CRANFIELD UNIVERSITY

EHINMOWO ADEGBOYEGA BOLU

STABILISING SLUG FLOW AT LARGE VALVE OPENING USING AN INTERMITTENT ABSORBER

OIL AND GAS ENGINEERING

PhD
Academic Year: 2014 - 2015

Supervisor: DR YI CAO
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ABSTRACT

Slugging is one of the challenges usually encountered in multiphase transportation of oil and gas. It is an intermittent flow of liquid and gas which manifests in pressure and flow fluctuations capable of causing upset in topside process facilities. It can also induce structural defects in pipeline-riser system. The threat of slugging to oil and gas facilities has been known since the early 1970s.

This study investigated a new method for slug flow stability analysis and proposed the use of active feedback control and intermittent absorber (a passive device) for hydrodynamic and severe slugging attenuation. The geometry impact on the hydrodynamic slug flow in pipeline-riser systems was established using modelling (LedaFlow and OLGA) and experimental studies. The unit cell model in both software packages, the slug tracking model of OLGA and slug capturing model of LedaFlow were employed for hydrodynamic slug modelling. Three distinct slug regions were reported for a typical pipeline-riser system. The H-region typifies the slug flow regime in the pipeline-riser system due to slug formed in the horizontal pipeline upstream the riser pipe. The V-region represents the slug flow regime due to the riser pipe while the I-region describes slug flow regime where both horizontal and vertical pipes contributes to the dynamics of the slug flow in pipeline-riser system.

A simple but yet robust methodology that can be used for pipeline-riser system and slug controller design was proposed. The active feedback control was shown to help stabilise hydrodynamic slug flow at larger valve opening compared with manual valve choking. For the case study, a benefit of up to 5% reduction in riserbase pressure was recorded for the proposed method. This in practical sense means increase in oil production.

The analysis also showed that the new slug attenuation device (intermittent absorber) possesses the potential for slug attenuation. Experimental studies showed that the device was able to reduce the magnitude of riserbase pressure fluctuation due to hydrodynamic slugging up to 22%. The absorber enables

larger valve opening for both hydrodynamic and severe slugging stabilisation. For severe slugging attenuation for example, a benefit of 9% reduction in riser base pressure was recorded for the case studied. This is of great benefit to the oil and gas industry since this translates to increased oil production.

Slug attenuation index (SAI) and pressure benefit index (PBI), have been proposed to quantify the slug attenuation potential and the production benefits of the intermittent absorber respectively. The SAI and the PBI provided consistent results and methods for estimating the slug attenuation potential of the intermittent absorber concept. They could also be used to quantify the slug attenuation benefits of other slug mitigation techniques.

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The works of the LORD are great, sought out of all them that have pleasure therein (Ps111:2). Gratitude flows from my innermost being to God Almighty for enablement, sustenance and provision and the pleasure to search out part of His great works. In you LORD I live, move and have my being. Thank you LORD!

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NOMENCLATURE

Symbol	Description	Units
A	Cross-sectional area of the pipe	m^2
G	Mass source rate in OLGA	kg/s
g	Acceleration due to gravity	m/s^2
H_s	Enthalpy	J/kg
L_f	Gas bubble tail length	m
L_s	Slug length	m
P	Pressure	bar
Q	Gas volume flow rate	m^3/s
S	Wetted perimeter	m
V_{sl}	Liquid superficial velocity	m/s
V_{sg}	Gas superficial velocity	m/s
v_r	Relative velocity	m/s
σ	Surface tension	N/m
θ	Angle of inclination	rad
μ_g	Gas phase dynamic viscosity	kg/m.s
μ_l	Liquid phase dynamic viscosity	kg/m.s
ρ_m	Mixture density	kg/m^3
ρ_g	Gas phase density	kg/m^3
ρ_l	Liquid phase density	kg/m^3
ψ_g	Mass transfer rate between phases	$kg/m^3.s$
ψ_e	Entrainment rate	$kg/m^3.s$
ψ_D	Deposition rate	$kg/m^3.s$
λ	Friction coefficient	[-]

LIST OF ABREVIATIONS

Symbol	Description
DP	Pressure drop
ID	Internal pipe diameter
K	Gain
KH	Kelvin Helmholtz
L/D	Length to diameter ratio
NSC	Non slug capturing (Unit cell)
NSlug	Non Slugging
NST	Non slug tracking (Unit cell)
RGV	Risertop gas vessel
SC	Slug capturing
SCADA	Supervisory-control and data acquisition
ST	Slug tracking
V_D	Droplet volume fraction
V_g	Gas volume fraction
V_l	Liquid volume fraction

1 INTRODUCTION

1.1 Background of study and motivation

Oil and gas activities in many oil producing nations have shifted to deep offshore and the transportation of the produced crude from the well head to the processing facility is usually done with multiphase pipelines. Many of these deep offshore fields are either too small to accommodate standalone offshore processing facility or in plateau production / decline phase. This has made the tying of production pipelines from satellite fields to an existing pipeline very popular. In so doing, slugging is one of the challenges usually encountered. Slugging is an intermittent flow of liquid and gas with inherent unsteady behaviour. It manifests in pressure and flow fluctuations capable of causing upset in topside process facilities and structural integrity issues in the pipeline-riser system.

One of the ways of suppressing or eliminating fluctuation due to slugging is by choking. The oil and gas industry have used this method for many years to eliminate severe slugging by manipulating the valve opening at the exit of the riser, which unfortunately could negatively affect production [1]. The use of controllers however, has been reported to be able to help alleviate this problem by stabilizing the system at larger valve opening [2]. Significant efforts have been concentrated on modelling and understanding the slug attenuation mechanism for choking [3; 4] and active slug control [5-9]. These models can be used to gain insight into the mechanism and control design. However they might not accurately represent real systems due to the complexity of multiphase flow [10-12]. This leaves the robustness of slug control systems designed based on these models questionable. There is therefore a need for a simple yet robust methodology that can be used for system analysis and controller design.

1.2 Research Gap

Considerable advancement has been made in the study of severe slug flow and its mitigation. A number of mitigation techniques such as the use of wavy pipes, pipe diameter modification, riser base gas injection, gas re-injection, the use of slug catcher, manual and active choking of the riser top valves, use of flow conditionals, and foaming agents have been identified. However, only a few of these techniques have been deployed for industrial use [13-15].

Despite advancements in severe slug prediction and control, it appears hydrodynamic slug control has not received much attention although significant efforts have been concentrated on its prediction. This could be as a result of the general knowledge that they are short, high frequency slugs that can be accommodated by the system or handled by slug catcher. However, the observation from the work of Brill et al. [16] that hydrodynamic slug could be severe, the problematic nature of hydrodynamic slug reported in Guzman and Fairuzov [17] and the complex slugging resulting from hydrodynamic and terrain slug interaction reported for a ConocoPhillips field in the North Sea by Danielson et al. [18] are sufficient reasons for a renewed interest in the control of hydrodynamic slugs.

The observable gaps from existing knowledge include: First, the need for better understanding of hydrodynamic slug flow in pipeline-riser system. Second, the geometry impact on slug flow in pipeline-riser system, and the optimization of slug control techniques.

1.3 Aim and Objectives

This work is aimed at developing a new approach to slug flow attenuation using an intermittent absorber. To achieve this aim, the research objectives were:

1. To investigate the behaviour of hydrodynamic slug flow in pipeline-riser systems
2. To develop an approach to slug flow stability analysis

3. To investigate the hydrodynamic slug attenuation potential of intermittent absorber in pipeline-riser system and its ability to optimise the parameter variation technique

4. To investigate severe slugging attenuation potential of the intermittent absorber

1.4 Methodology

This section provides an overview of the method adopted in this work. This research work employed both experimental and modelling approaches.

1.4.1 Modelling of hydrodynamic and severe slug flow in pipeline-riser system

This work sought to gain more insight into the behaviour of hydrodynamic slug flow in a pipeline-riser system and to develop a method for its attenuation. To achieve this, two industrial software, OLGA and LedaFlow, were used to model a pipeline-riser system, the horizontal and vertical pipes that constitute the pipeline-riser system independently. Slug envelopes were developed for a 17" pipe diameter and three distinct regions were observed. The severe slugging attenuation potential of the intermittent absorber was also modelled using OLGA and the results compared well with the experimental observations.

1.4.2 Experimental work on hydrodynamic and severe slugging in a pipeline-riser system

The Cranfield University experimental facility was used for experimental studies aimed at validating the behaviour observed using the OLGA and LedaFlow for the hydrodynamic slug modelling. The 2 inch horizontal rig was used to study the behaviour in horizontal pipeline while the three phase loop was used for both vertical and pipeline-riser pipe studies.

The 4” pipeline-riser experimental facility was used for experimental studies aimed at investigating the behaviour of severe slugging in a catenary riser system and the attenuation potential of the intermittent absorber on severe slugging. Full description and operating procedure is documented in Chapter 3.

1.4.3 Approach to slug flow mitigation

The traditional choking method (parameter variation technique) and a new approach-intermittent absorber were employed for slug attenuation. The ability of the risertop choking to alter the system behaviour when varied was explored.

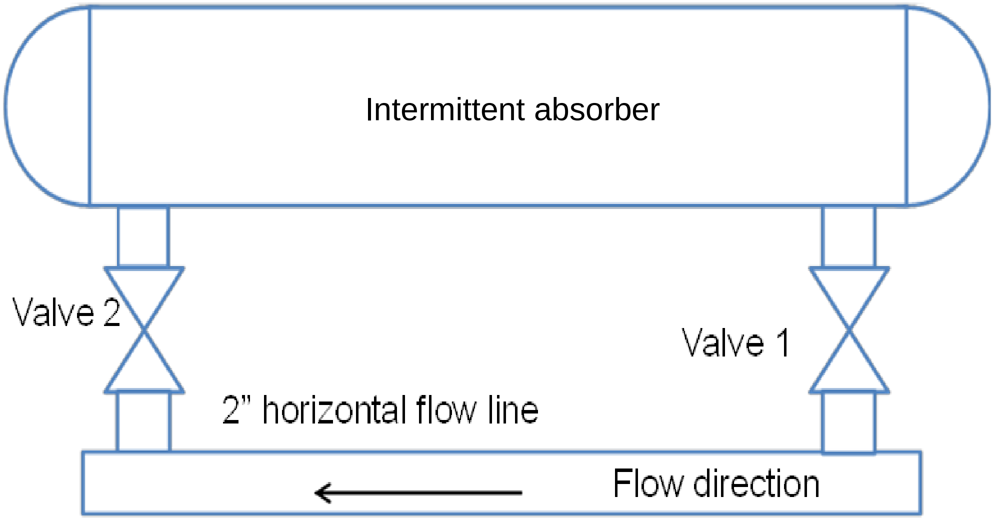


Figure 1-1 Schematic diagram of an intermittent absorber

The intermittent absorber concept was implemented as a risertop gas vessel (RGV), which is a horizontal vessel designed and installed on the riser top upstream of the two-phase test separator for hydrodynamic slug attenuation. This concept is believed to be able to provide slug attenuation benefit by altering the flow characteristics. Figure 1.1 is a diagrammatic representation of an intermittent absorber. This concept was also investigated for severe slugging attenuation by coupling the 2” pipeline-riser system (as an absorber) to the 4” pipeline-riser system.

1.5 Thesis outline

Chapter two presents a literature survey on multiphase flow with emphasis on hydrodynamic and severe slug flow modelling and control. The use of gas vessel in slug studies and other industries was also reviewed.

Chapter three detailed the method adopted to achieve the objectives set out in section 1.2. The numerical tools and simulations conducted as well as the industrial pipeline-riser system investigated were described. The Cranfield University multiphase experimental facilities used for the experimental studies and the experimental procedures were explained. The intermittent absorber concept was described and investigated for slug attenuation.

Chapter four is dedicated to gaining insight into the behaviour of hydrodynamic slug flow in pipeline-riser systems. The understanding of this behaviour can be very important in the development of effective control strategy and design of pipeline-riser system. Slug envelopes were produced using two multiphase commercial codes, OLGA and LedaFlow. Experimental studies were also conducted to validate results from the numerical studies.

Chapter five presents a new methodology for slug flow stability analysis using feedback and non-feedback approaches.

