re_{mL} = \frac{D_H \rho_L V_M}{\mu_L} \quad (7-33)$$

To compute the frictional pressure drop for the liquid film zone, the following expression is employed:

$$\left(\frac{dp}{dL} \right)_{f_{LFZ}} = \frac{4 \tau_{WL}}{D_H} \quad (7-34)$$

However, if $\bar{\delta} < 0.0001$, then the liquid film zone pressure drop is computed using:

$$\left(\frac{dp}{dL}\right)_{fLFZ} = \frac{2f_m V_M^2 \rho_M}{D_H} \quad (7-35)$$

After all these have been determined, the total frictional pressure drop in the intermittent flow region is computed from Equation (7-25).

7.2 Single-Phase Water Test

It is important to provide a benchmark for the experimental setup employed for this study particularly as it relates to pressure drop estimation. In order to do this, single phase water test were carried out in the concentric and fully eccentric annulus setups utilized for two-phase flow studies. The essence was to validate the accuracies of instrumentation by comparing with properly developed and widely used models for correlating single-phase flows. The test matrix used for the single phase water test are presented on Table 7-1.

Table 7-1: Single-Phase Water Test Matrix

Annulus Diameter (m)		Eccentricity	Vw (m/s)
Inner pipe diameter	Outer pipe diameter		
0.060	0.0768	Concentric	0.27 – 2.77
0.060	0.0768	Fully Eccentric	0.27 – 2.77

7.2.1 Pressure Drop Analysis

Over 60 experimental tests were conducted in each annulus setup (about half of those were for repeatability of data) for single phase water tests. The water velocity ranged between 0.27 – 2.77 m/s in both the concentric and fully eccentric annulus setups. Two static pressure transducers separated a distance of 4.91 m were employed for pressure drop estimation. The observed trend is presented in Fig 7-1 and is similar to what is to be expected. The pressure drop in both annulus is observed to increase with increase in velocity of water. This is because the pressure drop is a function of the square of flow velocity.

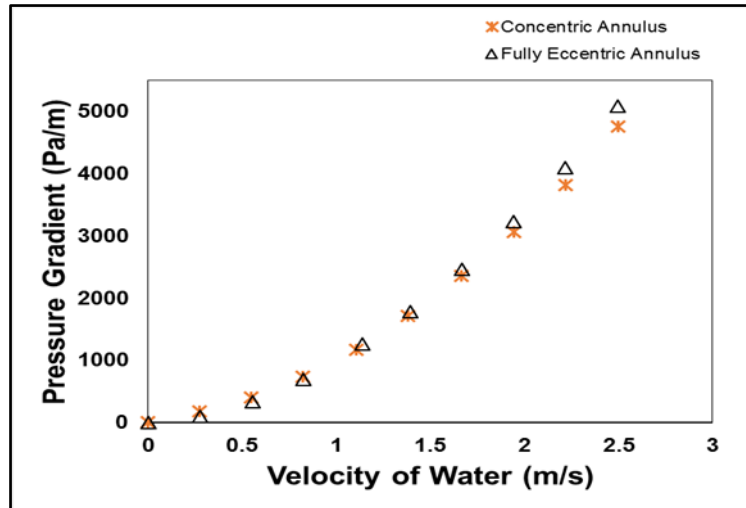


Figure 7-1: Pressure drop as a function of water velocity in horizontal concentric and fully eccentric annuli

The effect of the eccentricity on the single-phase water pressure can also be noticed in the Figure 7-1. At low water superficial velocity (0.2 – 0.8 m/s), the pressure drop in the concentric annulus is slightly higher than that of the fully eccentric annulus. However, at water superficial values above 0.8 m/s, the pressure drop is higher in the fully eccentric annulus than the concentric annulus. This is because at the lower velocities, the gravitational effects are the dominant component in the annulus and hence the concentric annulus leads in this regard but subsequently the frictional components become dominant at higher flow velocities.

7.2.1.1 Comparison of Measurements and Friction Factor

Experimental measurements obtained for single-phase water flow in horizontal concentric and fully eccentric annulus setups were compared with the phenomenological expression for pressure drop prediction developed by Darcy-Weisbach and the results are presented. Different friction factor correlations developed for single-phase pipe flow including those by Blasius, Swamee-Jain and Haaland as outlined by Kijjarvi (2011) were used to predict the pressure drop. The annulus geometry was incorporated into the friction factor correlations for circular pipe flow by using the different diameter concepts already outlined in this study. Of the three friction factor correlations employed for pressure drop

prediction, the correlation of Blasius and Swamee-Jain performed best with mean error E_1 values of 0.2 and 0.21 respectively, although the Swamee-Jain correlation has a better standard deviation value of 0.11 when compared with 0.12 for Blasius. Results of the comparison of the pressure drop as a function of water velocity is presented in Figure 7-2 using the Blasius friction factor and different hydraulic diameter definitions.

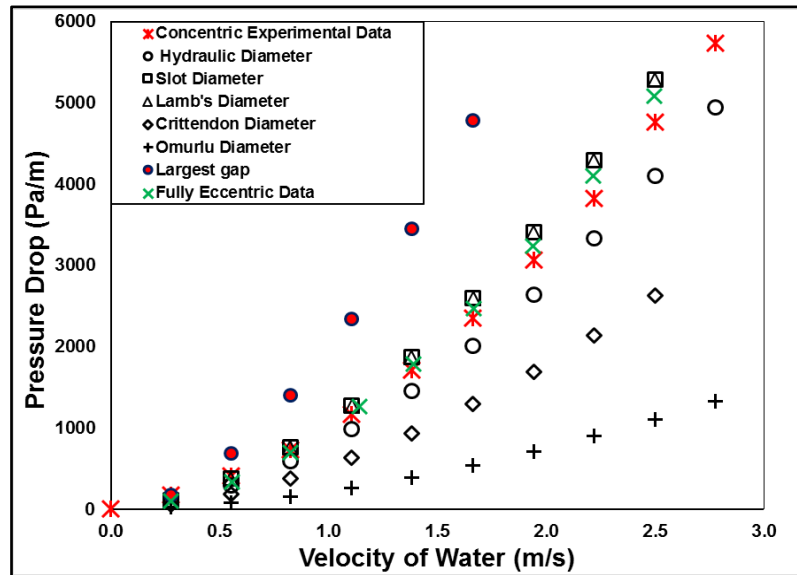


Figure 7-2: Pressure drop as a function of water velocity using different diameter concepts and the Blasius friction factor correlation.

It can be observed from the plot that the slot and Lamb diameter concept predict the experimental pressure drop in both annulus setups as a function of water velocity with an mean error value of 0.03. The hydraulic diameter concept slightly underpredicts the pressure drop and has a mean error value of 0.20, while the diameter concepts suggested by Crittendon and Omurlu largely underpredict the experimental results with mean error values of 0.48 and 0.78 respectively. The largest gap approach considered in the study on the other hand overpredicts the pressure drop with mean error value of 0.89. Similarly, a direct comparison of the experimental and predicted pressure gradient is shown in Figure 7-3. The hydraulic, slot and Lamb diameter concepts predict the experimental pressure drop within an error margin of $\pm 20\%$; the Crittendon and Omurlu diameter definitions underpredict the pressure drop well below the -20% error margin while

the largest gap definition overpredicts the pressure drop above the +20% error margin.

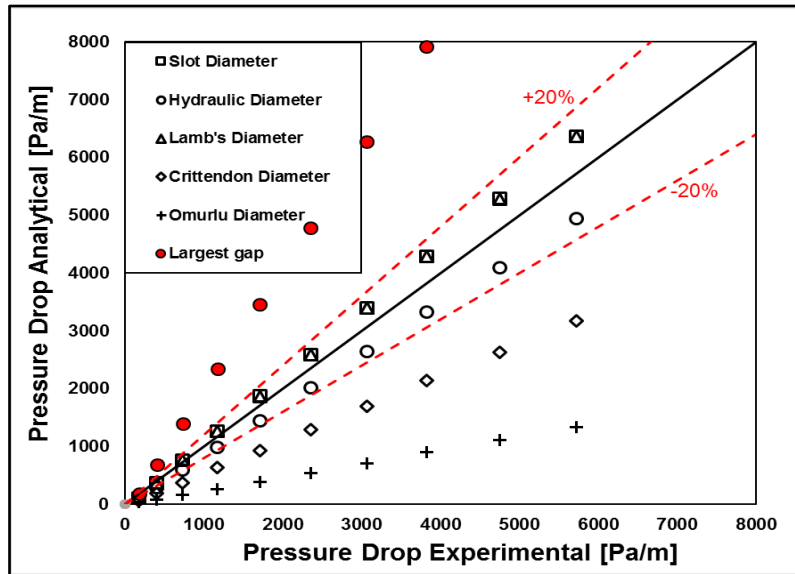


Figure 7-3: Pressure drop of single-phase water in horizontal concentric annulus test section

Generally speaking, the trend observed with the single-phase water measurement is similar to what is observed in most experimental setups. Also, the predicted pressure drop using at least three diameter concepts is within a margin of error that is acceptable using a friction factor correlation that was developed for flow in circular pipes. The difference in geometries is therefore the source of the discrepancy. The obtained results therefore validate the reliability and functionality of the horizontal annulus test rig as well as the instrumentation such as the static pressure transducers.

7.3 Mean Pressure Drop in Horizontal Concentric Annulus

The mean air-water pressure drop in the horizontal concentric test section employed for this study was measured using the same static pressure transducers used for the single-phase water pressure drop estimation described. The pressure drop as a function of gas superficial velocity for the air-water tests conducted in the concentric annulus is shown in Figure 7-4 below. Generally, the pressure drop in the horizontal concentric annulus in this study increased with

increase in gas and liquid superficial velocity. At low liquid superficial velocities, increase in pressure drop due to an increase in gas superficial velocity is minimal, however at higher liquid superficial velocity, increase in gas superficial velocity results in more significant increase in the mean measured pressure drop. This shows that the main contributor to pressure drop in gas-liquid two-phase flow is the liquid.

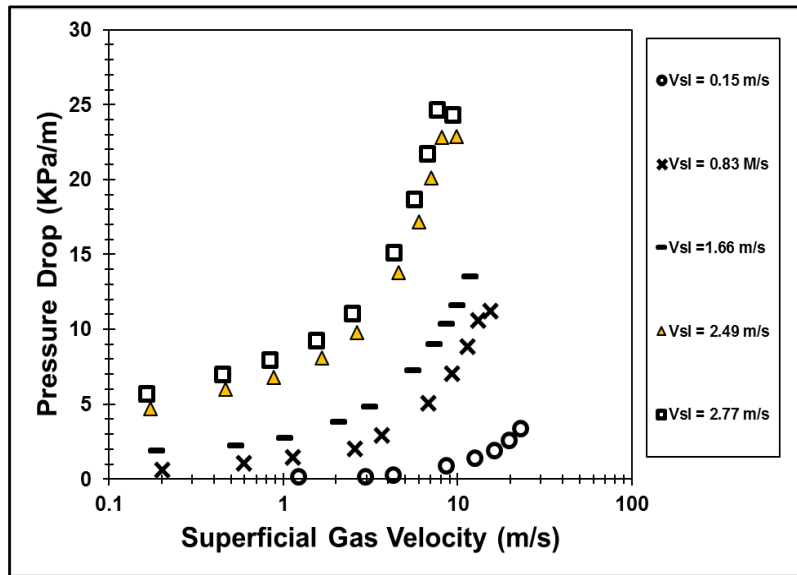


Figure 7-4: Pressure drop as a function of superficial gas velocity for different liquid superficial velocities in horizontal concentric annulus

Also observed is the fact that much steeper pressure drop increase is noticed at the higher gas superficial velocities. This is as a result of an increase in the shear on the walls of the annulus particularly in the annular flow region where the liquid phase flows at the annulus wall. At similar gas superficial velocities, an increase in liquid superficial velocity results in increased pressure drop. An increase in the liquid superficial velocity increases the liquid content in the annulus section, thereby increasing the shear and hence the pressure drop.

7.3.1 Comparison of Pressure Drop in Concentric with Predictive Models

In this section, the mean measured pressure drop in the 3" horizontal concentric annulus rig is compared with five different models from three different predictive modelling approaches as outlined in section 7.1. The homogeneous model of

Dukler (1964), the two-fluid models by Lockhart & Martinelli (1949), Friedel (1979), Muller-Steinhagen (1968) and Sun & Mishima (2009) as well as the mechanistic model for the intermittent flow region of Petalas & Aziz (2000). These models are dependent on the conduit diameter and have been evaluated using the different definitions of annular diameter for the concentric in this section. The best performing diameter will be determined for each model group using the Mean Error (E_1) and the Mean Absolute Error (E_2) statistical analysis.