Chapter six is devoted to investigating the hydrodynamic slug attenuation potential of intermittent absorber and its ability to optimise parameter variation (choking). This chapter presents the parameter variation technique using the bifurcation maps for the pipeline-riser system with risertop choke valve opening as the parameter of variation; Proof of concept for the slug flow attenuation potential of the intermittent absorber; the effect of the absorber on the overchoking induced slug phenomenon and methods for quantifying the slug attenuation potential of the intermittent absorber. The mechanism for the slug attenuation of the intermittent absorber was also proposed.

Chapter seven was devoted to investigating the severe slugging attenuation potential of the intermittent absorber and its ability to optimise parameter variation (choking) was also revealed. The flow of severe slugging in 4" catenary riser was investigated and four distinct regions were identified based on the riser pressure drop response and physical observation. Numerical studies were carried out using OLGA a multiphase flow code to ascertain the slug attenuation potential of the absorber. Parametric studies were attempted to establish the optimum volume for severe slug attenuation under a given condition. The effect of coupling configuration on the absorber performance was also revealed and a new method for quantifying the severe slugging attenuation potential for the absorber was also proposed.

Chapter eight presents the conclusion and provides recommendations for future work.

1.6 Publications

The following publications have resulted from this work.

Chapters 2 and 4

Ehinmowo, A.B., Cao, Y., Yeung, H. (2014) Taming of severe slugs. Presented at BHR Goeff Hewitt Conference London, United kingdom, 23rd-25th July, 2014

Chapter 5

Ehinmowo, A.B., Cao, Y., (2015) Stabilizing slug flow at large valve opening using active feedback control. 21st International Conference on Automation & Computing, University of Strathclyde, Glasgow, UK, 11-12 September 2015 (To be presented).

2 LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature survey on multiphase flow with focus on hydrodynamic and severe slug flow and control. As shown in Figure 2-1, an overview of multiphase transport in oil and gas facilities was presented after which the various flow patterns resulting from multiphase flow for various configurations were discussed. An attempt was also made to review the various types of slug flow and attenuation strategies.

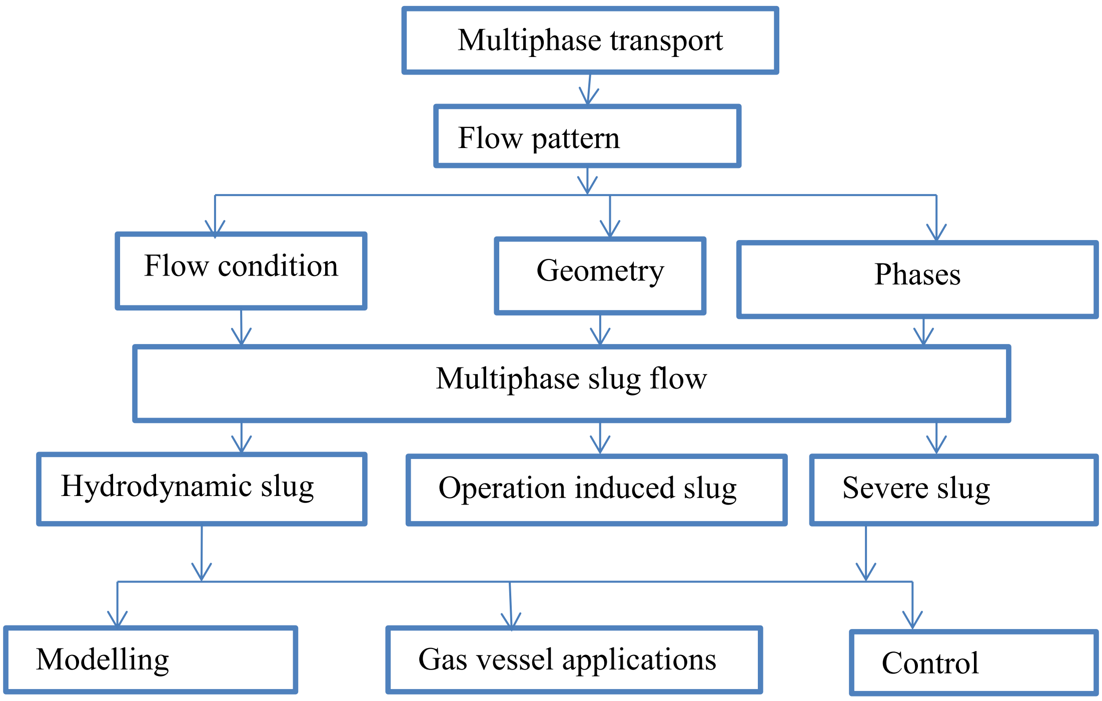


Figure 2-1 Flow chart showing area covered in the literature review

2.2 Multiphase transport in oil and gas pipelines

Multiphase flows are commonly encountered in various industries ranging from oil and gas, aerospace, automotive, power generation and medicine.

Multiphase flow is the concurrent flow of more than one phase in a single pipeline or conduit. The constituent phases could be liquid, gas and / or solid. The flow of gas, liquid and solid in a pipeline for example is a three-phase system whereas when two of these phases are present a two-phase flow is formed. A common example of a two-phase flow encountered in the petroleum industry is the gas-liquid flow.

The hydrodynamic interactions between these phases for a given pipe configuration (horizontal, inclined or vertical), subject to the flow rates of the constituent phases give rise to what is usually called flow regime . Figure 2-2 for example, shows the various flow patterns observed by [19] for a horizontal pipe. Other patterns exist for other configurations and for three phases [20].

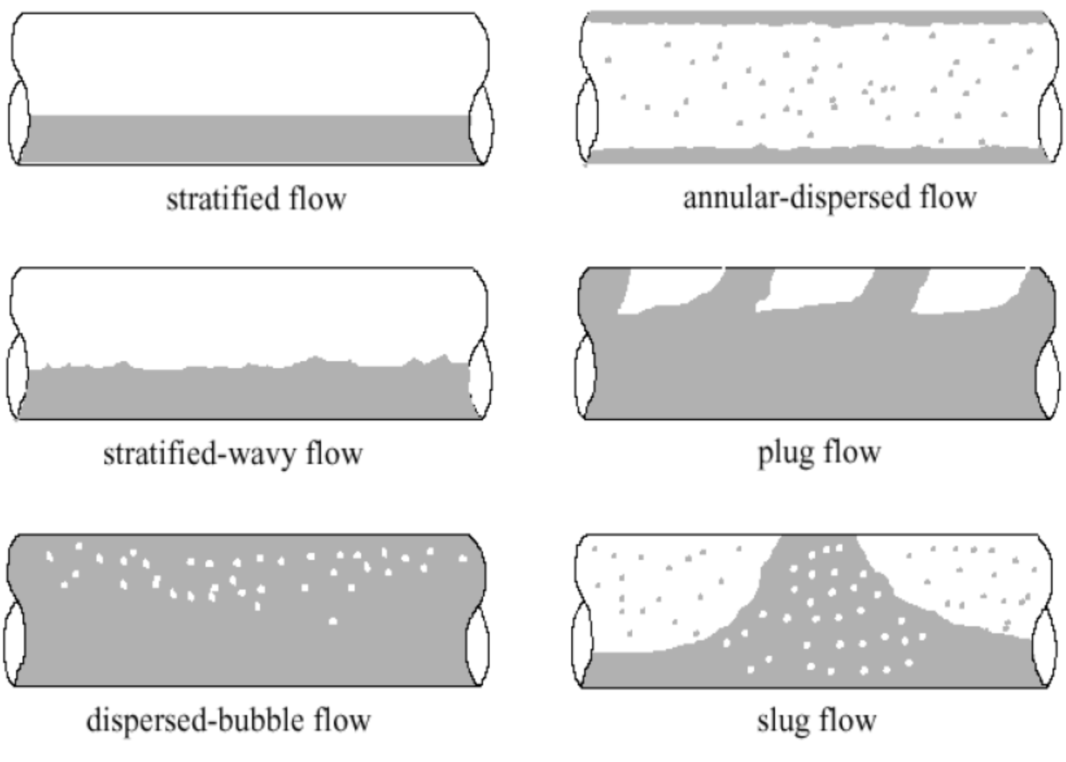


Figure 2-2 Horizontal gas-liquid flown pattern [19]

Based on the flow conditions, the flow regimes are usually organised in a graphical form usually referred to as a flow regime map. The phase superficial velocities are usually used as mapping parameters. Other parameter like Froude number and variation of the phase velocities have been used as mapping parameters by some authors [21-23]. Examples of such maps are shown in Figures 2-3 and 2-4 for horizontal and vertical flow configurations respectively. The data shown in Table 2.1 were used to produce Figure 2-3.

Table 2.1 Range of parameter values for data used in [24]

Inside pipe diameter *(ID)*	0.5-6.5 in
Liquid phase density (P_L)	44.0-63.0 Ibift^3
Gas phase density (P_G)	0.05-3.15 lb./ft^3
Liquid phase viscosity (μ_L)	0.30-90.0 centipoise
Gas phase viscosity (μ_G)	0.010-0.022 centipoise
Surface tension (σ)	24.0-103.0 dynes/cm
Superficial liquid velocity (V_{SL})	0.003-24.0 ft./s
Superficial gas velocity (V_{SG})	0.14-560 ft./s

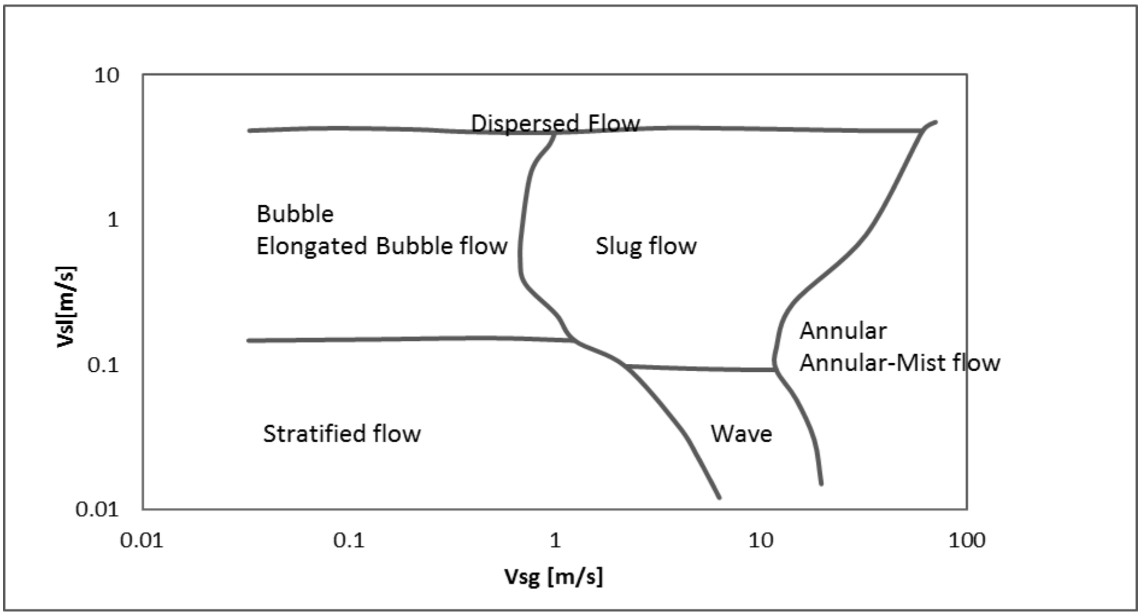


Figure 2-3 Horizontal multiphase flow regime map [24]

Many flow regimes have been proposed by many authors depending on the configurations (horizontal, vertical or inclined), the number of phases (two or three-phases), properties and flow conditions. Few of such identified patterns include: Annular Flow, Bubble Flow, Churn flow, Slug Flow, plug flow Stratified flow, stratified wavy flow etc.

2.2.1 Flow conditions influence on flow regime

The flow conditions play a major role in determining the flow regime obtainable in a system. For a horizontal two-phase gas-liquid system, stratified flow occurs when gas and liquid flow rates are low. The difference between the densities of the phases and gravitational force helps keep the lighter fluid on top and the heavier fluid at the bottom. This results in distinct separation of the two phases.