7.3.1.1 Homogeneous Pressure Drop Model Comparison in Concentric Annulus

The homogeneous modelling approach of Dukler (1964) was applied to the dispersed bubble flow regime region of the experimental pressure drop. The performance evaluation of the different diameter concepts is undertaken and the results are presented in Figure 7-5 and Table 7-2.

Table 7-2: Comparison of the measured & predicted pressure drop using Dukler (1964)

Diameter Concept	Mean Error (E_1)	Mean Absolute Error (E_2)
Hydraulic Diameter	0.06	0.05
Slot Diameter	0.33	0.32
Lamb's Diameter	0.33	0.32
Crittendon Diameter	0.33	0.34
Omurlu Diameter	0.71	0.71
Largest Gap	1.46	1.44

As it can be seen from the results, the homogeneous model is able to predict the pressure drop in horizontal concentric annulus reasonably accurately depending on the diameter concept used. The hydraulic diameter concept gives the best results predicting the experimental results with E_1 and E_2 values of 0.06 and 0.05 respectively.

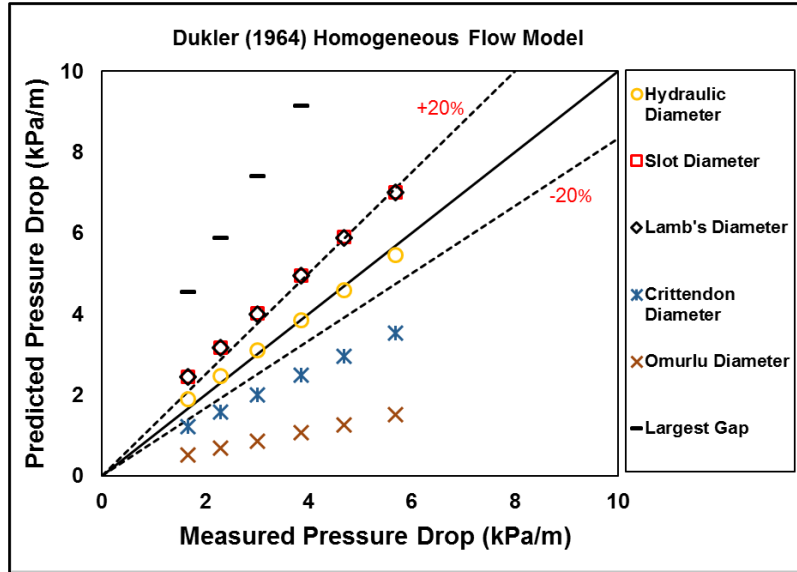


Figure 7-5: Pressure drop comparison based on the homogeneous flow model of Dukler (1964) using different diameter concepts in concentric annulus.

The slot and Lamb diameters both give identical results when used in the Dukler (1964) model; tending to overpredict the pressure drop in the concentric annulus. E_1 and E_2 values for both concepts were 0.33 and 0.32 respectively. Similarly, the largest gap concept performs worst of all the diameter approaches and should not even be considered for this modelling approach. It has E_1 and E_2 values of 1.46 and 1.44 respectively. Finally, the Crittendon diameter and Omurlu diameters both underpredict the experimental pressure drop when used in the Dukler (1964) model. E_1 and E_2 values for Crittendon diameter were 0.33 and 0.34 while those for Omurlu were 0.71 and 0.71 respectively. Based on the foregoing, the hydraulic diameter concept is the best when predicting pressure drop in concentric annulus using the Dukler (1964) homogeneous model.

7.3.1.2 Two-Fluid Pressure Drop Model Comparison in Concentric Annulus

The two-fluid models were applied to the wavy annular and annular flow regimes of the horizontal concentric annulus setup. The models of Lockhart & Martinelli (1949), Friedel (1979), Muller-Steinhagen (1986) and Sun & Mishima (2009) were compared with experimental pressure drop in concentric annulus using the different diameter concepts. Only the best performing diameter concept is

presented in Figure 7-6. The Slot and Lamb diameter provide the best fit with experimental data in terms of mean error E_1 and mean absolute error E_2 all the models evaluated.

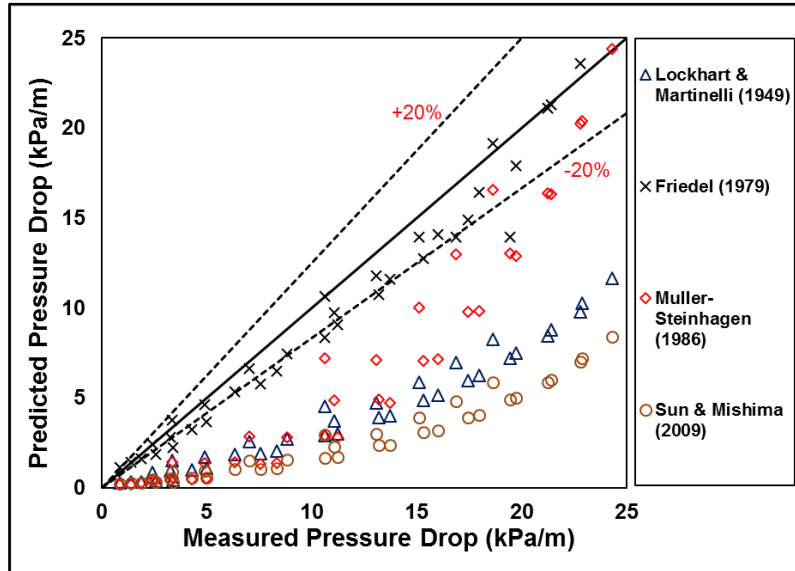


Figure 7-6: Pressure drop as a function of experimental measurement using the two-fluid model approach in concentric annulus based on Slot diameter concept.

Table 7-3: Comparison of evaluated pressure drop models based on the Slot diameter concept in concentric annulus

Model	Mean Error (E_1)	Mean Absolute Error (E_2)
Lockhart & Martinelli (1949)	-0.67	0.67
Friedel (1979)	-0.10	0.13
Muller-Steinhagen (1986)	-0.56	0.56
Sun & Mishima (2009)	-0.79	0.79

Figure 7-6 and Table 7-3 show that the two-fluid model by Friedel (1979) is the best performing model with E_1 and E_2 values of -0.10 and 0.13. The next best model is the Muller-Steinhagen (1986) with E_1 and E_2 of -0.56 and 0.56

respectively, followed by the models of Lockhart & Martinelli (1949) and Sun & Mishima (2009) in that order with E_1 and E_2 values of -0.67 and 0.67; -0.79 and 0.79 respectively. The results of all diameter concepts can be found in Appendix B1.

7.3.1.3 Mechanistic Model Pressure Drop Comparison for Intermittent Flow Region in Concentric Annulus

The intermittent flow regimes of the concentric annulus studies including elongated bubble, slug, wavy slug and churn were evaluated against the Petalas & Aziz (2000) model using the different diameter definitions. The results are presented in Figure 7-7 and Table 7-4.

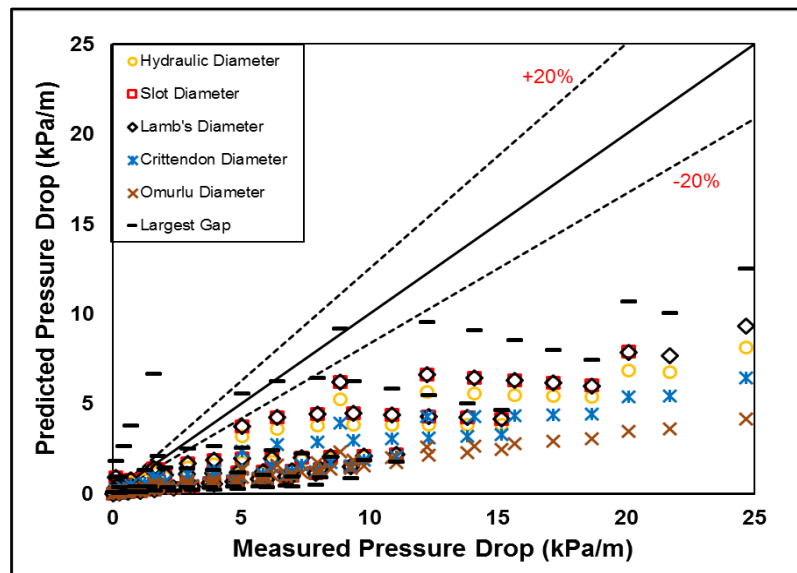


Figure 7-7: Comparison of Petalas & Aziz (2000) pressure drop model with experimental data based on different diameter concepts

It can be observed that the modified Petalas & Aziz (2000) model for the intermittent flow region of the horizontal concentric annulus largely underpredicts the experimental pressure drop data irrespective of the diameter concept utilized for modification.

Table 7-4: Comparison of experimental data with the Petals & Aziz (2000) model for different diameter concept in concentric annulus

Diameter Concept	Mean Error (E ₁)	Mean Absolute Error (E ₂)
Hydraulic Diameter	-0.84	0.96
Slot Diameter	-0.82	1.06
Lamb's Diameter	-0.82	1.06
Crittendon Diameter	-0.78	0.80
Omurlu Diameter	-0.85	0.85
Largest Gap	-0.71	1.68

However, of all the diameter concepts considered, the largest gap performs best in terms of mean error E_1 with value of -0.71 but with E_2 value of 1.68. The performance of all the other diameter concepts are as presented in Table 7-4 above. In order to use this modelling approach for pressure drop prediction, modification of other parameters (including the friction factors) within the model will be necessary.

7.4 Mean Pressure Drop in Horizontal Fully Eccentric Annulus

To measure the mean pressure drop in horizontal fully eccentric annulus, the same pressure transducers located 4.91 m apart as used in the concentric annulus were used. The pressure drop as a function of gas superficial velocities at different liquid superficial velocities is presented in Figure 7-8 for gas-liquid flow in fully eccentric annulus. A similar trend observed in the concentric annulus where the pressure drop increased with increase in gas and liquid superficial velocities. Also, at higher gas superficial velocities, a much steeper pressure drop is noticed due to the shear effect on the annulus walls. The fully eccentric annulus has the inner pipe lying at the bottom of the outer pipe and as such, greater shear forces will be distributed the bottom of the annulus where a restriction in the flow of the liquid phase is experienced particularly in the annular flow region where the gas phase travels in the core of the annulus and the liquid film travels on the pipe wall. This will probably results in greater pressure drop in this annulus.

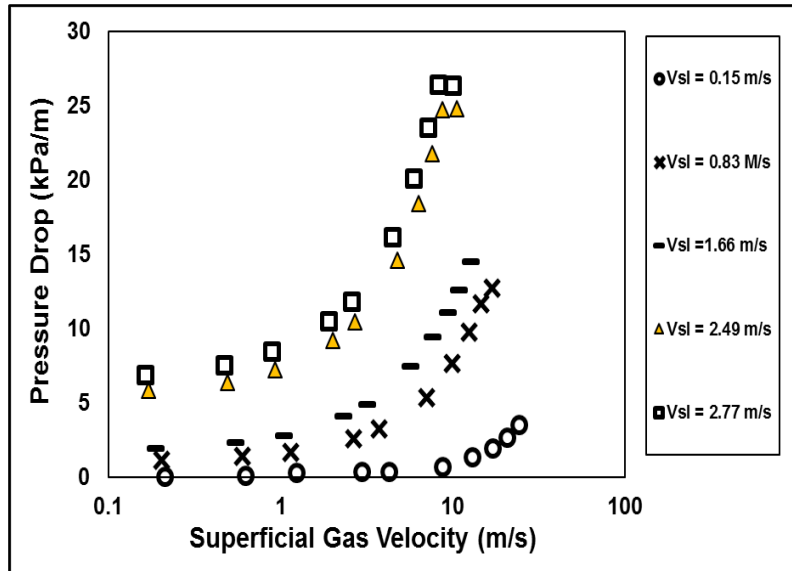


Figure 7-8: Pressure drop as a function of gas superficial velocities in fully eccentric annulus

7.4.1 Comparison of Pressure Drop in Fully Eccentric Annulus with Predictive Models

Similar to what was done in section 7.3.1 where predictive pressure drop models were compared with experimental data in concentric annulus, the same models were compared to the experimental data obtained in the fully eccentric annulus setup using different diameter concepts and presented in the sections that follow.