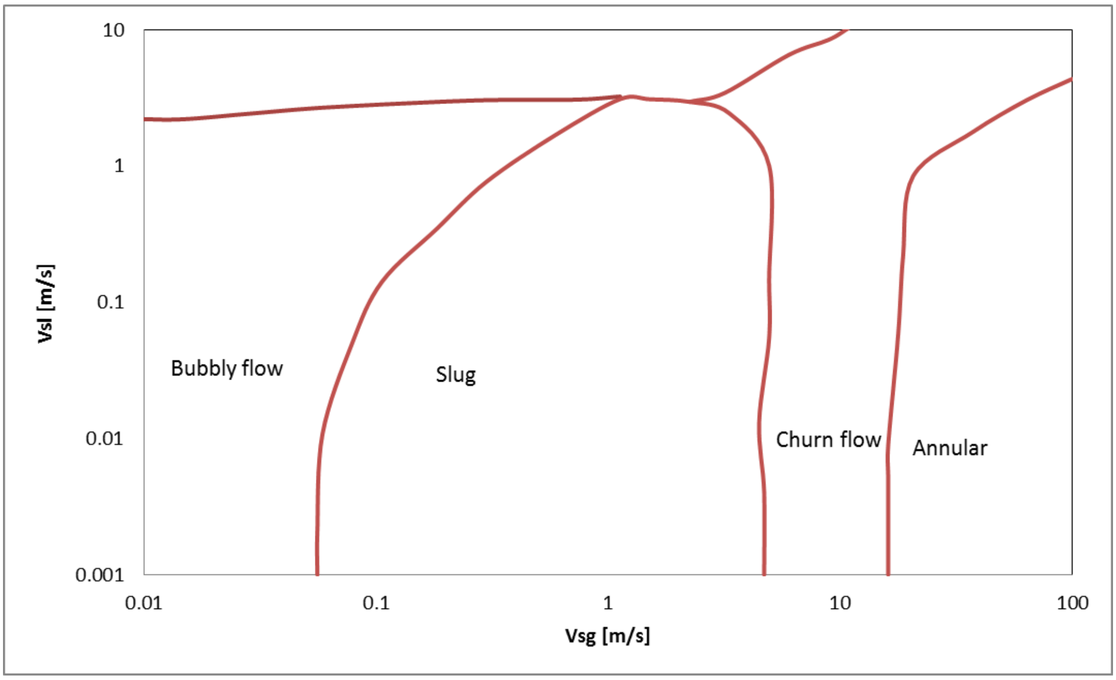


Figure 2-4 Vertical multiphase flow regime map [25]

An increase in the gas velocity increases the interfacial shear forces, and instability sets in producing a wavy interface. This new regime with the wavy interface has been named as stratified-wavy by some authors for example [26; 27].

Further increase in the gas flow rate will cause a growth in the interfacial waves until the liquid blocks the whole cross section of the pipe and a new regime is formed. This regime is referred to as slug regime. When the gas flow is increased further, the gas phase occupies the centre of the pipe and an annulus of liquid is kept close to the pipe wall with the help of gravity. This is termed annular regime. When the liquid flow rate is considerably high, with buoyancy at play, small gas bubbles are dispersed throughout the liquid phase. Here the liquid is the continuous phase. Although bubble concentration is higher in the upper part of the pipe, this regime is called dispersed-bubble flow.

2.2.2 Geometry influence on flow regime

The inclination of the geometry (horizontal, near horizontal, vertical and pipeline-riser) can play a major role in determining the flow pattern that will occur in such a system. For example, from Figures 2-3 and 2-4, the flow conditions under which slug flow occurred differ for the two geometries (horizontal and vertical respectively). A flow regime can also occur in a geometry and be absent in another. It is known that in horizontal, or near horizontal systems, stratified flow is one of the major flow regime identified, whereas in vertical pipes and inclined pipes at high angles, stratified flow is absent [28].

Schmidt et al. [29] reported the dependence of severe slugging on the geometry of the pipeline-riser system and the need for the horizontal pipeline leading to the riser base to be negatively inclined. An attempt was also made by [30] to experimentally look at normal slug flow in a pipeline-riser system in a 2” ID pipe. Two regions of slug flow were reported and referred to as normal slug flow and severe slug flow. A normal slug flow of length less than the riser pipe dimension was observed in the pipeline-riser system. These slugs were said to travel through the riser ‘nearly unchanged’. However recently Vazquez and Fairuzov

[17] reported the long hydrodynamic slug which travel in the riser with velocity of five order of magnitude compared to slug flow in the horizontal pipeline. The complex phenomenon that could lead to this behaviour in a pipeline-riser system and the impact of such on control is not yet fully understood. These geometry interactions leave gaps in the understanding of the full behaviour of slug flow in pipeline-riser system.

2.2.3 Flow regime dependence on the number of phases

The number of phases present in a multiphase system can also influence the flow regime observed in such. Based on the number of phases present in a system, different numbers of flow pattern have been named. In three-phase liquid-liquid-gas flow for example, Açikgöz et al. [20] identified and named many new flow patterns that are not observed in two- phase gas-liquid systems. Similar observations have been reported by other authors [31-35].

Tek [36] for example and some recent studies such as those carried out by Oddie et al. [37] and Huang et al. [38], argued that the three-phase liquid-liquid-gas flow can be qualitatively represented as a two-phase liquid-gas system. However, it appears that the behaviour of these systems is substantially different due to difference in phase properties, change in flow conditions, and the possibility of phase inversion in liquid-liquid-gas systems. This difference is said to be pronounced during the latter stages of a well [39]. It can therefore be said that the qualitative behaviour of flow regimes identified in gas-liquid two phase flow is same with those in gas-liquid-liquid three-phase flow but differs quantitatively.

2.3 Multiphase slug flow

The transportation of both gas and liquid in a multiphase pipeline is a common practice in the oil and gas industry. This practice gives rise to flow regimes that slug flow is part of. Slug flow is an intermittent flow of liquid and gas with inherent unsteady behaviour that manifests in pressure and flow behaviour capable of causing upset in topside process facilities and structural integrity issues in the pipeline-riser system. Three types of slugging are widely known: operation induced, hydrodynamic and terrain/severe slugging.

2.3.1 Operationally induced slugging

During the life of an oil field, various operational changes are possible. Such changes includes: flow ramp up, pigging operations, restart and system depressurization. These operations can significantly generate huge volume of liquid body in form of slugs. The type of slug due to these operations is called operational induced slug.

2.3.2 Terrain /severe slugging

The threat of severe slugging to production facilities has been known since the 70's [1]. This undesirable flow phenomenon continues to attract the attention of researchers and operators alike. Severe slugging is a type of slug that occurs at low flow rates with the help of favourable pipeline configuration (negative inclination and/ or undulation) and is characterised by slug length greater equal or to the length of the riser pipe. This type of slug is known to exhibit large fluctuation in flow rates and pressure resulting in pipeline fatigue, significant reduction in production and ultimately plant trip-off. Severe slugging occurrence has been heightened by the recent deep and ultra-deep offshore developments that necessitate the use of single platforms by many satellite fields. The produced fluids from these satellites fields are transported using multiphase pipelines, which usually travel along undulating seabed before connecting the platforms through a vertical or near vertical riser pipe.

2.3.2.1 Severe slugging formation mechanism

Many authors including Ogazi [2] have described severe slug flow as a four-stage cyclic phenomenon (as shown in Figure 2-5). However, severe slugging could refer to any type of slugging capable of causing operational problems to the pipeline-riser system and the receiving facilities.

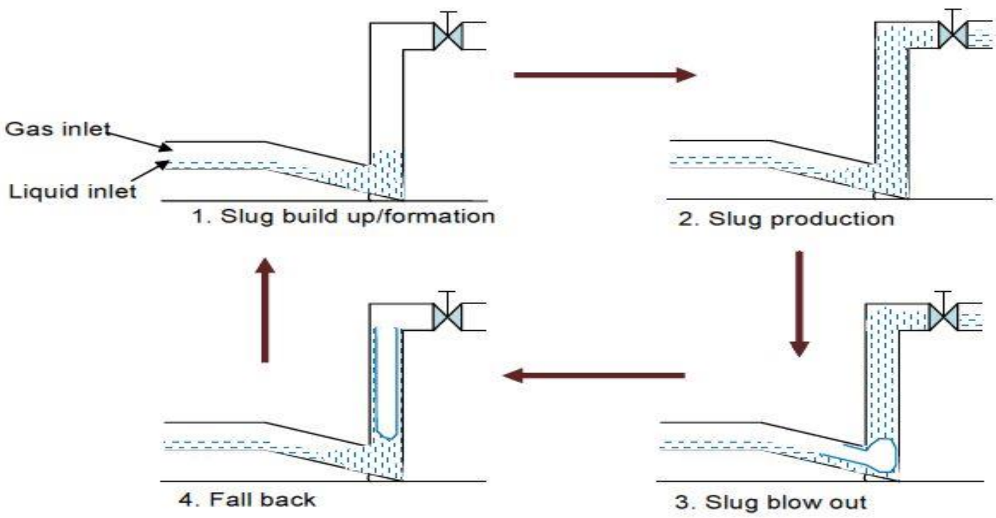


Figure 2-5 Severe slugging mechanism [2]

The presence of an inclined configuration immediately upstream to the riser pipe (as shown in Figure 2-5) has been reported as a perquisite for severe slug formation [30].This configuration allows for stratification, which encourages the separate flow of individual phases.

The first stage of severe slug formation is usually referred to as slug formation and starts when the liquid settles at the riser base and causes a blockage. This hinders the flow of gas into the riser while only liquid flows through. This continues until the riser is filled with liquid phase and the pressure in the pipeline peaks at maximum value. The second stage, which is the slug production, kicks in as the slug flows out of the riser while the gas built up in the pipeline gain access into the riser and the gas is then blown out. This is the third stage. The pressure in the pipeline at this time is at minimum value and the liquid falls back in the riser and blocks the riserbase since there is no sufficient pressure to overcome the head in the riser. This is the fourth stage and cycle starts all over again.

2.3.2.2 Severe slugging prediction and stability

Initially, efforts were concentrated on finding simple flow stability criteria for slug prediction and solution for its attenuation. At this time, choking for example which is one of the earliest known solutions could lead to about 50% production loss Yocum [1]. Few years later however, Schmidt [40] and Schmidt et al. [41] reported that slug flow could be attenuated by careful manual chocking with little or no negative impact on production. Automated choking was also proposed to achieve the 'careful chocking'. Over the years, focus has now shifted to developing control algorithm which is not only able to manipulate the topside choke automatically but also to achieve potential increase in production [42].

A typical study of severe slugging seeks to ascertain three things: prediction (under what condition will slug occur), characteristics (behaviour) and attenuation (control).The prediction of slugging generally started with the development of flow regime maps. This is usually done through laboratory experimental studies or theoretical means. Yocum [1] chart for severe slug prediction is one of the earliest maps known. The map was developed mainly for the vertical riser pipe. It was however later reported in Schmidt et al. [30] that the upstream horizontal pipe plays a major role in the flow pattern observed in the riser pipe. It would therefore be inappropriate to use either the transition criteria for horizontal pipes or vertical pipe only to predict severe slugging.

The use of flow pattern maps for flow regime prediction is as old as the multiphase flow phenomenon itself. The knowledge of flow patterns is very important in the design of multiphase pipelines. This is because the pressure gradient and liquid hold are dependent greatly on the flow regime and no single theory seems to have been able to estimate the pressure gradient or liquid holdup satisfactorily for all flow patterns [24].

Before 1980, efforts were concentrated on developing flow regime transition criteria in horizontal/near horizontal pipes for example Taitel and Duckler [43] and for vertical pipes [1].