7.4.1.1 Homogeneous Pressure Drop Model Comparison in Fully Eccentric Annulus

The homogeneous model of Dukler (1964) was compared with experimental pressure drop measured in the fully eccentric annulus based on the different diameters utilized in this study and the results are presented in Figure 7-9. Also, statistical performance of each diameter concept based on mean error E_1 and mean absolute error E_2 are presented on Table 7-4.

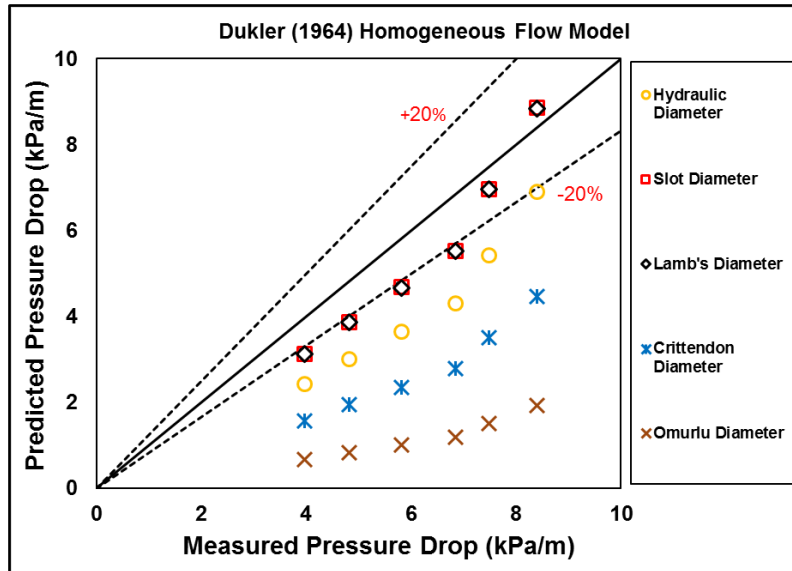


Figure 7-9: Pressure drop comparison based on the homogeneous flow model of Dukler (1964) using different diameter concepts in fully eccentric annulus.

Table 7-5: Comparison of the measured & predicted pressure drop using Dukler (1964) in fully eccentric annulus

Diameter Concept	Mean Error (E ₁)	Mean Absolute Error (E ₂)
Hydraulic Diameter	-0.33	0.33
Slot Diameter	-0.14	0.15
Lamb's Diameter	-0.14	0.15
Crittendon Diameter	-0.56	0.56
Omurlu Diameter	-0.81	0.81

From Figure 7-9, it can be seen that the Dukler (1964) homogeneous pressure drop model under-predicts the experimental data irrespective of the diameter concept used. However, from the statistical analysis of the performance of the diameter concept, the slot and Lamb diameter concepts performed best with mean error E_1 and mean absolute error E_2 values of -0.14 and 0.15 respectively. Comparing the performance of this modelling approach in the fully eccentric annulus with the concentric annulus, it can be observed that while the hydraulic diameter concept performs best in the concentric annulus, the slot and Lamb diameter concepts perform best in the fully eccentric annulus. The observed difference could be because of the increased shear in the fully eccentric annulus.

As the liquid superficial velocity increased, the pressure drop is higher in the fully eccentric annulus when compared with the concentric one.

7.4.1.2 Two-Fluid Pressure Drop Model Comparison in Fully Eccentric Annulus

The two-fluid models enumerated in section 7-1 are applied to the wavy annular and annular flow regimes of the fully eccentric annulus using different diameter concepts. The results presented in Figure 7-10 show the different pressure drop correlations based on slot diameter which performed best of all the diameter concepts on these models.

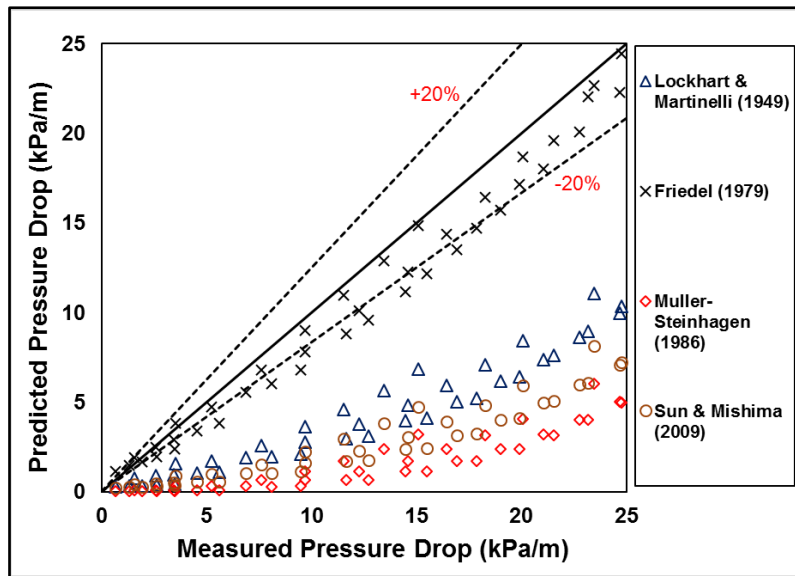


Figure 7-10: Pressure drop as a function of experimental data using the two-fluid model approach in fully eccentric annulus based on Slot diameter concept.

Of all the models, the Friedel (1979) performed the best of the models compared, followed by the Lockhart & Martinelli (1949) model. The third best model model is the Sun & Mishima (2009) while the worst model is Muller-Steinhagen (1986). Table 7-6 shows the performance of each model based on statistical analysis. Details of the performance of other diameter concepts are presented in Appendix B2.

Table 7-6: Comparison of evaluated pressure drop models based on the Slot diameter concept in fully eccentric annulus

Model	Mean Error (E ₁)	Mean Absolute Error (E ₂)
Lockhart & Martinelli (1949)	-0.67	0.67
Friedel (1979)	-0.10	0.15
Muller-Steinhagen (1986)	-0.89	0.89
Sun & Mishima (2009)	-0.78	0.78

7.4.1.3 Mechanistic Model Pressure Drop Comparison for Intermittent Flow Region in Fully Eccentric Annulus

The Petalas & Aziz (2000) intermittent pressure drop modelling approach was similarly compared with the experimental pressure drop data from the fully eccentric annulus based on different diameter concepts. The results are presented in Figure 7-11 and Table 7-7.

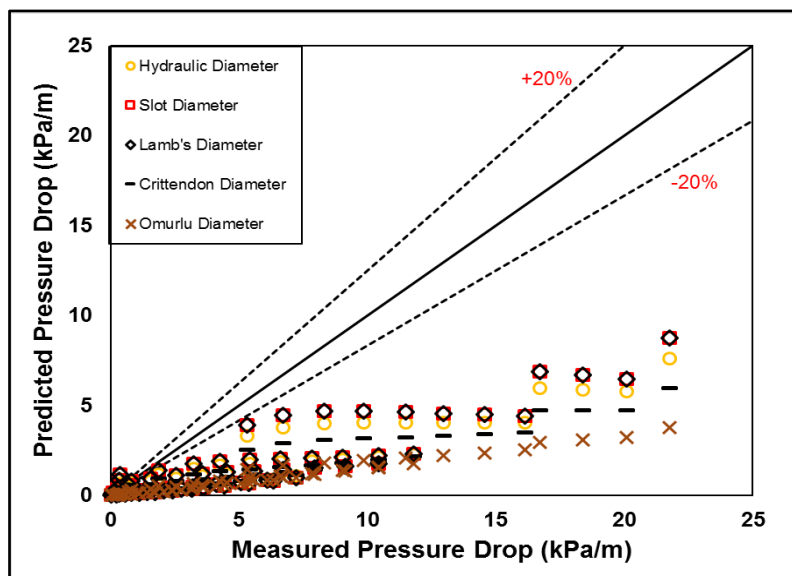


Figure 7-11: Comparison of Petalas & Aziz (2000) pressure drop model with experimental data based on different diameter concepts

Experimental pressure drop data are underpredicted irrespective of the diameter concept used. However, statistical analysis of the mean error E_1 and E_2 presented on Table 7-7 shows that the slot and Lamb's diameters performed best while the Omurlu diameter is the worst diameter concept. This modelling approach will also need modification to be applicable for pressure drop determination of the intermittent flow region in the fully eccentric annulus.

Table 7-7: Comparison of experimental data with the Petals & Aziz (2000) model for different diameter concept in fully eccentric annulus

Diameter Concept	Mean Error (E_1)	Mean Absolute Error (E_2)
Hydraulic Diameter	-0.63	0.73
Slot Diameter	-0.56	0.74
Lamb's Diameter	-0.56	0.74
Crittendon Diameter	-0.76	0.76
Omurlu Diameter	-0.83	0.83

7.5 Effect of Annulus Eccentricity on Mean Pressure Drop

To study the effect of annulus eccentricity on the mean pressure drop in horizontal annulus, a comparison is made between the measured pressure drop in concentric annulus and those of the fully eccentric annulus for similar gas and liquid superficial velocities. Figure 7-12 presents the result of the effect of annulus eccentricity of mean measured pressure drop as a function of gas superficial velocities at different liquid superficial velocities in horizontal annulus. The general trend observed shows that the pressure drop is higher in fully eccentric annulus than the concentric annulus at increasing gas and liquid superficial velocities. This could be due to flow geometry changing in fully eccentric annulus, where the inner pipe lies at the bottom of the outer pipe restricting the flow of the liquid phase, therefore, the velocity profile within this annulus might be different from the concentric annulus and this may affect the shear forces at the bottom of the annulus resulting in increased pressure drop.

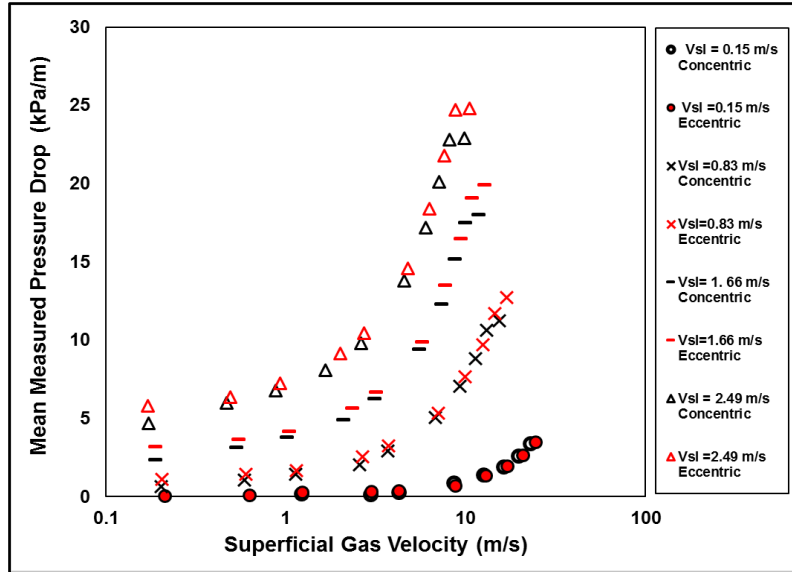


Figure 7-12: Effect of annulus eccentricity on mean measured pressure drop in horizontal annulus

7.6 Chapter Summary

In this chapter, mean experimental pressure drop measured in the concentric and fully eccentric annulus of this study are presented. Static pressure transducers located 4.91 m apart are used to determine the pressure drop in both annulus setup. Initially, a review of two-phase pressure drop modelling approaches applied for evaluation of horizontal annulus data based on different diameter definition are summarized. Single-phase water tests are carried out to benchmark the test facilities against properly established facilities and models in literature. The main findings of this chapter are as follows:

- The pressure drop analysis of single-phase water in horizontal concentric and fully eccentric annulus shows slightly higher pressure drop in the concentric annulus when compared with the fully eccentric annulus at low water superficial velocities (0.2 – 0.8) m/s. However, at superficial water velocity above 0.8 m/s, the fully eccentric annulus has higher pressure drop than the concentric one. This implies that the gravitational effects are dominant at the lower superficial velocities of water which seem higher in the concentric annulus while the frictional effects are dominant at the

higher water superficial velocities and the fully eccentric annulus seem to be dominated by that.

- In both concentric and fully eccentric annulus studied, the pressure drop is observed to increase with increase in gas and liquid superficial velocity. A minimal increase in pressure drop is observed with increase in gas superficial velocity at low liquid superficial velocity, however at higher liquid superficial velocity, a significant increase is observed in pressure drop due to increase in gas superficial velocity. This shows that the liquid phase is the main contributor of pressure drop.
- The homogeneous model of Dukler et al., (1964) applied to the dispersed flow regime of the concentric annulus using different diameter concept shows that the hydraulic diameter concept is the best performing with mean error E_1 and mean absolute error E_2 of 0.06 and 0.05 respectively.
- The two-fluid models of Lockhart & Martinelli (1949), Friedel (1979), Muller-Steinhagen (1986) and Sun & Mishima (2009) are compared with experimental pressure drop data of the wavy annular and annular flow regimes of the concentric annulus using different diameter concepts. The best performing diameter concept for all the models examined are the Slot and Lamb's diameter, however, the Friedel (1979) model is the best performing two-fluid model with E_1 and E_2 of -0.10 and 0.13 respectively.
- The intermittent flow regimes including the elongated bubble, slug, wavy slug and churn flow regimes are evaluated for concentric annulus against the Petalas & Aziz (2000) model using different diameter concepts. The model hugely underestimates the mean pressure drop irrespective of the diameter concept.
- The Dukler (1964) homogeneous model applied to the fully eccentric annulus dispersed bubble flow regime using different diameter concepts. All the diameter concepts under-predict the experimental pressure drop but the Slot and Lamb's diameter perform the best with E_1 and E_2 of -0.14 and 0.15 respectively.
- Similarly, the two-fluid models are applied to the full eccentric annulus experimental data in the wavy annular and annular flow regimes using the

different diameter concepts. The Slot diameter is again the best performing concept of all the diameter concepts for all the models and just like in the concentric annulus, the Friedel (1979) model performs best with E_1 and E_2 of -0.10 and 0.15 respectively.

- The effect of annulus eccentricity is observed to result in higher pressure drop in the fully eccentric annulus when compared to the concentric one. The difference in the flow geometry in the fully eccentric annulus causes a restriction of the liquid phase in that annulus setup probably resulting in higher shear forces and as a result, higher pressure drop due to difference in velocity profile.

In conclusion, this chapter provides the best diameter concepts to use depending on the modelling approach used to predict pressure drop in concentric or fully eccentric annulus and also the effect of annulus eccentricity on pressure drop.

8 CONCLUSION AND RECOMMENDATIONS

A detailed systematic study has been undertaken in horizontal annulus setup. The gas-liquid two-phase flow hydraulics have been investigated include the flow regimes, liquid holdup and pressure drop. In order to study the effect of annulus eccentricity on the flow parameters highlighted, experiments were performed in a fairly large 2 inch in 3 inch horizontal annulus. Two eccentricity positions were investigated including concentric and fully eccentric.

A major challenge in studying gas-liquid two-phase flow in annular geometries is acquiring accurate experimental data which are detailed and could be employed for mechanistic model development. This is further complicated by the narrow gap and asymmetry of an eccentric annulus, which makes it extremely difficult to characterize particularly the unsteady flow with disturbances at the interface.

The modelling attempts available in literature for calculation of parameters including liquid holdup and pressure drop in annular geometries are based on the extension of two-phase flow models and correlations to these geometries mainly using the hydraulic diameter concept. This approach has been observed to be incorrect especially in eccentric annulus. Different hydraulic diameter definitions are therefore tested with some of these models to determine the most suitable concept depending on the model and annulus eccentricity.

As a result of the systematic experimental studies, experimental data is provided which will be very important to increase and bridge the gap in the available database. Also, the instrumentation utilized to study the flow properties in detail in this geometry is a first. The geometries investigated are realistic and could be encountered in the oil and gas industry during oil well drilling, well production and well cleaning. The effect of annulus eccentricity on the gas-liquid two-phase flow parameters is also highlighted in details with the underlying physics behind the observed differences. New models are also developed where necessary to estimate some of the flow parameters.

A summary of the main conclusions made from this study and recommendations for future research efforts are presented.

8.1 Conclusions

8.1.1 Flow Regimes and Their Identification

- Flow regimes have been characterized using high speed camera images together with times series and PDF trends of the mean liquid holdup measured using conductance probes. A new flow regime is classified as wavy slug flow in the intermittent flow region for this study.
- Elongated bubble flow is encountered in the concentric annulus and slug flow in the fully eccentric annulus at low air and lowest water superficial velocities due to the annulus eccentricity as observed in this study.
- The bubble shape observed in the elongated bubble flow regime and the liquid film height during the wavy annular and annular flow regimes are affected by annulus eccentricity, visually observed difference were also confirmed from statistical PDF trends.
- The flow regime transitions from elongated bubble to slug, slug to wavy slug and wavy slug to annular flows take place at higher liquid superficial velocities and lower gas superficial velocities in the fully eccentric annulus when compared to the concentric one. This shift is consistent with the observed effect of eccentricity on phase separation.
- Both experimental flow regime maps were significantly different from maps available in literature for two-phase gas-liquid flow in pipes and annulus including those proposed by Beggs & Brill (1973), Mandhane et al., (1974), Taitel & Dukler (1976) (all developed for flow in circular pipes) and Osgouei et al., (2010) (developed for flow through horizontal annulus). The differences observed with circular pipe flow regime transitions may be due to less dominant gravitation factor in the annulus due to the uniqueness of the geometry. The density difference in the annulus channel results in the suppression of the on the gas/liquid separation.
- Flow regime transition parameters developed for this study predicted experimental data with up to 86% accuracy overall. However, it is not recommended for extension to other setups with dimensions differ from

those whose data formed a part in developing it until further testing and improvement is done.

- Kernel Principal Component Analysis of PDF data from conductance probes can be used together with Support Vector Machine for objective real-time automatic flow regime identification in horizontal annulus and other conduits for that matter.

The conclusions reached in the flow regime identification study can serve as a guide for drilling design engineers enabling them to design proper underbalanced drilling operations. The understanding provided by this study will help to properly identify flow regime, leading to accurate selection of models for the design of equipment and or processes during gas-liquid flow in annulus. Model developing physicist can utilize the high quality data as well as the transition parameters provided to develop models which can be incorporated into commercial software packages by simulation code developers. Finally, the potential application of the real-time objective identification tool using SVM include providing more information of the two-phase flow and for switching between hybrid multiphase flow models using the flow regime charts developed. This could be beneficial to process control engineers who could use the technique to switch between flow regime dependent models for estimating specific flow properties or model based control.

8.1.2 Characterization of Slug Flow in Annuli

- Slug frequency is independent of the gas superficial velocities investigated. However, an increase in the slug frequency was observed as the liquid superficial velocity was increased in both annulus setups. The annulus eccentricity causes a higher slug frequency in the fully eccentric annulus when compared with concentric one.
- The annulus eccentricity has no effect on the slug translation velocity observed in horizontal annulus.
- The annulus eccentricity affects the slug length in horizontal annulus with average length of 37D in concentric annulus and average of 57D in fully

eccentric annulus. The film region length on the other hand is unaffected by annulus eccentricity.

- Dimensionless slug lengths in the concentric and fully eccentric annulus setups could be brought closer together by using the largest gap diameter concept. The approach reduces the difference between the average slug lengths of both annulus by 10%.
- Annulus eccentricity causes higher slug body holdup in the fully eccentric annulus when compared with the concentric one.

It can be inferred from the slug characterization studies carried out in this study that the predictive models available in literature for two-phase slug flow characterization were mainly developed for flow in circular pipes and extended to annulus using the hydraulic diameter concept. As such the discrepancies observed during comparisons with experimental data is a result of the difference in conduit geometries. Irrespective of this fact, this a valuable first step in characterizing slug flow in annular geometries. The slug flow parameters measured will be suitable for equipment design engineers to design slug catchers, separators and pipe lines for the oil and gas industry. Also, process control engineers can find useful information for implementing slug control measures which may become necessary at certain conditions due to overall economics of processes where annular geometries are encountered.

8.1.3 Liquid Holdup in Gas-Liquid Flows in Horizontal Annuli

- The annulus eccentricity results in a higher mean liquid holdup in concentric annulus when compared to the fully eccentric annulus at the lower gas superficial velocities investigated. However, at gas superficial velocities above 6.8 m/s, the fully eccentric annulus is observed to have higher liquid holdup values when compared to the concentric one at the same conditions.
- The observed cross over point in the liquid holdup between the concentric and fully eccentric is observed to be the transition to the annular flow

region. To explain the effect of the annulus eccentricity on mean measured liquid holdup, the Froude number is plotted as a function of liquid holdup.

- For the lower to intermittent mixture velocity ranges, the gravitational forces are observed to be more important due to the density difference in the concentric annulus when compared with the same flow conditions in the fully eccentric annulus.
- At higher mixture velocities, the frictional forces become more significant than the gravitational forces and the fully eccentric annulus seems to have higher frictional forces at the higher mixture velocities when compared with the concentric one.
- The liquid holdup in horizontal (concentric and fully eccentric) annulus is observed to reduce with increase in the gas superficial velocity and increase with increase in the liquid superficial velocity.
- The Homogeneous modelling performs well both in the concentric and fully eccentric annulus for predicting the liquid holdup in dispersed bubble flow regime. However, it is slightly better in the concentric annulus.
- Chisholm (1973) model performs the best in terms of the mean error and absolute mean error in both concentric and fully eccentric annulus of the separated flow modelling approaches evaluated.
- Fabre & Line (1992) performs the best in terms of mean error of the Drift Flux modelling approaches evaluated in the concentric annulus while the Bonnecaze et al., (1971) closure relationships is the best in the fully eccentric annulus. The hydraulic diameter concept can be used for drift flux modelling irrespective of the annulus eccentricity.
- The Beggs & Brill (1973) flow regime dependent model under-predicts the predicted mean liquid holdup at the low and very high liquid holdup values in both annulus setups investigated irrespective of the diameter concept utilized. The Omurlu diameter is the best in terms of performance in flow regime based models in both annulus setup.
- The Petalas & Aziz (2000) is used to predict the intermittent flow regime in both annulus setups and mainly predicts the mean liquid holdup within an error range of $\pm 20\%$ irrespective of the diameter concept utilized.

- A new liquid holdup correlation is proposed based on dimensionless numbers as presented in Equation (6-29) and evaluated against data from literature integrated with experimental data.

In terms of multiphase flow relevance, the liquid holdup is important in determining other parameters include flow regimes and pressure drop. The evaluation of different modelling approached using the various diameter definitions and the data provided by this study will help model development engineers to develop adequate models using the right diameter concept depending on the approach which could be implemented in commercial simulation software packages. Also, equipment design engineers would be able to design equipment like separators and pipelines which rely on liquid holdup information.

8.1.4 Pressure Drop in Gas-Liquid Flows in Horizontal Annuli

- The effect of annulus eccentricity of single phase pressure drop shows slightly higher pressure drop in the concentric annulus when compared with the fully eccentric annulus at low water superficial velocities (0.2 – 0.8) m/s. However, at superficial water velocity above 0.8 m/s, the fully eccentric annulus has higher pressure drop than the concentric one. It can be implied from this observation that the gravitational effects are dominant at the lower superficial velocities of water in the concentric annulus while the frictional effects are dominant at the higher water superficial velocities in the fully eccentric annulus.
- The pressure drop in both concentric and fully eccentric annulus increases with increase in gas and liquid superficial velocity. The liquid phase is the main contributor to pressure drop in horizontal annulus flow.
- The hydraulic diameter concept is the best performing with mean error E_1 and mean absolute error E_2 of 0.06 and 0.05 when applied to the homogeneous model of Dukler et al., (1964) in the concentric annulus setup. On the other hand, the Slot and Lamb diameter concepts perform the best with E_1 and E_2 of -0.14 and 0.15 respectively in the fully eccentric annulus.

- The Friedel (1979) correlation is the best performing two fluid model for evaluating experimental pressure drop in concentric annulus E_1 and E_2 of -0.10 and 0.13 respectively while the best performing diameter concept for all the models examined are the Slot and Lamb's diameter. Similarly, the Friedel (1979) model performs best with the Slot diameter concept being the most suitable for use in the fully eccentric annulus.
- The Petalas & Aziz (2000) model using different diameter concepts hugely underestimates the mean pressure drop irrespective of the diameter concept used in both the concentric and fully eccentric annulus setup studied.
- The effect of annulus eccentricity is observed to result in higher pressure drop in the fully eccentric annulus when compared to the concentric one. The difference in the flow geometry in the fully eccentric annulus causes a restriction of the liquid phase in that annulus setup resulting in higher shear and as a result, higher pressure drop.