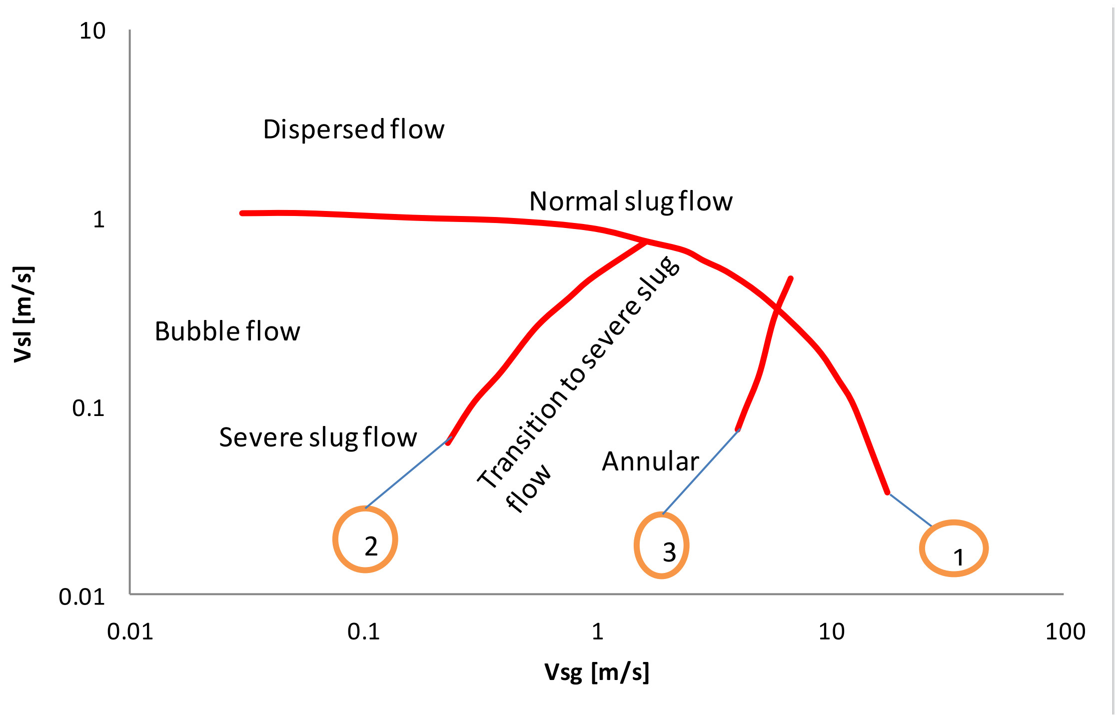


Figure 2-6 Pipeline-riser flow pattern map [44]

As better insight was gained into the severe slugging phenomenon, the influence of upstream horizontal pipe was also considered instead of just using transition criteria in vertical pipes. Schmidt et al. [44] as shown in Figure 2-6, considers both transition criteria for horizontal and vertical flows in the construction of the transition lines. Line 1 for example was due to Taitel and Duckler [43] which was developed for horizontal and near horizontal configurations, while lines 2 and 3 were based on the hydrodynamics of the vertical riser pipe flow.

In Figure 2-6, it was suggested that severe slugging would only occur under the conditions below line 1 and to the left of lines 2 and 3. It was however observed that for the conditions experimentally tested annular flow was reported for conditions below line 1 and to the left of line 3 and there was no demarcation for such.

There have also been some attempt to theoretically develop stability criteria for severe slug and some unified mechanistic models capable of predicting flow transitions [3; 4; 25; 45; 46] .

Bøe [46] developed a stability criterion to predict the occurrence of severe slugging based on force balance on the liquid body blocking the riser pipe entrance. The two forces considered were the hydrostatic head due to the liquid column in the riser and the pressure build up due to gas in the pipeline. The Bøe criterion is given by equation 2. 1.

$$V_{SL} \geq \frac{P_p}{\rho_l g \alpha L} V_{SG} \tag{2.1}$$

Where P_p is the pipeline pressure, V_{SL} and V_{SG} are the liquid and gas superficial velocities respectively, α is the gas hold up in the pipeline, L is the pipeline length and ρ_l is the liquid density.

However, Jansen and Shoham [4] have observed that this criterion is only valid for cases without severe slugging control methods.

Taitel [3] provided a stability analysis of severe slugging and proposed a stability criterion. The work shows that when the pressure downstream the riser (separator pressure) is less than the head due to the liquid column in the riser pipe, severe slugging will occur. However, the frictional and acceleration effect were neglected in the analysis. These terms could be very significant in reality. The Taitel criterion is shown in equation 2.2.

$$\frac{P_s}{P_o} > \frac{\left(\alpha/_{\alpha'}\right) l - h}{P_o/_{\rho_l g}} \tag{2.2}$$

Where P_s is the separator pressure, P_o is the atmospheric pressure, α is the gas hold up in the pipeline, α' is the gas hold up in the riser, and ρ_l is the liquid density.

Pots et al. [45] proposed a criterion for severe slugging occurrence designated as severe slugging group (Π_{ss}) which is the ratio of pressure in the pipeline to that of the hydrostatic head in the riser. This criterion was developed based on the assumption that during the build-up stage, the hydrostatic head due to the liquid in the riser pipe must be greater than the pressure in the pipeline due to gas build up. For severe slugging to occur, Π_{ss} must be less than 1. This criterion is however obtained with the simplification that liquid fall back is negligible in the riser. But liquid fall back has been reported as a key contributor to severe slugging formation [3; 29; 40; 44]. The Pots et al. criterion is described by equation 2.3.

$$\Pi_{ss} = \frac{z\,{}^{RT}/_{M}\; w_g}{g L_F \bar{y}_{gF}\, w_L} \tag{2.3}$$

Where w_g is the gas mass flow rate, w_L is the liquid mass flow rate, $\bar{y}_{gF}$ is the average gas hold up in the pipeline, L_F is the flowline length, z is the gas compressibility factor, T is the temperature, R is the gas constant, and M is the molecular weight of gas.

These criteria helped to define conditions for flow stability and hence served as simple prediction technique. However, the transition boundaries in pipeline-riser systems have been reported to be dependent on the type of riser [44]. It is therefore expected that the type of riser would determine significantly the behaviour of the severe slugging in a pipeline-riser system.

2.3.2.3 Classification of severe slug flow

Tin [47] and most recently Xing [48] have studied and characterised the severe slugging behaviour in catenary risers. While Tin reported five severe slug flow regimes (severe slugging 1, severe slugging 1a, severe slugging 2, severe slugging 3, and oscillation flow), Xing [48] classified the observed severe slug flow regimes in a 4” catenary riser system of Cranfield University into four categories. These severe slugging regimes observed are described below.

- Severe slugging (SS): This type of severe slugging is similar to the classical severe slugging that has been reported for vertical risers by other authors [30; 40; 44; 49]. It is characterised by a cyclic flow behaviour usually described in four stages. The liquid build-up stage, slug production, bubble penetration and gas blow down/liquid fallback. The liquid slug length is usually greater than the riser height.
- Transitional severe slugging (TSS): Here the slug growth occurs only in the riser and gas flow into the riser before the slug front reaches the riser top. The slug production stage was reported to be absent in this type of severe slugging and the liquid slug length is approximately equal to the riser height
- Oscillation flow (OSC): Although the riser pressure drop traces still exhibit cyclic behaviour, the magnitude of fluctuation of severe slugging of this type is smaller than that of SS and TSS. It was also observed that alternating transient flow of liquid and gas constitute the liquid build up stage. This could be likened to the severe slugging type 3 of Malekzadeh et al. [50].
- Continuous flow (CON): This type of flow regime is characterised by small amplitude fluctuations caused by continuous flow of slug precursors into the riser. The liquid build-up stage could not be clearly seen but yet the riser pressure drop exhibit nearly constant small amplitudes fluctuations.

2.3.2.4 Severe slug flow in flexible risers

Yeung and Montgomery [51] investigated the hydrodynamic behaviours of flexible riser both experimentally and numerically. The experiment was conducted in the Cranfield University's three phase facility. Details of this facility can be found in Montgomery [52]. The study was aimed at understanding slugging phenomenon in S-shaped riser and to assess the capabilities of the transient codes. Apart from the type of severe slugging observed in vertical risers, some other distinct types were identified. In comparison with the classical severe slugging in a catenary or vertical risers, the transient surge in S-shaped risers is broken into two parts as a result of the bend in the configuration. The investigation of the stability of fluid production from an S-shaped riser has also revealed two distinct behaviours of slugging in terms of response to pressure increase. The typical classical severe slugging was observed to be responsive to pressure while the other slugs in the transition regions were not substantially affected by pressure increase. This is again traceable to the decoupled behaviour from the two limbs of the riser [53]. The analysis of flow behaviour in S- shaped riser, the transition slugs were observed to be as problematic as classical severe slugging typical of vertical or catenary risers. A criterion for the occurrence of severe slugging in S-shaped riser was also developed in Montgomery [52].

Ogazi [2] developed an improved simplified model for severe slugging prediction but with more focus on control. Wang et al. [54] developed a simplified model for the prediction of severe slugging and performed experimental studies using the Cranfield University three phase facilities for its validation. The effect of riser geometry and separator pressure boundary conditions on severe slugging simulation was reported. The L-shaped model for example could not reproduce the slugging behaviour in hybrid riser. This supports the earlier work of Montgomery who observed different behaviours from the slugging produced from S-shaped risers from the classical severe slugs produced from catenary or vertical pipes.

Other researchers outside Cranfield University have also reported the clear influence of the riser type on the severe slugging [55; 56]. Jian [55] reported the influence of catenary riser geometry on severe slugging characteristics and formation process. However no full characterisation of severe slugging flow regimes was attempted.

2.3.3 Hydrodynamic slugging

Hydrodynamic slug is one of the types of slugging usually encountered in the transportation of both gas and liquid in a multiphase pipeline. Hydrodynamic slug is known to occur at high flow rates in horizontal or near horizontal pipes as a result of Kelvin Helmholtz (KH) instability [57; 58]. Instability occurs when the equilibrium between stabilizing and destabilizing forces acting at gas/liquids interface is altered.

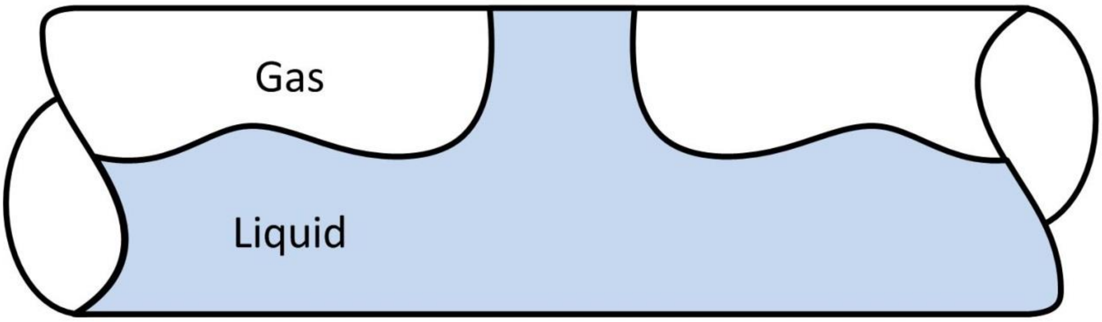


Figure 2-7 Hydrodynamic slug formation

The growth of this interfacial instability as shown in Figure 2.7 leads to the formation of hydrodynamic slug [57; 58]. The instability perturbations have been reported to propagate according to the equation in Wallis and Dobson [59]:

$$K\rho_l(V_L - C)^2 \coth Kh_L + K\rho_g(V_G - C)^2 \coth Kh_G = g\rho_l - \rho_g + \sigma K^2 \quad \textbf{(2.4)}$$

Where $K=2\pi/\lambda$, C, and σ are the wave number, the wave velocity and the surface tension respectively. For the wave to be stable, the wave velocity should be real. For a long wave where kh_L<<1 and kh_G<<1, if the surface tension contribution is neglected, instability would occur at:

$$(V_{SG} - V_{SL})^2 > (\rho_l - \rho_g) g \frac{(\rho_l h_G + \rho_g h_L)}{\rho_g \rho_l} \qquad \textbf{(2.5)}$$

The knowledge of hydrodynamic slug initiation is crucial in ensuring that flow assurance demands are satisfied. The understanding is quite useful for the optimum design of the pipelines and receiving facilities. A good number of experimental and numerical works have been conducted to study slug initiation and evolution in horizontal pipe two phase flows [58; 60-64].

The transition of a stratified pattern to a slug flow for a horizontal gas-liquid flow has been well researched both theoretically and experimentally. In horizontal or near horizontal pipes, slugs can be formed from stratified regime by two main mechanisms. They are: the theory of hydrodynamic instabilities growth and liquid accumulation due to instantaneous imbalance between pressure and gravitational forces caused by pipe undulation. The theory of hydrodynamic instability growth is based on the KH instability theory while the second is usually referred to as terrain induced slug. It has been reported that slug formation can be as a result of either of these mechanisms or combination of both [58].