In summary, all the data obtained from this study could be utilized in development of better theoretical models with higher accuracies which would have a huge impact on energy and cost effective processes including drilling and cleaning of horizontal wells and also ensure steady production of oil from horizontal wells with a long reach.

8.2 Recommendations for Further Research

- The present study was undertaken using air and water as the testing fluids, although these fluids are sufficient for describing two-phase flow in annuli for chemical reactors and nuclear applications, the drilling applications in practical terms would involve more viscous fluid and as such, it is necessary to study the effect of annulus eccentricity on flow regimes, liquid holdup and pressure drop using testing fluids with viscosities similar to what would be encountered in the oil and gas industry.
- The entrance length of fully developed two-phase flow in annulus should be investigated.

- Different annulus diameter ratios could be investigated to see the effect these ratios would have on the two-phase flow hydraulics in horizontal annulus.
- More advanced instruments (tools) should be utilized to provide more details of the phase and velocity distribution. Also certain properties of the flow could be measured to further deepen understanding of the gas-liquid two-phase flow hydraulics in annulus. For instance, during this study, the effect of the annulus eccentricity is observed on the film thickness during the wavy annular and annular flow regimes, the film thickness should be measured using a film thickness probe which would enhance the modelling of the annular flow region. Similarly, a Particle Image Velocimetry (PIV) system can could be used to study the shear stress on the wall of the annulus. This would provide further clarity about the effect of annulus eccentricity on the pressure drop in annulus.
- Slight deviations in inclinations in multiphase flow systems has been known to affect the flow hydraulics considerable. It is important to study the effect of annulus eccentricity on two-phase flow parameters in slightly inclined annuli.

REFERENCES

Akbar, M. K. and Ghiaasiaan, S. M. (2003) 'Stability of stratified gas-liquid flow in horizontal annular channels', *Experimental Thermal and Fluid Science*, 28(1), pp. 17–21. doi: 10.1016/S0894-1777(03)00086-4.

Al-Lababidi, S. (2006) *Multiphase Flow Measurement in the Slug Regime Using Ultrasonic Measurement Techniques and Slug Closure Model*. Cranfield University.

Al-Safran, E. (2009) 'Investigation and prediction of slug frequency in gas/liquid horizontal pipe flow', *Journal of Petroleum Science and Engineering*, 69(1–2), pp. 143–155. doi: 10.1016/j.petrol.2009.08.009.

Al-Safran, E. M. (2016) 'Probabilistic modeling of slug frequency in gas/liquid pipe flow using the Poisson probability theory', *Journal of Petroleum Science and Engineering*. Elsevier, 138, pp. 88–96. doi: 10.1016/j.petrol.2015.12.008.

Andreussi, P. and Bendiksen, K. (1989) 'An Investigation of Void Fraction in Liquid Slugs for Horizontal and Inclined Gas-Liquid Pipe Flow', *International Journal of Multiphase Flow*, 15(6), pp. 937–946.

Baker, O. (1954) 'Design for Pipelines for Simultaneous Flow of Oil and Gas', *The Oil and Gas Journal*, pp. 185–192. doi: 10.2118/323-G.

Barnea, D. (1987) 'A Unified Model for Predicting Flow-Pattern Transitions for the Whole Range of Pipe Inclinations', *Int. J. Multiphase Flow*, 13(1), pp. 1–12.

Barnea, D., Shoham, O. and Taitel, Y. (1980) 'Flow pattern characterization in two phase flow by electrical conductance probe', *Int. J. Multiphase Flow*, 6(5), pp. 387–397. doi: 10.1016/0301-9322(80)90001-4.

Beattie, D. and Whalley, P. B. (1982) 'A Simple Two-phase Frictional Pressure Drop Calculation Method', *Int. J. Multiphase Flow*, 8(1), pp. 83–87.

Beggs, H. D. and Brill, J. P. (1973) 'A Study of Two Phase Flow in Inclined Pipe', *Jpt*, pp. 606–617.

Bendiksen, K. (1984) 'An Experimental Investigation of the Motion Long Bubbles in Inclined Tubes', *International Journal of Multiphase Flow*, 10(4), pp. 467–483.

Bertola, V. (ed.) (2003) *Modelling and Experimentation in Two-Phase Flow*. New York: Springer-Verlag Wien GmbH. doi: 10.1007/978-3-7091-2538-0.

Bhagwat, S. M. and Ghajar, A. J. (2014) 'A flow pattern independent drift flux

model based void fraction correlation for a wide range of gas-liquid two phase flow', *International Journal of Multiphase Flow*. Elsevier Ltd, 59, pp. 186–205. doi: 10.1016/j.ijmultiphaseflow.2013.11.001.

Bonnecaze, R. ., Erskine and Greskovich, E. . (1971) 'Holdup and pressure drop for two phase slug flow in inclined pipelines', *AIChE Journal*, 17, pp. 1109–1113.

Butterworth, D. (1975) 'A comparison of some void fraction relationships for co-current gas-liquid flow', *International Journal of Multiphase Flow*, 1(6), pp. 845–850.

Caetano, E. ., Shoham, O. and Brill, J. P. (1992a) 'Upward Vertical Two-phase Flow through an Annulus - Part II: Modeling Bubble, Slug and Annular Flow', *Journal of Energy Resources Technology-Transactions of the Asme*, 114, pp. 14–30.

Caetano, E. ., Shoham, O. and Brill, J. P. (1992b) 'Upward Vertical Two-phase flow through an annulus -Part I: Single-phase friction factor, Taylor Bubble rise velocity, and Flow pattern prediction', *Journal of Energy Resources Technology-Transactions of the Asme*, 114, pp. 1–13.

Carneiro, J. N. E. et al. (2011) 'Statistical characterization of two-phase slug flow in a horizontal pipe', *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 33(spe1), pp. 251–258. doi: 10.1590/S1678-58782011000500007.

Chisholm, D. (1967) 'A Theoretical Basis for the Lockhart-Martinelli Correlation for Two-Phase Flow', *Int J Heat Mass Transfer*, 10(18), pp. 1767–1778. doi: [http://dx.doi.org/10.1016/0017-9310\(67\)90047-6](http://dx.doi.org/10.1016/0017-9310(67)90047-6).

Chisholm, D. (1973) 'Pressure gradients due to friction during the flow of evaporating two-phase mixtures in smooth tubes and channels', *International Journal of Heat and Mass Transfer*, 16(2), pp. 347–358. doi: 10.1016/0017-9310(73)90063-X.

Chisholm, D. (1973) 'Pressure Gradients due to friction during the flow of evaporating two-phase mixtures in smooth tubes and channels', *International Journal of Heat and Mass Transfer*, 16(29), pp. 347–358.

Chisholm, D. and Laird, A. (1958) 'Two-phase flow in rough tubes', *Journal of Heat Transfer*, 83, pp. 276–286.

Cristianini, N. and Shawe-Taylor, J. (2014) *An Introduction to Support Vector Machines and Other Kernel-based Learning Methods*, Kybernetes. Cambridge University Press. Available at: <https://doi.org/10.1017/CBO9780511801389>.

Crittendon, B. and Crittendon, B. C. (1959) 'The Mechanics of Design and Interpretation of Hydraulic Fracture Treatments', *Journal of Petroleum Technology*, 11(10), pp. 21–29. doi: 10.2118/1106-G.

D.Chisholm (1967) 'Lockhart-Martinelli Basis for the Correlation Flow for Two-Phase', *International Communications in Heat and Mass Transfer*, 10(18), pp. 1767–1778.

Das, G. *et al.* (1999) 'Gas Liquid Upflow Through Vertical Concentric Annuli — Part I: Experimental', *Journal of Fluids Engineering ASME*, 121(December 1999), pp. 2–8.

Das, G. *et al.* (2008) 'Flow Pattern Transition During Gas Liquid Upflow Through Vertical Concentric Annuli—Part II: Mechanistic Models', *Journal of Fluids Engineering*, 121(4), p. 902. doi: 10.1115/1.2823553.

Devia, F. and Fossa, M. (2003) 'Design and optimisation of impedance probes for void fraction measurements', *Flow Measurement and Instrumentation*, 14(4–5), pp. 139–149. doi: 10.1016/S0955-5986(03)00019-0.

Dillon, C. *et al.* (2004) 'Two-phase pressure drop in a horizontal thin annulus: Effects of channel vibration and wall gas injection', *Experimental Thermal and Fluid Science*, 30, pp. 67–78.

Dukler, A E., Wicks III, M. and Cleveland, R. G. (1964) 'Frictional pressure drop in two-phase flow', *AIChE Journal*, 10(1), pp. 38–51.

Dukler, A. E. and Hubbard, M. G. (1975) 'A Model for Gas-Liquid Slug Flow in Horizontal and Near Horizontal Tubes', 14(May), pp. 337–347. doi: 10.1021/i160056a011.

Dukler, A. E., Wicks III, M. and Cleveland, R. G. (1964) 'Frictional pressure drop in two-phase flow: A comparison of existing correlations for pressure loss and holdup', *AIChE Journal*, 10(1), pp. 38–43. doi: 10.1002/aic.690100117.

Eaton, B. A., Knowles, C. R. and Silberbrg, I. H. (1967) 'The Prediction of Flow Patterns, Liquid Holdup and Pressure Losses Occurring During Continuous Two-Phase Flow In Horizontal Pipelines', *Journal of Petroleum Technology*, 19(06), pp. 815–828. doi: 10.2118/1525-PA.

Ekberg, N. P. et al. (1999) 'Gas - liquid two-phase flow in narrow horizontal annuli', *Nuclear Engineering and Design*, 192(1), pp. 59–80. doi: 10.1016/S0029-5493(99)00078-3.

Fabre, J. and Line, A. (1992) 'Modeling two -phase slug flow', *Annual Review of Fluid Mechanics*, (24), pp. 21–46.

Fan, S. and Yan, T. (2014) 'Two-phase air-water slug flow measurement in horizontal pipe using conductance probes and neural network', *IEEE Transactions on Instrumentation and Measurement*, 63(2), pp. 456–466. doi: 10.1109/TIM.2013.2280485.

Fossa, M. (1998) 'Design and performance of a conductance probe for measuring the liquid fraction in two-phase gas-liquid flows', *Flow Measurement and Instrumentation*, 9(2), pp. 103–109. doi: 10.1016/S0955-5986(98)00011-9.

Fossa, M., Guglielmini, G. and Marchitto, A. (2003) 'Intermittent flow parameters from void fraction analysis', *Flow Measurement and Instrumentation*, 14(4–5), pp. 161–168. doi: 10.1016/S0955-5986(03)00021-9.

Friedel, L. (1979) 'Improved Friction Pressure Drop Correlations for Horizontal and Vertical Two-Phase Pipe Flow', in *European Two-phase Flow Group meeting*. Ispra, Italy, pp. 485–491.

Gregory, G. A., Nicholson, M. K. and Aziz, K. (1978) 'Correlation of the liquid volume fraction in the slug for horizontal gas-liquid slug flow', *International Journal of Multiphase Flow*, 4(1), pp. 33–39. doi: 10.1016/0301-9322(78)90023-X.

Gregory, G. A. and Scott, D. . (1969) 'Correlation of liquid slug velocity and frequency in horizontal cocurrent gas-liquid slug flow', *AIChE Journal*, 15, pp. 933–935.

Gschnaidtner, T. (2014) *Two-Phase Flow (Air-Water) Characteristics in Annulus*. Cranfield University, Bedfordshire UK.

Haciislamoglu, M. Langlinais, J. (1990) 'Non-Newtonian Flow in Eccentric Annuli', *Journal of Energy Resources Technology*, 112(September 1990), pp. 163–169.

Hasan, A. R. and Kabir, C. S. (1992) 'Two-Phase Flow in Vertical and Inclined Annuli', *Int. J. Multiphase Flow*, 18(2), pp. 279–293.

Hastie, T., Tibshirani, R. and Friedman, J. (2009) *The Elements of Statistical Learning*. 2nd edn. California: Springer-Verlag.

Hewitt, G. F. and Jayan, S. (1993) 'To Churn or Not To Churn', 19(3), pp. 527–529.

Ibarra, R. and Nossen, J. (2018) 'Bubble velocity in horizontal and low-inclination upward slug flow in concentric and fully eccentric annuli', *Chemical Engineering Science*, 192, pp. 774–787. doi: 10.1016/j.ces.2018.08.022.

Jones, O. C. and Zuber, N. (1975) 'The interrelation between void fraction fluctuations and flow patterns in two-phase flow', *International Journal of Multiphase Flow*, 2(3), pp. 273–306. doi: 10.1016/0301-9322(75)90015-4.

Julia, J. E., Ozar, B., Dixit, A., Jeong, J.J., Hibiki, T., and Ishii, M. (2009) 'Axial Development of Flow Regime in Adiabatic Upward Two-Phase Flow in a Vertical Annulus', *Journal of Fluids Engineering*, 131(2), p. 021302. doi: 10.1115/1.3059701.

Julia, J. E., Ozar, B., Dixit, A., Jeong, J.J., Hibiki, T., and Ishii, M. (2011) 'Flow regime development analysis in adiabatic upward two-phase flow in a vertical annulus', *International Journal of Heat and Fluid Flow*. Elsevier Inc., 32(1), pp. 164–175. doi: 10.1016/j.ijheatfluidflow.2010.09.003.

Julia, J. E., Hibiki, T. and Ishii, M. (2010) 'Flow Regime Transition Criteria for

Two-Phase Flow in Vertical Annulus', in *International Conference of Multiphase flow*. Tampa, FL USA, pp. 1–12.

Karatzoglou, A., Meyer, D. and Hornik, K. (2006) 'Support Vector Machines in R', *Journal of Statistical Software*, 15(9), pp. 1–28.

Kelessidis, V. C. and Dukler, A. E. (1989) 'Modeling flow pattern transitions for upward gas-liquid flow in vertical concentric and eccentric annuli', *Int. J. Multiphase Flow*, 15(2), pp. 173–191.

Kijjarvi, J. and Kij, J. (2011) 'Darcy Friction Factor Formulae in Turbulent Pipe Flow', *Lunowa Fluid Mechanics Paper*, pp. 1–11. Available at: http://www.kolumbus.fi/jukka.kijjarvi/clunowa/fluid_mechanics/pdf_articles/darcy_friction_factor.pdf.

Kleinstreuer, C. (2003) *Two Phase Flow: Theory and Applications*. First. New York, London: Taylor & Francis.

Lage, A. C. V. M., Rommetveit, R. and Time, R.W. (2000) 'An Experimental and Theoretical Study of Two-Phase Flow in Horizontal or Slightly Deviated Fully Eccentric Annuli'.

Lage, A. C. V. M. and Time, R. W. (2000) 'Mechanistic Model for Upward Two-Phase Flow in Annuli', *SPE Annual Technical Conference and Exhibition*, (1), pp. 1–11. doi: 10.2523/63127-MS.

Lamb, H. S. (1945) *Hydrodynamics*. 6th edn. Cambridge: The University Press.

Lockhart, R. W. and Martinelli, R. C. (1949) 'Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes', *Chemical Engineering Progress*, pp. 39–48. doi: [http://dx.doi.org/10.1016/0017-9310\(67\)90047-6](http://dx.doi.org/10.1016/0017-9310(67)90047-6).

Lockhart, R. W. and Martinelli, R. C. (1949) 'Proposed Correlation of Data for Isothermal Two Phase Flow, Two Component Flow in Pipes', *Chemical Engineering Progress*, pp. 39–48.

M.C. Cook, C.H. Newton, M. B. (1995) 'Experimental investigation of air-water slug flow in horizontal pipes and comparison with existing models', *Twelfth Australian*

Fluids Mechanics Conference, pp. 699–702.

Malnes, D. (1979) 'Slip relations and momentum equation in two-phase flow', *journal of chemical engineering communications*, 141, pp. 71–102.

Mandhane, J. M., Gregory, G. A. and Aziz, K. (1974) 'A Flow Pattern Map for Gas-Liquid Flow in Horizontal Pipes', *Int. J. Multiphase Flow*, 1(9), pp. 537–553.

Matsui, G. (1984) 'Identification of flow regimes in vertical gas-liquid two-phase flow using differential pressure fluctuations', *International Journal of Multiphase Flow*, 10(6), pp. 711–719. doi: 10.1016/0301-9322(84)90007-7.

McAdams, W. H. (1954) *Heat Transmission*. 3rd edn. New York: McGraw-Hill.

Mendes, F. A., Rodriguez, O.M., Estevam, V., and Lopes, D. (2011) 'Flow Patterns in inclined gas-liquid annular duct flow', *WIT Transactions on Engineering Sciences*, 70, pp. 271–283. doi: 10.2495/MPF110.

Metin, C. O. and Ozbayoglu, M. E. (2007) 'Analysis of Two-Phase Fluid Flow Through Fully Eccentric Horizontal Annuli', pp. 373–384.

Metin, C. O. and Ozbayoglu, M. . (2007) 'Two-Phase Fluid Flow through Fully Eccentric Horizontal Annuli: A Mechanistic Approach', in *SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition*. Texas, pp. 1–7.

Metin, C. O. and Ozbayoglu, M. E. (2009) 'Friction factor determination for horizontal two-phase flow through fully eccentric annuli', *Petroleum Science and Technology*, 27(15), pp. 1771–1782. doi: 10.1080/10916460802686178.

Mitsubishi, N. and Aoyagi, Y. (1973) 'Non-Newtonian Fluid Flow in Eccentric Annulus', *Journal of Chemical Engineering Japan*, 6, pp. 402–408.

Mullersteinhagen, H. and Heck, K. (1986) 'a Simple Friction Pressure-Drop Correlation for 2-Phase Flow in Pipes', *Chemical Engineering and Processing*, 20(6), pp. 297–308. doi: 10.1016/0255-2701(86)80008-3.

Na, W., Jia, J., Yu, X., Faraj, Y., Wang, Q., Meng, Y. and Wang, M. (2015) 'Imaging of gas – liquid annular flows for underbalanced drilling using electrical resistance tomography', *Flow Measurement and Instrumentation*. Elsevier, 46,

pp. 319–326. doi: 10.1016/j.flowmeasinst.2015.07.003.

Nakoryakov, V. E., Kuznetsov, V. and Vitovsky, O. (1992) 'Experimental Investigation of Upward Gas- Liquid Flow in Vertical Narrow Annulus', *International Journal of Multiphase Flow*, 18(3), pp. 313–326.

Nicholson, M. K. and Gregory, G. A. (1978) 'Intermittent two-phase flow in horizontal pipes: predictive models', *Canadian Journal of Chemical Engineering*, 56, pp. 653–663.

Nicklin, D. J., Wilkes, M. and Davidson, J. (1962) 'Two-phase flow in vertical tubes', *Trans.Instn. Chem. Engrs*, 40, pp. 61–68.

Nossen, J., Liu, L., Skjaeraasen, O., Tutkun, M., Amundsen, J.E., Sleipnaes, Popovici, N., Hald, K., Langsholt, M. and Ibarra, R. (2017) 'An experimental study of two-phase in horizontal and inclined annuli', in *HBR Cannes*. Cannes, France, pp. 87–102.

Nydal, O. J., Pintus, S. and Andreussi, P. (1992) 'Statistical Characterization of Slug Flow in Horizontal Pipes', *International Journal of multiphase flow*, 18(3), pp. 439–453.

Omurlu, C. (2006) *Mathematical modeling of horizontal two-phase flow through fully eccentric annuli*. Middle East Technical University.

Omurlu, C. and Ozbayoglu, E. M. (2006) 'A New Mechanistic Model For Two-Phase Flow Through Eccentric Horizontal Annulus', *SPE Europe/EAGE Annual Conference and Exhibition*. Vienna, Austria, (June), pp. 1–7. doi: 10.2523/100300-MS.

Omurlu, C. and Ozbayoglu, M. E. (2006) 'Friction factors for two-phase fluids for eccentric annuli in CT applications', 2006, pp. 282–286. doi: 10.2523/100145-MS.

Osamusali, S. and Chang, J. (1988) 'Two phase flow regime transition in a horizontal pipe and annulus flow under gas-liquid two-phase flow', *ASME Fundamentals of Gas-Liquid Flows*, FED-72, pp. 63–69.

Osamusali, S. I. (1988) Study of Gas-Liquid Two-Phase Flow Pattern Transitions in Horizontal Pipe , Annulus and Nuclear Fuel Type Rod Bundle Flow Systems. McMaster University Ontario, Canada.

Osgouei, R. E. (2010) Determination of cuttings transport properties of gasified drilling fluids. Middle East Technical University.

Osgouei, R. E., Ozbayoglu, M. E., Ozbayoglu, A.M. and Yuksel, E.H. (2013) 'The determination of two phase liquid-gas flow behavior through horizontal eccentric annular geometry by modification of Beggs & Brill and Lockhart & Martinelli models', in *Proceedings of the ASME 2013 Fluids Engineering Division Summer Meeting*. Nevada: ASME, pp. 1–9. Available at: <http://proceedings.asmedigitalcollection.asme.org>.

Osgouei, R. E., Ozbayoglu, M. E., Ozbayoglu, A.M. and Yuksel, E.H. (2015) 'A New Model to Determine the Two-phase Drilling Fluid Behavior Through Horizontal Eccentric Annular Geometry, Part A: Flow Pattern Identification and Liquid Hold-up Estimation', *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. Taylor and Francis Inc., 37(15), pp. 1663–1673. doi: 10.1080/15567036.2011.574192.

Osgouei, R. E. and Ozbayoglu, E. M. (2010) 'Flow pattern identification of gas-liquid flow through horizontal annular geometries', in *SPE Oil and Gas India Conference and Exhibition*, pp. 1–9.

Osgouei, R. E., Ozbayoglu, M. E. and Ozbayoglu, A. M. (2012) 'A mechanistic model to characterize the two phase drilling fluid flow through inclined eccentric annular geometry', in *SPE Oil and Gas India Conference and Exhibition*. Mumbai, India.

Ozar, B., Jeong, J. J., Dixit, A., Julia, J.E., Hibiki, T. and Ishii, M. (2008) 'Flow structure of gas-liquid two-phase flow in an annulus', *Chemical Engineering Science*, 63(15), pp. 3998–4011. doi: 10.1016/j.ces.2008.04.042.

Ozbayoglu, M. E. and Omurlu, C. (2007) 'Modelling of two-phase flow through concentric annuli', *Petroleum Science and Technology*, 25(8), pp. 1027–1040.

doi: 10.1080/10916460600695132.

Paglianti, A., Andreussi, P. and Nydal, O. J. (1993) High pressure three-phase (gas-liquid-liquid) flow. Imperial College London.

Papadimitriou, D. A. and Shoham, O. (1991) 'A mechanistic model for predicting annulus bottomhole pressures in pumping wells', *Proceedings of SPE Production Operations Symposium*. doi: 10.2118/21669-MS.

Petalas, N. and Aziz, K. (2000) 'A mechanistic model for multiphase flow in pipes', *Journal of Canadian Petroleum Technology*, 39(6), pp. 43–55. doi: 10.2118/00-06-04.

Platt, J., Cristianini, N. and Shawe-Taylor, J. (2000) 'Large margin DAGs for multiclass classification', *International Conference on Neural Information Processing Systems*, pp. 547–553. doi: 10.1.1.158.4557.

Sadatomi, M. and Sato, Y. (1982) 'Two-phase flow in vertical noncircular channels', *International Journal of Multiphase Flow*, 8(6), pp. 641–655.

Schölkopf, B., Smola, A. and Müller, K.-R. (1998) 'Nonlinear component analysis as a kernel eigenvalue problem', *Neural Computation*, 10(5), pp. 1299–1319. doi: 10.1162/089976698300017467.

Scott, S. L., Kouba, G. E. and Spe (1990) 'Advances in slug flow characterization for horizontal and slightly inclined pipelines', *65th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers*, pp. 125–140. doi: 10.2118/20628-MS.

Shoham, O. (2006) *Mechanistic Modeling of Gas-Liquid Two-Phase Flow in Pipes*. Richardson, Texas: Society of Petroleum Engineers.

Sorgun, M., Osgouei, R. E., Ozbayoglu, M.E. and Ozbayoglu, A.M. (2011) 'Gas-liquid flow through horizontal eccentric annuli: CFD and experiments compared', in *ASME -JSME -KSME 2011 Joint Fluid Engineering Conference*. Shizuoka, Japan, pp. 3–8. Available at: <http://proceedings.asmedigitalcollection.asme.org/>.

Sorgun, M., Osgouei, R. E., Ozbayoglu, M.E. and Ozbayoglu, A.M. (2013) 'An

Experimental and Numerical Study of Two-phase Flow in Horizontal Eccentric Annuli', *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 35(10), pp. 891–899. doi: 10.1080/15567036.2011.559524.