Issa and Kempf [58] proposed a mechanistic model for the predictions of initiation, growth and further development of hydrodynamic slug in horizontal and inclined pipes and interaction between severe (terrain) slugging and hydrodynamic slugs in a V-section of a pipe was reported. The interaction resulted into much longer slugs than normally experienced in horizontal pipelines. In their work, they solved 1D governing equations in the two fluid framework and reported the ability of this model to compute the process of slugging due to its mathematical well-posedness. One of the merits of the approach is the ability to capture slug flow without many phenomenological models. The results compared favourably well with experimental data but some discrepancies were observed in the overall hold up. However this method can be very computationally expensive.

Valluri et al. [63] conducted a study on the onset of slug initiation in a 2D laminar horizontal channel flow using the level set method. Their results confirmed the theory of minimum height requirement for slug formation. Likelihood for slug formation was reported at sufficiently high initial interface level. Coalescence of short waves to form large- amplitude longer waves, which can either grow or collapse also possesses tendency for slug formation

Other authors have performed stability analysis on stratified flow to understand hydrodynamic slug formation. They presented a two fluid model and performed linear stability analysis of a stratified flow and the formation of non-stratified flows. It was reported that the Inviscid Kelvin-Helmholtz criterion predict poorly the stable region while the Viscous Kelvin-Helmholtz criterion predict favourably well this phenomenon when the flow is allowed to fully develop [65-67]

The Kelvin-Helmholtz (KH) instability describes the situation where the gas-liquid interface is perturbed and this disturbance evolves and grows. Should the growth be sufficient, slug would be formed otherwise the stratified pattern will give rise to wavy pattern or plug flow. Thus it is certain that the instability will give rise to transition from stratified pattern to other flow pattern. Many other authors had reported the transition from stratified flow to slug regime as a function of Kelvin-Helmholtz (KH) instability [57; 68-70].

Hurlburt and Hanratty [71] compared available theories to experiments on the transition from stratified flow to plug and slug flow. The authors observed that three different criteria define the transition of stratified flow to slug flow at low superficial gas velocities. They are: Kelvin-Helmholtz instability, viscous linear instability of stratified flow to long wavelength (VLW) instability, and slug stability. They came up with a method capable of estimating the transition to slug flows for long pipelines. The height of liquid layer needed for the onset of

Kelvin-Helmholtz waves, viscous long wavelength waves and for slug stability were estimated.

Guo et al. [72] derived the dispersive equation of interfacial waves using the two fluid model approach. However the contribution of the surface tension was omitted. This assumption however is far from the observed mechanism in the experimental studies. Their work contributed to the understanding of disturbance at the interface, its propagation and growth. They supported the view that the growth of waves was prerequisite to slug formation.

Soleimani and Hanratty [73] worked on prediction of the initiation of roll waves employing the concept of long wavelength. Slugs would be formed and stable should the conditions favour the coalescence of the roll waves. They reported that the critical superficial liquid velocity was poorly predicted when the work of [71] was employed. Kalogerakos et al. [74] used Fluent to investigate the propagation and growth rate of wave in a 30m long, 0.078m diameter horizontal pipe. This was done by introducing a perturbation at the inlet of a pipe. Different growth initiation was observed when compared with results from one dimensional software called EMAPS (Eulerian Multiphase Adaptive Pipeline Solver). However similar growth rate was recorded. Their results gave more support to the capability of fluent in simulating three dimensional two phase flows using two dimensional formulations. This was found to reduce simulation time by order of 10.

Bonizzi and Issa [75] proposed a model for slug aeration in two phase pipes. The liquid phase continuity equation was formulated as a mixture model and a sub model was used to estimate the liquid entrained in form of bubble. The results from the model were compared well with experimental data. Marginal improvement was observed in the prediction of liquid hold up and slug frequency compared to those for unaerated slug assumptions. But for v-section, the effect of aeration was pronounced. This confirms the view that such configuration as bends, y-shape and so on affect the dynamics of slug formation and its characteristics.

Danielson [76] proposed a simple model for hydrodynamic slug flow based on first principle with a potential for easy implementation and replacement for Lagrangian slug tracking model. Though the model was able to predict slug length and frequency as well as slug hold-ups, there is a need to develop the model further for robust predictive capabilities.

Brill et al. [16] brought a new perspective to hydrodynamic slug flow that hydrodynamic slugs could be severe. Other authors have also reported results which support this view [17; 77-82].

The problematic behaviour of hydrodynamic slugs in pipeline-riser system was reported in [17; 82]. This type of slug was reported to exhibit velocity in the riser of five order of magnitude compared with the average velocity in the pipeline and can also grow to be of length greater than the riser. However, no control technique was proposed for the attenuation of this slug.

The transient nature of hydrodynamic slugs has not been well understood till date. The commercial software packages used at the point of design usually do not have the capability to accurately predict hydrodynamic slugs and its interaction with severe slugs which can cause a complex slugging. This type of complex slugging resulting from hydrodynamic and terrain slug interaction has been reported for a ConocoPhillips field in the North Sea [18].

2.4 Slug modelling and simulation

There are three basic approaches to slug flow modelling. They are: unit cell model, slug capturing and slug tracking. In unit cell model, the slug is modelled as a series of slug liquid body (head) followed by gas bubble (tail) [83]. For slug capturing approach, slugs are automatically generated from the physics of flow whereas slugs are introduced at predetermined rate and tracked in slug tracking method. All of these methods have been employed for slug modelling in the past [58; 84]. These approaches have also been implemented in commercial codes, OLGA and LedaFlow for example and a brief review will be attempted next.

2.4.1 Slug flow modelling and simulation using OLGA

Over the past few years continuous efforts have been geared towards the development of codes to meet industrial flow assurance demands. The earlier commercial code -OLGA uses both the unit cell model and slug tracking method for slug flow modelling. OLGA is a dynamic multiphase transient simulator extensively used in the oil and gas industry. It is a one dimensional code based on the two-fluid model formulation made up of seven conservation equations, three for mass, three for momentum and one energy . A brief description of the equations is shown next.

The continuity equations for gas and bulk liquid phases are shown in (2.6) and (2.7) respectively while the equation for the liquid droplet within gas phase is shown in (2.8).

$$\frac{\partial}{\partial t}(V_g\rho_g) = -\frac{1}{A}\frac{\partial}{\partial z}(AV_g\rho_g v_g) + \psi_g + G_g \tag{2.6}$$

$$\frac{\partial}{\partial t}(V_l\rho_l) = -\frac{1}{A}\frac{\partial}{\partial z}(AV_l\rho_l v_l) - \psi_g\frac{V_l}{V_l + V_g} - \psi_e + \psi_D + G_l \tag{2.7}$$

$$\frac{\partial}{\partial t}(V_D\rho_l) = -\frac{1}{A}\frac{\partial}{\partial z}(AV_D\rho_l v_D) - \psi_g\frac{V_D}{V_l + V_D} + \psi_e - \psi_D + G_D \tag{2.8}$$

In equations 2.6, 2.7 and 2.8, V_g, V_l, and V_D are the volume fraction of gas (subscript as g), liquid (subscript as l) and liquid droplets (subscript as D), A is the pipe cross sectional area, ψ_g is the mass transfer between the phases, ψ_e and ψ_D are entrainment and deposition rates and G' is the mass source.

The momentum equations for gas phase, liquid droplets are shown in (2.9) and (2.10) respectively while momentum equation for the liquid at the wall is shown in (2.12). In these equations, P is the pressure, S is the wetted perimeter, θ is the angle of the inclination from the vertical, v_r is the relative velocity, $\boldsymbol{\lambda}_g$, $\boldsymbol{\lambda}_l$, $\boldsymbol{\lambda}_i$ are the friction coefficients for gas, liquid and interface respectively. F_D is the gas/droplet drag term.

$$\frac{\partial}{\partial t}(V_g\rho_g v_g) = -V_g\left(\frac{\partial P}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}(AV_g\rho_g v_g^2) - \lambda_g\frac{1}{2}\rho_g|v_g|v_g \times \frac{S_g}{4A} - \lambda_i\frac{1}{2}\rho_r|v_r|v_r\frac{S_i}{4A} + V_g\rho_g g\cos\theta + \psi_g v_a - F_D \quad (2.9)$$

$$\frac{\partial}{\partial t}(V_D\rho_l v_D) = -V_D\left(\frac{\partial P}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}(AV_D\rho_l v_D^2) + V_D\rho_l g\cos\theta - \psi_g\frac{V_D}{V_l + V_D}v_a + \psi_e v_i - \psi_D v_D + F_D \quad (2.10)$$

When equations (2.9) and (2.10) were combined, the gas/droplet drag term cancel and a combined momentum equation ensued in equation (2.11).

$$\frac{\partial}{\partial t}(V_g\rho_g v_g + V_D\rho_l v_D) = -(V_g + V_D)\left(\frac{\partial P}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}(AV_g\rho_g v_g^2 + AV_D\rho_l v_D^2) - \lambda_g\frac{1}{2}\rho_g|v_g|v_g\frac{S_g}{4A} - \lambda_i\frac{1}{2}\rho_r|v_r|v_r\frac{S_i}{4A} + (V_g\rho_g + V_D\rho_l)g\cos\theta + \psi_g\frac{V_l}{V_l + V_D}v_a + \psi_e v_i - \psi_D v_D \quad (2.11)$$

$$\frac{\partial}{\partial t}(V_l\rho_l v_l) = -V_l\left(\frac{\partial P}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}(AV_l\rho_l v_l^2) - \lambda_l\frac{1}{2}\rho_l|v_l|v_l \frac{S_l}{4A} + \lambda_i\frac{1}{2}\rho_r|v_r|v_r\frac{S_i}{4A} + V_l\rho_l g\cos\theta - \psi_g\frac{V_l}{V_l + V_D}v_a - \psi_e v_i + \psi_D v_D - V_D d(\rho_l - \rho_g)g\frac{\partial V_l}{\partial z}\sin\theta \quad (2.12)$$

Equation (2.13) describes the mixture energy-conservative equation. E is the internal energy per unit mass, H_s is the enthalpy from the mass source, U is the heat transfer from the pipe walls and m=v.ρ.

$$\frac{\partial}{\partial t}\left[\mathrm{m}_g\left(\mathrm{E}_g+\frac{1}{2}v_g^2+\mathrm{gh}\right)+\mathrm{m}_l\left(\mathrm{E}_l+\frac{1}{2}v_l^2+\mathrm{gh}\right)+\mathrm{m}_D\left(\mathrm{E}_D+\frac{1}{2}v_D^2+\mathrm{gh}\right)\right]$$

$$=-\frac{\partial}{\partial z}\begin{bmatrix}\mathrm{m}_g\mathrm{v}_g\left(\mathrm{H}_g+\frac{1}{2}v_g^2+\mathrm{gh}\right)+\mathrm{m}_l\mathrm{v}_l\left(\mathrm{H}_l+\frac{1}{2}v_l^2+\mathrm{gh}\right)\\+\mathrm{m}_D\mathrm{v}_D\left(\mathrm{H}_D+\frac{1}{2}v_D^2+\mathrm{gh}\right)\end{bmatrix}+\mathrm{H}_s+U \qquad (2.13)$$

The theory and the development of the code, the closure equations and the numerical methods used in solving these equations can be found in [85].

In OLGA, the numerical method applied is stable for large time steps and not restricted by the velocity hence the use coarse grids. A coarse grid is not suitable to resolve interfacial hydrodynamic instability which is believed to be responsible for hydrodynamic slugs hence the limitation of OLGA in predicting accurately hydrodynamic slug characteristics. Although with proper tuning, the slug tracking module is able to match the characteristics of experimental and field data however its capability to satisfactorily model slug generation is limited [86].

2.4.1.1 OLGA unit cell model

The unit cell modelling approach appears to be the traditional method for slug flow modelling.