Sorgun, M. and Ozbayoglu, M. E. (2010) 'A mechanistic model for predicting frictional pressure losses for newtonian fluids in concentric annulus', *Petroleum Science and Technology*, 28(16), pp. 1665–1673. doi: 10.1080/10916460903226064.

Sun, L. and Mishima, K. (2009) 'Evaluation analysis of prediction methods for two-phase flow pressure drop in mini-channels', *International Journal of Multiphase Flow*. Elsevier Ltd, 35(1), pp. 47–54. doi: 10.1016/j.ijmultiphaseflow.2008.08.003.

Sun, X., Kuran, S. and Ishii, M. (2004) 'Cap bubbly-to-slug flow regime transition in a vertical annulus', *Experiments in Fluids*, 37, pp. 458–464. doi: 10.1007/s00348-004-0809-z.

Sunthakar, A. A., Miska, S., Kuru, E. and Kamp, A. (2000) 'New Developments in Aerated Mud Hydraulics for Horizontal Well Drilling', *SPE Journal*, 9(01), pp. 5–12. doi: 10.2118/87675-PA.

Sunthakar, A. A., Miska, S., Kuru, E. and Kamp, A. (2001) 'New developments in aerated mud hydraulics for drilling in inclined wells', *Spe Drilling & Completion*, 18(2), pp. 152–158.

Sunthakar, A. A. (2002) Study of the flow of aerated drilling fluids in annulus under ambient temperature and pressure conditions. University of Tulsa.

Taitel, Y. and Dukler, A. (1976) 'A model for predicting flow regime transitions in horizontal and near horizontal gas liquid flow. 1976.pdf', *AIChE Journal*, 22(1), pp. 47–55.

Thaker, J. and Banerjee, J. (2015) 'Characterization of two-phase slug flow sub-regimes using flow visualization', *Journal of Petroleum Science and Engineering*. Elsevier, 135, pp. 561–576. doi: 10.1016/j.petrol.2015.10.018.

Vapnik, V. N. (2000) *The nature of statistical learning theory*, 2nd edn. Springer-Verlag.

Wallis, G. B. (1969) *One Dimensional two-phase flow*. New York: McGraw-Hill.

Wang, H. X. and Zhang, L. F. (2009) 'Identification of two-phase flow regimes based on support vector machine and electrical capacitance tomography', *Measurement Science and Technology*, 20(11). doi: 10.1088/0957-0233/20/11/114007.

Wang, N., Sun B., Gong, P. and Wang, Z. (2017) 'Improved Void Fraction Correlation for Two-Phase Flow in Large-Diameter Annuli', *Chemical Engineering and Technology*, 40(4), pp. 745–754. doi: 10.1002/ceat.201600119.

Wang, X., Guo, L. and Zhang, X. (2006) 'Development of Liquid Slug Length in Gas-Liquid Slug Flow along Horizontal Pipeline: Experiment and Simulation', *Chinese Journal of Chemical Engineering*, 14(5), pp. 626–633. doi: 10.1016/S1004-9541(06)60125-0.

Wang, X., Guo, L. and Zhang, X. (2007) 'An experimental study of the statistical parameters of gas-liquid two-phase slug flow in horizontal pipeline', *International Journal of Heat and Mass Transfer*, 50(11–12), pp. 2439–2443. doi: 10.1016/j.ijheatmasstransfer.2006.12.011.

Wongwises, S. and Pipathattakul, M. (2006) 'Flow pattern, pressure drop and void fraction of two-phase gas-liquid flow in an inclined narrow annular channel', *Experimental Thermal and Fluid Science*, 30(4), pp. 345–354. doi: 10.1016/j.expthermflusci.2005.08.002.

Wu, B., Firouzi, M., Mitchell, T., Rufford, T.E., Leonardi, C. and Towler, B. (2017) 'A critical review of flow maps for gas-liquid flows in vertical pipes and annuli', *Chemical Engineering Journal*, 326, pp. 350–377. doi: 10.1016/j.cej.2017.05.135.

Yadigaroglu, G., Banerjee, S. and Hewitt, G. F. (2018) *Introduction to Multiphase Flow*. 1st edn. Edited by G. Yadigaroglu and G. F. Hewitt. Zurich: Springer International Publishing. doi: 10.1007/978-3-319-58718-9.

Yu, T. T., Zhang, H., Li, M.X and Sarica, C. (2009) 'A Mechanistic Model for Gas / Liquid Flow in Upward Vertical Annuli', *SPE Annual Technical Conference and Exhibition*. New Orleans, Louisiana: SPE, (October), pp. 4–7.

Zhou, L., Ahmed, R.M., Miska, S. Z., Takach, N.E., Yu, M. and Pickell, M. B. (2004) 'Experimental Study of Aerated Mud Flows under Horizontal Borehole Conditions', *Proceedings of SPE/ICoTA Coiled Tubing Conference and Exhibition*, (March), pp. 23–24. doi: 10.2118/89531-MS.

Zivi, S. M. (1964) 'Estimation of steady-state steam void fraction by means of the principle of minimum entropy production', *Journal of Heat Transfer*, 86(2), pp. 247–251.

APPENDICES

Appendix A Conductance Probe Drawing

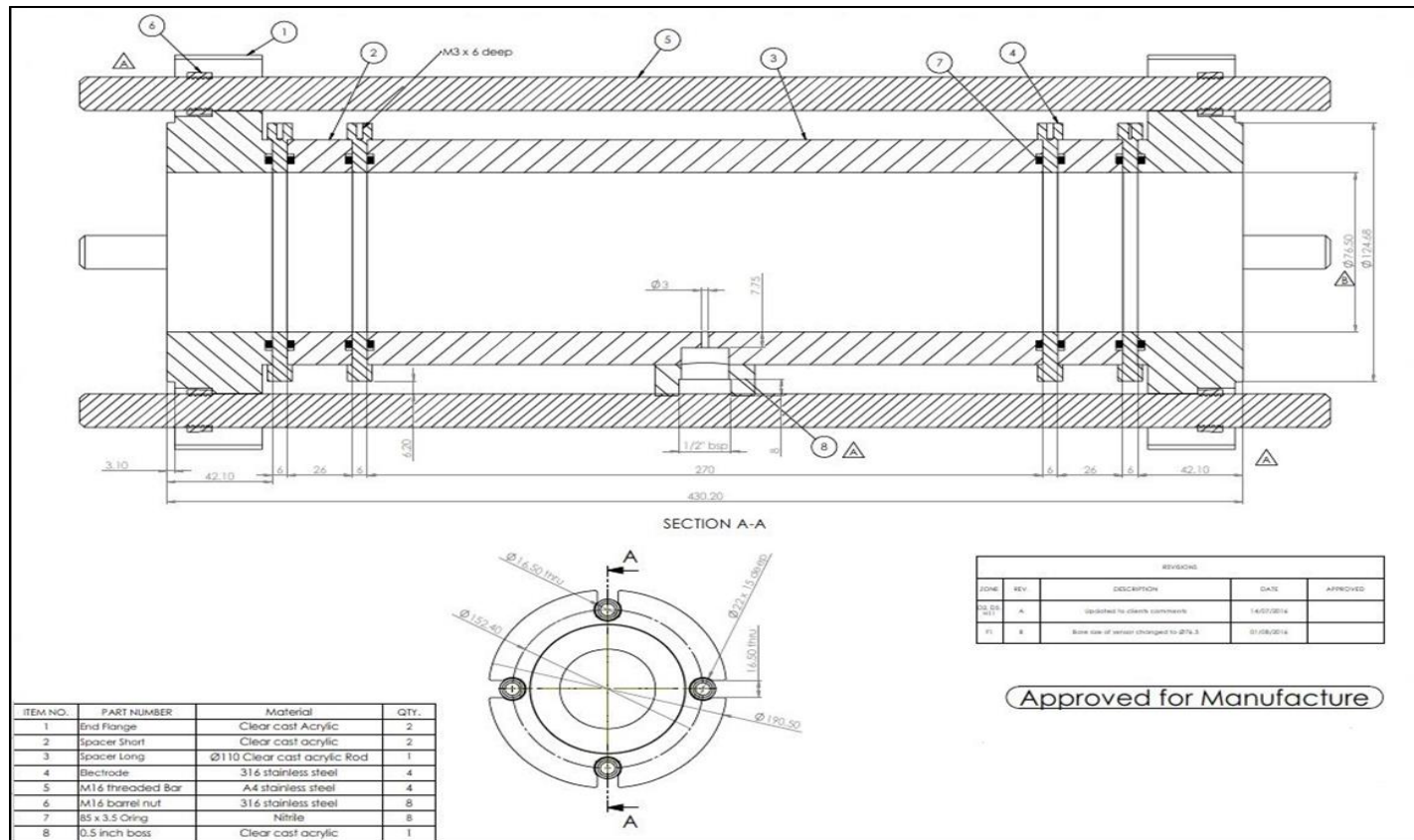


Figure A-1: Detailed drawing of conductance probe

Appendix B Error Analysis

B.1 Estimating Errors

An assumption is usually made when experimental values are taken, that there exist some true or exact value of the quantity being measured based on certain definitions. The error in measurement is therefore the deviation of the actual measured value from this exact value. Error sources in experiments include environmental factors (temperature, pressure, vibration etc.), performance of the instrument (bias, resolution, wear, drift etc.), calibration uncertainty, process stability (valves, pulsation, bends etc.) etc.

Three statistical parameters were employed for error analysis in this study. These include; mean error, E_1 , which gives an indication of the magnitude of the average error; absolute mean error, E_2 which indicates the magnitude of the average absolute error and the standard deviation, E_3 which indicates the degree of dispersion of the errors around their average value. The average error for the test point i , is defined as ϵ_i . Where N is the total number of test points in which values for ϵ_i are obtained.

Mathematically, they are defined as follows:

$$\epsilon_i = \frac{\epsilon_{predicted} - \epsilon_{measured}}{\epsilon_{measured}} \quad (B-1)$$

$$E_1 = \frac{1}{N} \sum_{i=1}^N \epsilon_i \quad (B-2)$$

$$E_2 = \frac{1}{N} \sum_{i=1}^N |\epsilon_i| \quad (B-3)$$

$$E_3 = \frac{1}{N} \sum_{i=1}^N (\epsilon_i - \bar{\epsilon})^{0.5} \quad (B-4)$$

B.2 Estimating Uncertainties

According to the International Standard Organisation (ISO) as documented in “An introduction to the ‘Guide to the expression of uncertainty in measurement (GUM)’”, uncertainty in measurement is a parameter which is associated with the result of a measurement, which gives an indication of how the dispersion of the values relate with how well the measurement is made. Analytical or Monte Carlo methods can be employed to estimate the uncertainty of measurements. In this study, the analytical method is used.

The transient nature of multiphase flow means that the commonly used methods of repeating experimental measurements at the same conditions in order to determine the uncertainty is too expensive and not practicable. Take for example, estimating the frictional pressure gradient where slight changes in environmental conditions could result in changes to the fluid viscosity and as such the measured frictional pressure drop.

A step-wise process for determination of the uncertainty as presented by Yan (2010) is adopted here and is as follows:

- a. For an experimentally measured output, y is a function of $x_1, x_2, x_3, x_n \dots x_n$ then:

$$y = f(x_1, x_2, x_3, x_n \dots x_n) \quad (\text{B-5})$$

- b. Determine uncertainty of x_i

$u(x_1)$ – uncertainty in absolute terms

$u(x_1)$ – uncertainty in fractional terms

- c. The sensitivity of y can then be computed to changes in x_i , that is partial differentiation of each input. The absolute and fractional inputs are as follows:

$$c_i = \frac{\partial y}{\partial x_i} \quad (\text{B-6})$$

$$c_i = \frac{\partial y}{\partial x_i} \cdot \frac{x_i}{y} \quad (\text{B-7})$$

- d. Combining the uncertainties for a set of uncorrelated inputs is obtained by summing the uncertainties for each input. The absolute and fractional terms are given as follows:

$$u_c(y) = \sqrt{\sum_{i=1}^n (c_i \cdot u(x_i))^2} \quad (\text{B-8})$$

$$u_c^*(y) = \sqrt{\sum_{i=1}^n (c_i^* \cdot u^*(x_i))^2} \quad (\text{B-9})$$

A simple calculation of the uncertainties in the superficial liquid and gas velocities, liquid holdup and pressure gradient are presented in the sections that follow.