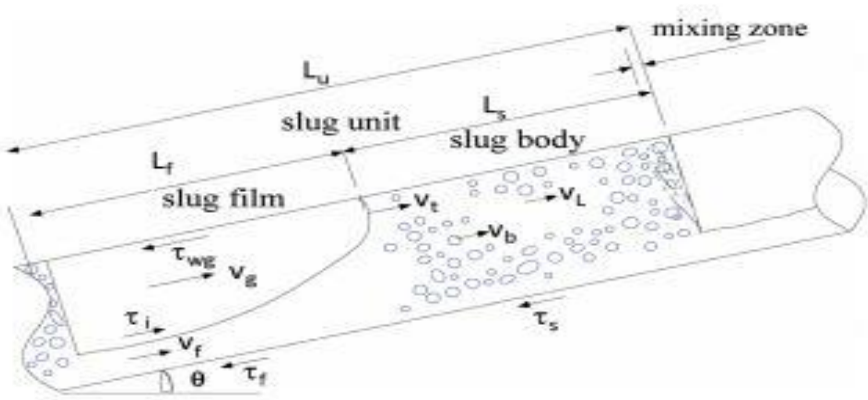


Figure 2-8 Diagrammatic representation of slug flow in unit cell model framework [87]

This classical steady state approach is based on the concept of dividing the slug unit into two distinct volumes as shown in Figure 2-8. The slug front which is the slug liquid body has length l_s and the gas bubble tail with liquid film of length l_f [83].

This module is the default module for slug flow modelling in OLGA. This method allows for slug flow simulation using coarse meshes; however the transient and complex behaviour of slug flow are not captured. Fundamentally, the assumption of fully developed flow upon which this method is based can be faulted since slug growth and decay are known phenomenon [77]. Other limitations of this method includes: inability to capture the information about individual slug, slug characteristics such as slug frequency and slug lengths [86] . However, this method can sufficiently accurately model severe slugging.

2.4.1.2 Slug tracking model

The slug tracking approach involves tracking the movement, growth and disappearance of individual slugs in the Lagrangian framework. This is usually done by introducing slugs of predetermined length and frequency at the inlet of the pipe. Subsequently the position of each slug is then tracked in Lagrangian framework with time.

Slug tracking schemes employ a grid moving with the fronts and allow for computations with coarse grids. In a tracking scheme, stratified flow between slugs is modelled with a two-fluid model while slugs are modelled as moving objects and the boundaries between slugs and bubbles are tracked with a moving grid [85; 88]. Zheng et al. [89] proposed a slug tracking technique which they claim is capable of predicting growth and dissipation of each individual slug; Nydal and Banerjee [90] developed a slug tracking method for dynamic gas-liquid slug flow using an object-oriented approach whereby slugs are treated as discrete computational objects. However, the initiation of slugs and the interaction between slugs cannot be accounted for by this approach hence it is far from what happens in reality. The commercial software OLGA employs this method for slug simulation, especially for hydrodynamic slug study. The slugs of predetermined length and frequency are introduced at the entrance of the pipe and individual slugs are tracked downstream pipe inlet. However, a predictive tool is needed since the behaviour of a field is unknown at the point of development, a method that can predict slug behaviour without introducing slug at pipe inlet would be more desirable. Slug capturing seems to be this desired approach for such application and it is discussed in the next section.

2.4.2 Slug flow modelling and simulation using LedaFlow

LedaFlow is a new commercial transient multiphase flow code with both 1D and multidimensional capability. The LedaFlow modelling approach is formulated using the multi- fluid multi-field concept. The fluid is defined based on all the materials which exhibit same thermal properties while the field describes the motion of a particular form of the fluid. A field could be droplets or continuous. Based on this formulation, 16 equations are solved: Nine mass conservation equations (one for each field), three momentum equation (one for each fluid / continuous mixture), three energy equations (one for each fluid / continuous mixture) and one volume conservation equation. More about LedaFlow development, the numerical solution approach can be found in the literatures [91; 92].

There are also two approaches in LedaFlow for slug modelling. There is a module based on the unit cell model and additional module based on slug capturing concept. In the unit cell model, slugs are treated in averaged manner based on steady state and fully developed flow assumption whereas in the slug capturing scheme, fine grid is used so that the hydrodynamic instabilities which give rise to slug can be resolved automatically but the computational times required for simulation of long pipeline can be prohibitive.

2.4.2.1 LedaFlow unit cell model

Again like OLGA, the LedaFlow has a module for the unit cell. This traditional steady state approach has been discussed in section 2.4.1.1. The fundamental principle for this model in both softwares is same. More attention would therefore be given to the slug capturing approach. It is important however to briefly mention that in LedaFlow, the unit cell model also allows for coarse mesh hence lower order in time and space discretization are applied.

2.4.2.2 Slug capturing model

It has been demonstrated that using a two-fluid model, with a set of conservation equations for both phases, slug or wave initiation can be captured automatically without many phenomenological models. This concept is described as slug capturing. In slug capturing approach, the slug flow regime is predicted as a mechanistic and automatic outcome of growth of hydrodynamic instabilities. The approach seeks to capture small scale dynamics by solving the transport equations for mass and momentum equations for each phase over a very fine grid size. At the pipe diameter length scale, individual slug and wave dynamics can then be captured numerically on a fine grid [58; 75; 93]. However accurate numerical resolution in both space and time must be ensured so as to capture small numerical perturbations and to grow naturally until the liquid volume fraction becomes unity which signifies the initiation of slugs. Such models must be well posed and the computational times can be prohibitive for simulation in long pipelines.

Issa [94] discussed some of the considerations for effective simulation of slug flow using slug capturing model. He observed that, fine mesh sizes and short time steps would be required to capture the details of hydrodynamic instabilities responsible for formation of roll waves or slugs. But the computational time required for such simulation in real pipelines which are hundreds of kilometres in length are prohibitive hence high cost. Some of the available methods for accelerating computation time are: Adaptive meshing, High order differencing scheme, efficient solution algorithm, and parallel computing. After critical review of these methods, parallel computing was identified as the best option.

This approach has been implemented in LedaFlow- new commercial software. Danielson et al [18] had reported an advantage of this module in modelling hydrodynamic slug flow and its ability to capture the interaction between hydrodynamic slugs and severe slugging. However, the slug capturing approach requires fine mesh, higher order discretization in space and time to counter numerical diffusion. This leads to high computational cost. Although the parallel computing technique has been implemented in LedaFlow to significantly reduce the computational time, when compared with OLGA it appears a lot needs to be done in this regard. This code has been compared with OLGA and experimental / field data by some authors and their observations still confirmed their ability to produce the data within reasonable percentage [18; 95-97]. Danielson et al. [95] also revealed that both OLGA and LedaFlow predict pressure drop and hold-up at the same level of uncertainty when compared to measured data. Danielson et al. [18] claimed that with the slug capturing module in LedaFlow has some predictive capabilities over OLGA. However when the lift curves were produced for the field studied using these two simulators, the curves showed that the system was stable whereas the field measurement revealed an unstable system.

2.5 Slug Control in multiphase pipeline-riser systems

Control systems capable of preventing or attenuating slugging in pipeline-riser systems have been proposed by many authors using commercial simulators, or simplified model based studies and experimental works. Some have been tested on the fields while others are still undergoing development. Some of the methods used for slug control include: Subsea separation and processing, homogenizing multiphase flow, gas re-injection, riser base gas lift, design modification of upstream and downstream facilities. Other methods include the use of slug catcher and topside choke manipulation [41; 98-101]. This section seeks to review the advancement in severe and hydrodynamic slug control.

2.5.1 Severe slug control

The oil and gas industry over the past four decades has witnessed incredible advancements in severe slugging attenuation and control. Various methods have been proposed by many authors and are currently in use. These methods have been broadly categorised into passive and active methods depending on weather the attenuation is achieved through external influence or not. In active slug control methods, the mitigation is achieved with the help of an external influencer whereas in the passive slug control techniques, the attenuation can take place without any external influencer [102]. This section will give a summary of passive and active slug mitigation techniques and their practicality.

2.5.1.1 Passive slug mitigation techniques

Many passive slug attenuation techniques have been proposed and tested in the industry. This method of slug attenuation is usually achieved through design modification of the facility such as reducing the flowline diameter, dual or multiple risers, riserbase mixers [1; 98] ,slug catcher [103], the use of flow conditioner in the pipeline [102; 104-111] , the venturi device of Almeida and

Goncalves [104], self-gas lifting method [112; 113] and the bubble breaker [114].

Pipeline diameter reduction

Yocum [1] proposed several ways of attenuating severe slugging. Some of these methods which fall under the passive technique include: reduction of the pipeline diameter, the use of mixers at the riser base, the use of dual or multiple risers. Further investigations have been conducted on these methods and their variations and various limitations have been reported. The reduction of pipe diameter for example has been reported to be subjected to the constraint of varying production rates throughout the life of a field. While reducing the pipeline size might attenuate severe slugging, it can also be a good condition for hydrodynamic slug initiation. It is therefore difficult to decide the optimum size reduction which will achieve slug attenuation for a field. The question of the possibility and practicality of laying a small size pipe has also been raised in [98].

Dual riser

Kaasa [115] proposed a subsea separator (T-splitter) to distribute the liquid and gas into two risers as a means of severe slugging elimination. The effectiveness of this technique is questionable as possibility of liquid carry over into the gas riser exists. Same liquid might fall back into the pipeline at low gas flow rate thereby blocking the entrance into the gas riser. Prickaerts et al. [116] also investigated the slug flow behaviour in a pipeline leading to a dual riser. The pipeline was splitted into two risers with the aid of a non-symmetric branch T-splitter.

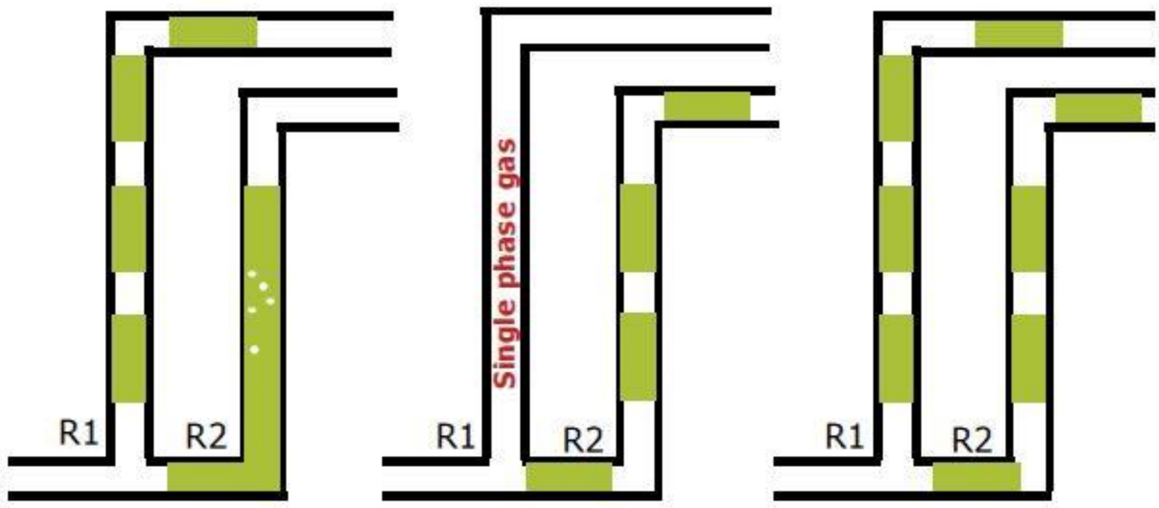


Figure 2-9 Slug attenuation using dual risers [116]

The liquid phase was reported to have preference for the second riser while the gas phase flow through the first riser. For various conditions investigated, it was reported that the second riser stands a chance of experiencing a considerable back pressure due to gravity dominated flow while both risers have a typical riserbase pressure which shows the likelihood of producing slug in both risers as shown in Figure 2-9. Apart from additional cost for a second riser, the issue of appropriate splitter to achieve optimum separation of the phases into the risers remain unresolved.

Flow conditioners

Based on Schmidt et al. [44] who posited that the pipeline upstream the riser pipe must be in stratified regime for severe slugs to occur, the use of flow conditioner to alter this regime and consequently attenuate slugging has been investigated by many authors, potential benefits and limitations reported [48; 102; 105; 106; 108; 109; 111; 117].