B.2.1 Superficial Liquid Velocity Uncertainty

The liquid superficial velocity is a function of the mass flow rate of the liquid, $\dot{M}_L$, the flow area A and the liquid density, ρ_L . The annulus hydraulic diameter and by extension the flow area is taken as constant. An electromagnetic flow meter is used to obtain the mass flow rate and density values. From the manufacturer's guide, the maximum measurement error is $\pm 0.5\%$ and $\pm 0.5 \text{ kg/m}^3$ respectively. The uncertainty is evaluated based on the steps highlighted in a – d as follows:

$$V_{SL} = \frac{\dot{M}_L}{\rho_L A} = \frac{4\dot{M}_L}{\rho_L \pi D_H^2} \quad (\text{B-10})$$

The partial derivatives of the inputs, $\dot{M}_L$ and ρ_L is as follows:

$$\frac{\partial V_{SL}}{\partial \dot{M}_L} = \frac{4}{\rho_L \pi D_H^2} \quad (\text{B-11})$$

$$\frac{\partial V_{SL}}{\partial \rho_L} = -\frac{4}{\pi(\rho_L D_H)^2} \quad (B-12)$$

A combination of the measurement uncertainty for the liquid superficial velocity is expressed as follows:

$$u_c(V_{SL}) = \sqrt{\sum_{i=1}^n (c_i^* \cdot u^*(V_{SL}))^2} = \sqrt{\left(u_c^*(\dot{M}_L) \cdot \frac{\partial V_{SL}}{\partial \dot{M}_L}\right)^2 + \left(u_c^*(\rho_L) \cdot \frac{-4}{\pi(\rho_L D_H)^2}\right)^2} \quad (B-13)$$

Test case

For the following case, the annulus hydraulic diameter is 0.0168 m for the test facility, $V_{SL} = 0.27$ m/s, $\dot{M}_L = 172.91$ kg/h, $\rho_L = 997.7$ kg/m³. It was previous indicated that the annulus hydraulic diameter is assumed to be constant while the uncertainty for the mass flow rates and density are provided by the manufacturer's manual. Table B-1 below gives a combined uncertainty at 95.4 % and for this particular condition, it is ± 4.1 %.

Table B-1: Sample uncertainty calculation for liquid superficial velocity

Superficial Liquid Velocity	Mass Flow Rate	Liquid Density	Pipe Diameter	Standard uncert., u^* Mass Flow	Standard uncert., u^* Density	Sensitivity, c_i^*	Sensitivity, c_i^*	Combined Uncert., U^* (95.4% Confidence)
m/s	kg/s	kg/m ³	m			Mass Flow	Density	
0.27	0.48	997.7	0.0168	0.0025	0.25	2.504152	8.164367	4.0822028

B.2.2 Superficial Gas Velocity Uncertainty

Measurement of the superficial gas velocities for this study are obtained from indirect measurements of the gas volumetric flow rates using Rosemount mass Probar flow meters. According to the user guide provided by the manufacturer, the uncertainty of the flow meter is given as ± 1.4 %. The superficial gas velocity is obtained as a function of the volumetric flow rate, Q_{FM} , the temperature at the flow meter, T_{FM} and the pressure at the flow meter, P_{FM} . Also important is the measurement of the temperature, T_{GI} , and pressure, P_{GI} , at the gas injection point into the main test section. This could be represented mathematically as follows:

$$V_{SG} = \frac{Q_G}{A} = \frac{4P_{FM}Q_{FM}T_{GI}}{P_{GI}T_{FM}\pi D_H^2} \quad (B-14)$$

The inputs are represented in partial derivatives as follows:

$$\frac{\partial V_{SG}}{\partial P_{FM}} = \frac{4Q_{FM}T_{GI}}{P_{GI}T_{FM}\pi D_H^2} \quad (B-15)$$

$$\frac{\partial V_{SG}}{\partial Q_{FM}} = \frac{4P_{FM}T_{GI}}{P_{GI}T_{FM}\pi D_H^2} \quad (B-16)$$

$$\frac{\partial V_{SG}}{\partial T_{GI}} = \frac{4P_{FM}Q_{FM}}{P_{GI}T_{FM}\pi D_H^2} \quad (B-17)$$

Combining the uncertainty in the superficial gas velocity is presented below:

$$u_c(V_{SG}) \quad (B-18)$$

$$= \sqrt{\left(u_c^*(P_{GI}) \cdot \left(-\frac{4P_{FM}Q_{FM}T_{GI}}{P_{GI}^2 T_{FM}\pi D_H^2} \right) \right)^2 + \left(u_c^*(T_{FM}) \cdot \left(-\frac{4P_{FM}Q_{FM}T_{GI}}{P_{GI} T_{FM}^2 \pi D_H^2} \right) \right)^2 + \left(u_c^*(P_{FM}) \cdot \frac{4Q_{FM}T_{GI}}{P_{GI}T_{FM}\pi D_H^2} \right)^2 + \left(u_c^*(Q_{FM}) \cdot \frac{4P_{FM}T_{GI}}{P_{GI}T_{FM}\pi D_H^2} \right)^2 + \left(u_c^*(T_{GI}) \cdot \frac{4P_{FM}Q_{FM}}{P_{GI}T_{FM}\pi D_H^2} \right)^2}$$

Test case

Considering a test case for annulus hydraulic diameter of 0.0168 m of the test facility, $V_{SG} = 0.21$ m/s, $Q_{FM} = 0.14$ kg/h, $\rho_G = 1.225$ kg/m³. Pipe hydraulic diameter is assumed constant and the uncertainties for Q_{FM} , $P_{FM,GI}$ and $T_{FM,GI}$ is obtained from the manufacturer's guide as ± 0.1 %. The combined uncertainty at 95.4 % confidence for this test condition is ± 13.75 % as shown Table-B2.

Table B-2: Sample uncertainty calculation for gas superficial velocity

Superficial Gas Velocity	Volumetric Flow Rate	Pressure at FM	Pressure at GI	Temperature, TFM	Temperature, TGI	Standard uncert., u* Volumetric Flow Rate	Standard uncert., u* P FM	Standard uncert., u* P GI
m/s	m3/s	bara	bara	degC	degC			
0.21	0.00038	4.9	1.08	15.15	23.26	0.0005	0.0005	0.0005

Standard uncert., u* T FM	Standard uncert., u* T GI	Sensitivity, ci*	Sensitivity , ci*	Sensitivi ty, ci*	Sensitivity, ci*	Sensitivit y, ci*	Combined Uncert., U* (95.4% Confidence)
		Volumetric Flow	P FM	P GI	T FM	TGI	
0.0005	0.0005	47.24590623	2.84144E-07	2.8414E-07	1.26099E-08	8.39782E-06	13.74713282

B.3 Pressure Drop Uncertainty

The pressure drop in this study is obtained from direct measurements by static pressure transducers. As a result, the uncertainty of the pressure drop measurement is directly obtained from the provided uncertainties provided by the manufacturers in their users guide. The uncertainties were given as ± 0.25 % of full scale for the range of 0 – 6 barg.

B.4 Liquid Holdup Uncertainty

The liquid holdup uncertainty for this study was obtained from the static calibration of the conductance probes designed and fabricated for liquid holdup measurements. They are given as ± 2 % but may be as high as ± 10 % because the liquid holdup values of this study were determined at dynamic conditions.

Appendix C Performance Evaluation of Liquid Holdup Models

C.1 Drift Flux Model Performance in Concentric Annulus Based on Different Diameter Concepts

Table C-1: Comparison of drift flux predictive liquid holdup models using the Slot diameter concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Slot Diameter	-0.028	0.137	0.208
Fabre & Line (1992)		-0.008	0.130	0.188
Wang et al.,(2016)		-0.085	0.125	0.134

Table C-2: Comparison of drift flux predictive liquid holdup models using the Lamb's diameter concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Lamb's Diameter	-0.028	0.137	0.208
Fabre & Line (1992)		-0.008	0.130	0.188
Wang et al.,(2016)		-0.086	0.125	0.134

Table C-3: Comparison of drift flux predictive liquid holdup models using the Crittendon diameter concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Crittendon Diameter	-0.032	0.138	0.210
Fabre & Line (1992)		-0.009	0.131	0.190
Wang et al.,(2016)		0.089	0.127	0.133

Table C-4: Comparison of drift flux predictive liquid holdup models using the Omurlu diameter concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Omurlu Diameter	-0.037	0.138	0.213
Fabre & Line (1992)		-0.009	0.132	0.191
Wang et al.,(2016)		0.010	0.131	0.133

Table C-5: Comparison of drift flux predictive liquid holdup models using the largest gap concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Largest Gap	-0.029	0.137	0.209
Fabre & Line (1992)		-0.007	0.130	0.187
Wang et al.,(2016)		0.087	0.126	0.134

C.2 Drift Flux Model Performance in Fully Eccentric Annulus Based on Different Diameter Concepts

Table C-6: Comparison of drift flux predictive liquid holdup models using the hydraulic diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Hydraulic Diameter	0.048	0.14	0.167
Fabre & Line (1992)		0.067	0.142	0.151
Wang et al.,(2016)		0.17	0.19	0.134

Table C-7: Comparison of drift flux predictive liquid holdup models using the slot diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Slot Diameter	0.049	0.143	0.166
Fabre & Line (1992)		0.068	0.142	0.151
Wang et al.,(2016)		0.172	0.19	0.134

Table C-8: Comparison of drift flux predictive liquid holdup models using the Lamb's diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Lamb's Diameter	0.049	0.143	0.166
Fabre & Line (1992)		0.068	0.142	0.151
Wang et al.,(2016)		0.172	0.19	0.134

Table C-9: Comparison of drift flux predictive liquid holdup models using the Crittendon diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)	Standard Deviation E_3 (-)
Bonnecaze et al., (1971)	Crittendon Diameter	0.046	0.142	0.168
Fabre & Line (1992)		0.067	0.142	0.151
Wang et al.,(2016)		0.177	0.193	0.133

Appendix D Performance of Two-Fluid Pressure Drop Models

D.1 Model Performance in Concentric Annulus Based on Different Diameter Concepts

Table D-1: Comparison of two-fluid pressure drop prediction models using the hydraulic diameter concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)		-0.74	0.74
Friedel (1979)	Hydraulic Diameter	-0.29	0.30
Muller-Steinhagen (1986)		-0.66	0.66
Sun & Mishima (2009)		-0.83	0.83

Table D-2: Comparison of two-fluid pressure drop prediction models using the Crittendon diameter concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)		-0.83	0.83
Friedel (1979)	Crittendon Diameter	-0.54	0.54
Muller-Steinhagen (1986)		-0.78	0.78
Sun & Mishima (2009)		-0.89	0.89

Table D-3: Comparison of two-fluid pressure drop prediction models using the Omurlu diameter concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)	Omurlu Diameter	-0.93	0.93
Friedel (1979)		-0.80	0.80
Muller-Steinhagen (1986)		-0.91	0.91
Sun & Mishima (2009)		-0.95	0.95

Table D-4: Comparison of two-fluid pressure drop prediction models using the largest gap concept in concentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)	Largest Gap	-0.41	0.41
Friedel (1979)		0.61	0.61
Muller-Steinhagen (1986)		-0.19	0.19
Sun & Mishima (2009)		-0.62	0.62

D.2 Model Performance in Fully Eccentric Annulus Based on Different Diameter Concepts.

Table D-5: Comparison of two-fluid pressure drop prediction models using the hydraulic diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)	Hydraulic Diameter	-0.74	0.74
Friedel (1979)		-0.30	0.31
Muller-Steinhagen (1986)		-0.92	0.92
Sun & Mishima (2009)		-0.83	0.83

Table D-6: Comparison of two-fluid pressure drop prediction models using the Lamb's diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)	Lamb's Diameter	-0.67	0.67
Friedel (1979)		-0.11	0.16
Muller-Steinhagen (1986)		-0.89	0.89
Sun & Mishima (2009)		-0.78	0.78

Table D-7: Comparison of two-fluid pressure drop prediction models using the Lamb's diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)	Crittendon Diameter	-0.83	0.83
Friedel (1979)		-0.54	0.54
Muller-Steinhagen (1986)		-0.95	0.95
Sun & Mishima (2009)		-0.89	0.89

Table D-8: Comparison of two-fluid pressure drop prediction models using the Omurlu diameter concept in fully eccentric annulus

Model	Diameter Concept	Mean Error E_1 (-)	Mean Absolute Error E_2 (-)
Lockhart & Martinelli (1949)	Omurlu Diameter	-0.93	0.93
Friedel (1979)		-0.80	0.80
Muller-Steinhagen (1986)		-0.98	0.98
Sun & Mishima (2009)		-0.95	0.95