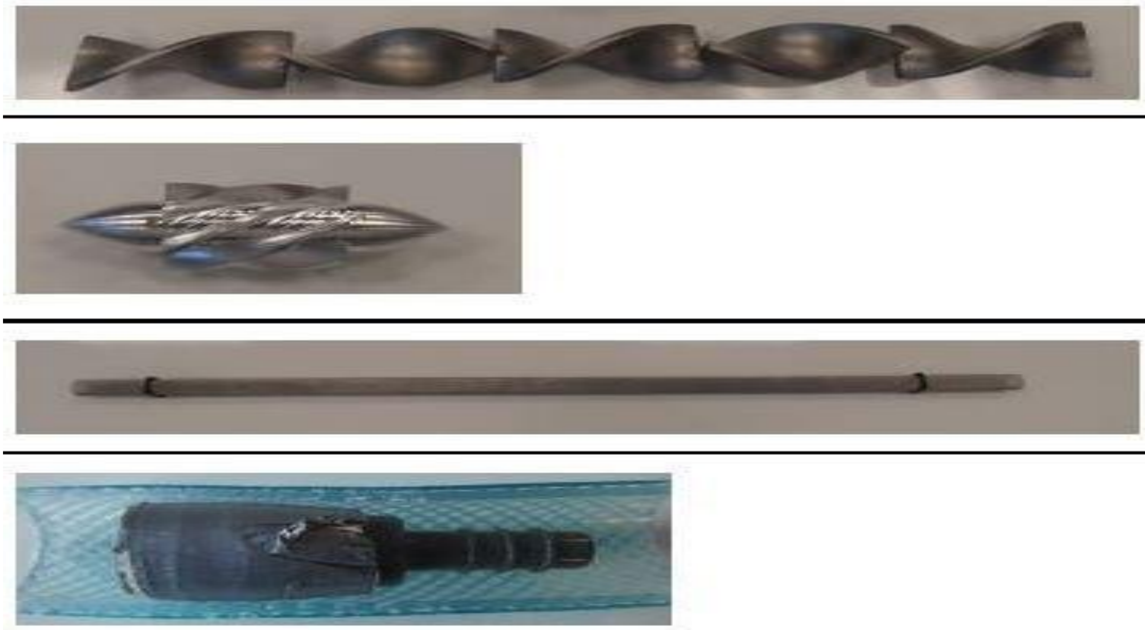


Figure 2-10 Mixing devices [110]

Brasjen et al. [110] investigated the use of four different mixing devices (mixer, swirl, perforated liners and choke) shown in Figure 2-10 for slug attenuation. These devices were introduced into the pipeline at different positions and positioning them near the exit of the pipeline was reported to achieve best performance. However the advantage accruable from the 16% reduction in pressure fluctuation claimed to have been achieved using these devices might not be able to offset the loss due to the increase in total pressure drop of the system. Also from the operational point of view, the intrusiveness of these devices is also a minus as pigging would be made difficult or impossible.

Adedigba et al. [109] and Adedigba [111] investigated the possibility of using a novel helical pipe section upstream a riser pipe to mitigate slugging. The setup is as shown in Figure 2-11.This method was reported to hinder the formation of stratified flow upstream the riser pipe, reduce the region of severe slugging and when severe slugging occurs, its severity was said to be substantially reduced. Though this method shows the potential for severe slug attenuation, like many other passive techniques, the challenge lies in the area of operability.

Figure 2-11 Novel pipe device for severe slugging attenuation [109]

Another special pipe device for slug mitigation was proposed in Makogan and Brook [108] as shown in Figure 2-12. The device (1) that attenuates the slugging from a multiphase pipeline (2) is positioned immediately upstream a riser pipe (3) which connects a separator (4). The device is made up a short upward inclined pipe (5) leading to a horizontal pipe (7) and a downward inclined pipe (6) which connects back to the pipeline upstream the riser.

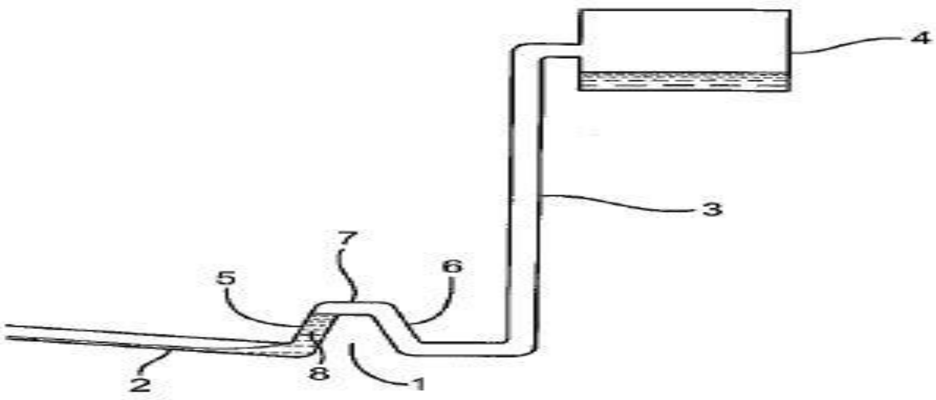


Figure 2-12 Device for controlling slugging [108]

The slug flowing from the pipeline is dissipated in the upward inclined pipe (8) as shown in Figure 2-12. This technique was claimed to reduce the length of the severe slugging by generating short high frequency slugs which can be transported through the riser and controlled by the topside facilities. It appears that effectively a short riser is used to generate slugs of length equivalent to its height. How short the slugs would be will be dependent on the height of the upward inclined pipe. It is therefore not clear if the overall reduction in the slug length will be sufficient to meet overall slug mitigation objectives.

The use of wavy pipe shown in Figure 2-13 as a tool severe slugging mitigation has been investigated both experimentally and numerically [102; 105; 106]. The concept of wavy pipe is still fundamentally aimed at reducing slug length and hinders stratification upstream the riser pipe just like Adedigba et al. [109] and Makogan and Brook [108].The installation of these pipes upstream riser pipe has been observed to reduce severe slugging region and effectively open up more region for stable flow. The modelling of this device has revealed the relationship between the amplitude of the wavy pipe, its length and the characteristics of the slugs produced in the pipeline-riser system. Inverse relationships were reported between the amplitude of wavy pipes and length of slug so also between the length of the wavy pipe and slug length [106].

Although further work is ongoing to solve the operability issues, like other passive techniques, this technique is not spared of the limitation of possible additional pressure drop and operability issues.

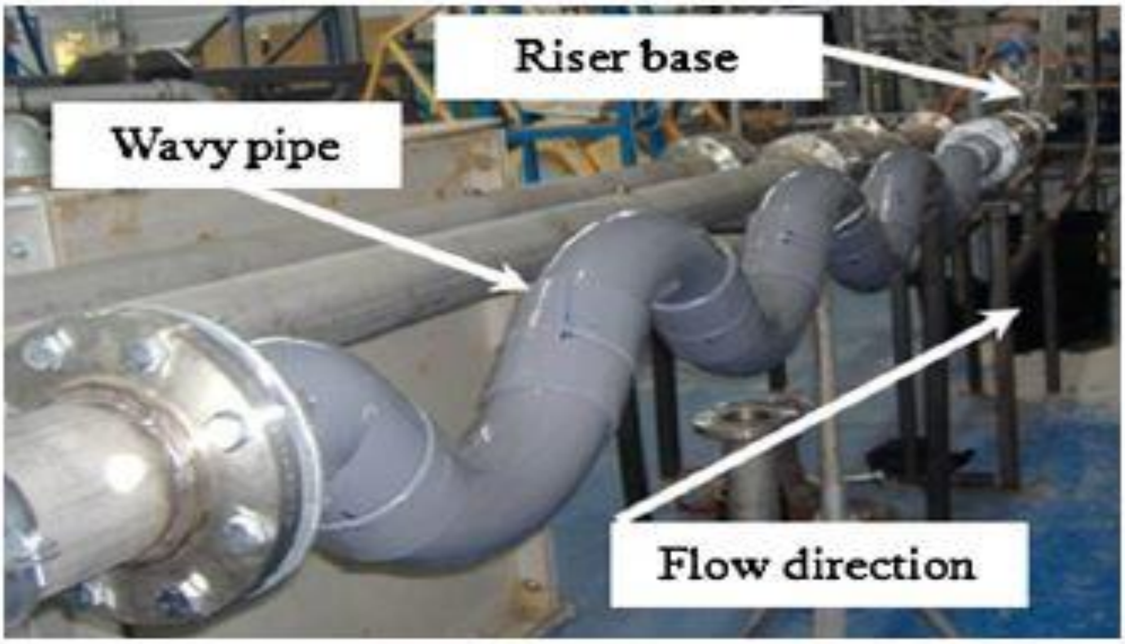


Figure 2-13 Wavy pipe for severe slugging attenuation [102]

Almeida and Goncalves [104] experimentally investigated the use venturi device as a severe slugging mitigation technique. The device was installed near the riserbase to hinder the formation of stratified flow and to accelerate the fluid into the riser. Although the severity of the slugging was reported to be reduced however there was an increase in pressure which could potentially lead to reduced production. The sudden reduction in the pipe size through the venturi device also could cause operational challenge for pigging for example.

Bubble breaker, a passive slug mitigation technique proposed by Schrama and Fernandes [114] is shown in Figure 2-14. The bubble breaker was designed to convert the slug flow into dispersed flow. It is usually introduced into a vertical pipe in order to generate more void fraction after the fluid flow through it. Through experimental and field trial, the efficiency of this device has been investigated and a 10% increase in production was reported. However, the pressure drop across this intrusive device might not be small for other flow conditions outside the experiment and field trial. Like many other intrusive passive methods of slug attenuation, it might not be attractive from operation point of view.

Figure 2-14 Diagrammatic representation of Bubble Breaker [114]

A non-intrusive passive slug mitigation technique was developed by Makogon et al. [107]. This comprises of ''ups and downs'' undulating pipes of same diameter as the pipeline diameter and are placed immediately upstream the riser pipe. This configuration as shown in Figure 2-15 was claimed to help better mixing of gas and liquid to produce a homogenous mixture which can then be transported through the riser without any problem. Other configuration such as shown in Figure 2-16 was investigated and was reported to have lesser mitigation effect on the severe slugging. Consideration was given to operational issues and it was posited that smart pigs could be suitable for the pipeline maintenance however no test was conducted to validate this claim. They can however be installed to compliment active techniques for optimum performance.

Figure 2-15 Non- intrusive passive slug attenuation device [107]

Figure 2-16 Non -intrusive passive device alternative configuration [107]

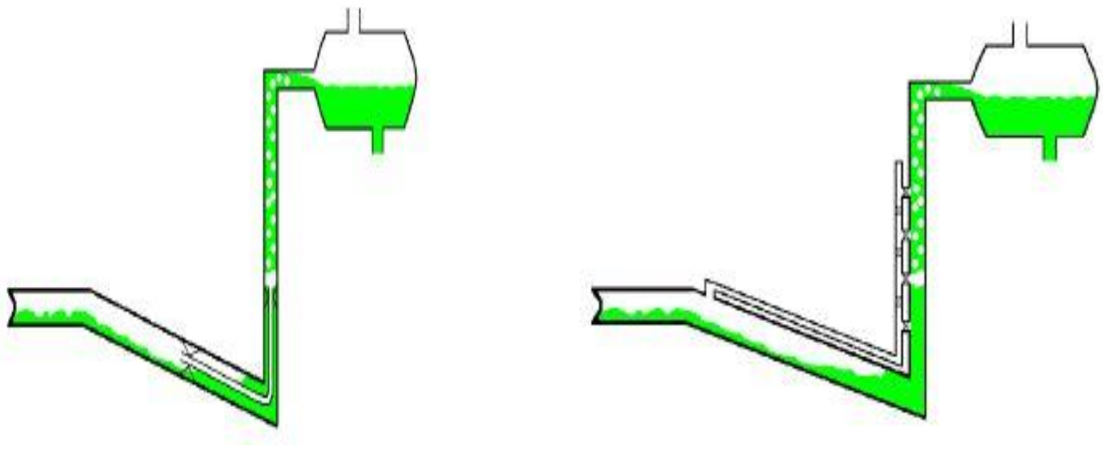
Self-gas lifting technique

The self-gas lifting method of Sarica and Tengesdal [112] was proposed to use the compressed gas within the pipeline upstream the riser pipe to mitigate severe slugging. This is done by splitting the multiphase flow into gas and liquid and transporting the gas into the riser through a bypass or a pipe-in-pipe concept to reduce the hydrostatic head and lessen or eliminate severe slugging.

Figure 2-17b shows the use of bypass while Figure 2-17a demonstrates the use a pipe- in- pipe concept to transport the in-situ compressed gas from the pipeline into the riser. The two concepts were reported to substantially mitigate severe slugging but from operation point of view the external bypass shown in Figure 2-17b was preferred. Further studies have investigated various aspect of this method ranging from the appropriate splitting point and connecting points, numerical and experimental proofs of concept [101; 118-120].

Tengesdal et al. [101] and Tengesdal et al. [119] carried out a thorough investigation experimentally to ascertain the best configuration of the bypass pipeline that will connect the splitting and injection point. It was reported that a pure horizontal or slightly inclined upward bypass pipe will deliver optimum performance. The response of this technique to variation in flow rate was also investigated and it was reported that this technique is not sensitive to changes in flow rates.

Tengesdal et al. [118] and Tengesdal et al. [120] developed a steady state model for the technique as a design tool to determine the region of injection (connection) and splitting (takeoff) points that will give optimum performance. The model was also used to estimate the pressure drop across the bypass line. The slight discrepancies observed between model and experimental results were attributed to the difficulty in obtaining accurate experimental measurement. Although this technique was novel as there is no need to incur cost on external compressed gas, and with minimal pressure drop across the bypass, the likelihood of having short slugs transported through the bypass line exist. It is also possible to have liquid accumulate at the entrance of the bypass thereby defeating its purpose.



(a) (b)

Figure 2-17 Self-gas lifting technique (a) pipe-in-pipe technique (b) bypass technique [100]

2.5.1.2 Active slug control

In active slug control methods, the mitigation is achieved with the help of an external influencer which could be manual or automated. The manual choking for example needs an operator (the external influencer) to vary the valve opening until stability is achieved, the automatic choking and feedback control systems need controller to influence the input element (valve) to stabilise the unstable system while a compressor is needed as the external influencer for gas injection methods [48]. The past four decades have witnessed tremendous advancements in active slug control and a quick review of this progress is attempted next.

Gas injection

Between 1970 and 1980, the fundamental methods for slug control which are still in use today were proposed. The industry knew choking could eliminate severe slugging but with attendant back pressure and consequent reduction in flow capacity. It was also known that gas injection at the riser base could help [1].

The use of gas injection as a method for severe slug attenuation has since received wide attention within the research community and oil and gas industry. Various injection positions have been investigated. Some authors have proposed gas injection at points upstream the riserbase and others at the riserbase [1; 15; 45; 121] . However the fact remains that the associated costs of gas injection could be prohibitive.

Schmidt et al. [44] proposed gas injection into the pipeline as a method for severe slugging attenuation and identified the costs of compressor and the injection pipeline as an additional burden. Pots et al. [45] investigated the use of gas injection for severe slugging attenuation through small scale experiments. Their results shows that for all the cases investigated the riserbase injection provided a better attenuation. However, even at 100% injection severe slugging of the order of the riser height was observed. It thus was observed that a prohibitive large amount of gas would be needed to make severe slugging completely disappear. Hill [15; 121] reported the riserbase gas injection studies conducted on a 65 metre pipeline-riser system of 0.05 metre diameter and the SE Forties field (0.3 and 0.15 diameter). Gas injection was shown not only to attenuate slugging but also helps a dead well to produce. Henriot et al. [122] investigated the effect of injection position and the efficacy of gas injection technique as a method for slug attenuation. The gas injection upstream the riserbase was shown to achieve better stability than riser-base injection at high flow rates. This is in consonance with Pots et al. [45] who opined that at 300% injection, the injection upstream riser-base might be preferred to riser-base injection.

Riser top choking

By 1980, it was known that choking the riser top valve carefully can be used to eliminate slugging without negatively impacting the flow capacity and pressure. The research community also welcome the automation of topside chocking as a severe slugging control technique [29; 30; 40; 41]. However the theoretical understanding of the working of choking and back pressure as a severe slugging attenuation was not known until Taitel [3] provided a stability analysis of severe slugging. The work shows that when the pressure downstream the riser (separator pressure) is greater than the head provided by the liquid column in the riser pipe, severe slugging will be eliminated and a stable flow will result. Farghaly [98] ascertained the effectiveness of choking as a method of severe slug control through a field study. The riser choking was implemented on upper Zakum field which was reported to suffer severe slugging and was able to stabilise the flow. It was observed that the stability could be achieved with/without slightly negative impact on pressure. This is in consonance with the observation of Schmidt et al. [41]

In the 1990s, focus shifted towards optimizing choking as a method of severe slug control. These efforts gave rise to investigation of the combination of choking with other slugging elimination methods [4; 123] and active feedback control systems [5; 14; 122; 124]. Hedne and Linga [5] performed an experimental study on the suppression of severe slugging using automatic and manual riser choking. The manual choking was reported to control severe slugging but at high valve closure of about 80% which means a significant reduction in capacity since only 20% valve opening was available for flow. The pressure drop across the valve was observed to be as high as 7 bar whereas for automatic choking with a PI controller using upstream pressure measurement , the coressponding pressure drop across the valve was 2.5 bar. This shows that with the implementation of a PI controller about 64% reduction in pressure drop across the valve is achievable which could translate into higher capacity. The superior performance of automatic choking over manual choking was investigated and ascertained.

Jansen and Shoham [4; 123] carried out detailed investigation on the optimization of two severe slugging elimination methods; chocking and gas lift and proposed the combination of the two methods for optimum performance. The operational disadvantages suffered by individual methods ; excessive back pressure for chocking and prohibit large volume of gas required for injection were reported to be reduced by the combination of both methods. Based on Taitel et al. [49], theoretical stability criteria were developed for riser top chocking and riserbase gas lifting. Jansen et al. [125] developed two models for severe slugging elimination by gas injection and chocking. The first model was reported to be able to establish the unstable flow conditions while the other could be used to predict the slug flow characteristics. Although the models were reported to produce result with excellent agreement with the experimental result, it is however noteworthy to mention that these works were carried out in a 2.54 cm diameter and 3 m high riser, it is therefore not known if this will still be the case for a large diameter pipelines and higher risers.

Hollenberg et al. [124] proposed a topside flow control method for severe slugging attenuation. The proposed controlled and manipulated variables were mixture velocity and topside valve respectively. The inability of this configuration to deliver the expected performance led to the introduction of a small separator which helped to separate the phases and measure the flow rates. Though this method was promising however, a considerable back pressure was imposed on the upstream to achieve the desired stability.

Courbot [14] developed a PID slug control system which used riserbase pressure and risertop choke valve as controlled and manipulated variables respectively for severe slug control in Dunbar multiphase flowline**.** The 16'' multiphase pipeline in the field was reported to suffer from both hydrodynamic and severe slugging but since hydrodynamic slugging occurred at high flow rates higher than the design capacity of the pipeline, strategy for severe slugging control was sought and automatic control was reported to be best option. The implementation of this strategy though reported to be successful was not without significant increase in the riserbase pressure.

Henriot et al. [122] performed a simulation study on the same Dunbar pipeline using TACITE compositional code for severe slugging and tested control schemes for its attenuation. Riser base pressure and topside valve opening were considered most favoured option as controlled and manipulated variables respectively for the PID controller employed. They used lower pressure set point 77 bar compared to 89 Barg of Courbot [14]. This is more desirable since lower pressure would lead to higher production unlike just automating the manual choking to suppress slugging whereas the production would be negatively impacted.

The last 15 years have experienced dramatic advancements in control algorithm developemnts for severe slugging attenuation. Better insights have been gained into methods for controlling difficult unstable slug flow and various suitable controlled variables have been proposed through controlability analyses using simplified models. These models are usually tuned to the predictions from commercial codes and/or experiment data from small to medium pipeline diameter. This act of tuning again shows the need for predictive capabilities. A few inroads have been made into the development and application of non-linear control systems too [2; 6-9; 11; 13; 42; 99; 126-138].

The choice of suitable controlled and manipulated variables have been extensively studied using controllability analyses by many authors in the recent years [9; 132; 135; 139-141]. Inlet pressure, pressure drop over choke and topside flow measurements were analysed as possible candidates [8; 9; 132; 139]. The pressure drop over the choke was reported not suitable for stabilizing control. The inlet pressure suffered time delay and the volumetric flow , low stationary gain. Apart from riserbase pressure that has been widely reported to be very suitable candidate for the controlled variable, other measured variables downstream the riserbase have been investigated and cascade control structure has been reported to enhance the suitabilty of these variables[130; 133; 135; 141]. The use of downhole pressure as controlled variable and subsea choke have also been investigated as successful field implementation in Asgard asset of Statoil has been reported. The strategy was observed to attenuate slugging and also increased production. The effect of delay could be pronounced using downhole pressure measurement and riser choke as controlled and input variables resectively [142] .

The slug control technique developed in Hollenberg et al. [124] was later improved and metamorphosised into the slug suppression system (S^3). The S^3 slug control system is made up of a small separator with automatic control valves at the outlets. This system is usually placed at the top of the riser immediately upstream production separator as shown in Figure 2-18. Apart from performing the function of an automated slug catcher to provide buffer capacity, this system serves to measure accurately gas and liquid flow rates. Here the control systems uses the flow rates as controlled variable instead of pressure measurements. Though the mini separator pressure is also measured and controlled but the slug control strategy is based on volume flow rates.From control point of view, this system provides an advantage of fast response time since the liquid and gas streams are separated compared with multiphase flow control valves with slower response time. The gas and liquid streams from the S^3 are recombined and introduced into the production separator which would have suffered the effects of slugging without such system upstream of it. However the application of this technique could be limited due to cost and space contraints.

Henkes et al. [128] conducted numerical, experimental and field studies to ascertain the performance of S^3 and claimed that it surpressed all types of slugs. However it appears the system does not prevent slug formation but reduced the fluctuation. Also manual intervention is still needed to set the pressure drop across the S^3 valves.

Kovalev et al. [138] proposed a more space and cost efficient version of the S^3 technology and was called vessel-less S^3 . A pipe was configured with a T-juction splitting the gas and the liquid and controlled with the S^3 algorithm to serve as a separator upstream the first stage separator. The fluids are then recombined and fed into the first stage separator like the traditional S^3 .

Although the system was reported to efficiently attenuate all types of slugging, the possibility of having long slugs blocking the gas outlet may exist and short slugs could be carried over into the gas pipe when the stratifier is overwhelmed. Should this occur, then the measurement capability of this system would be defeated.

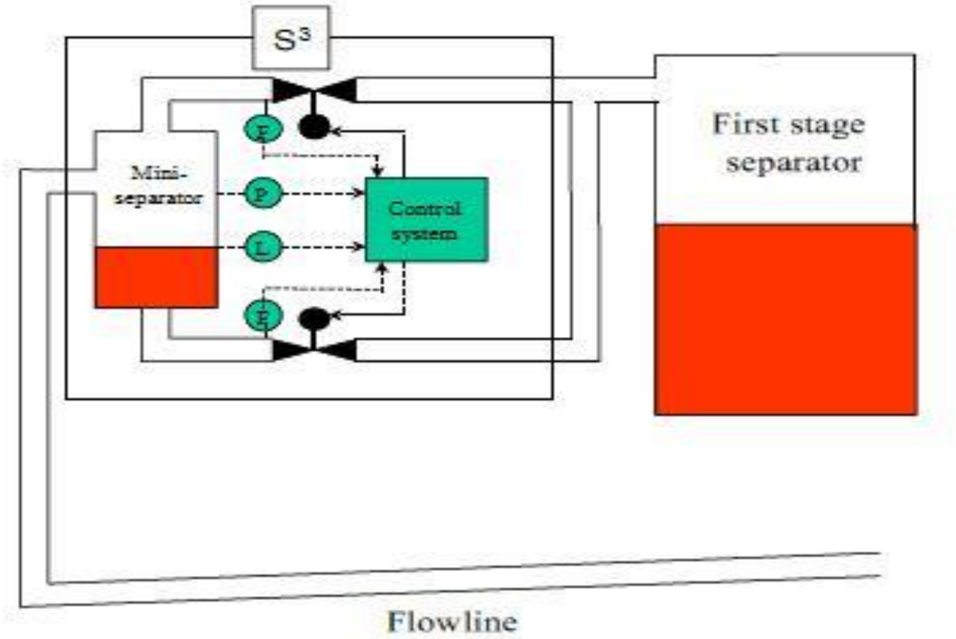


Figure 2-18 Schematic diagram of the slug suppression system (S^3) [13]

Havre et al. [126] and Havre and Dalsmo [127] reported the slug controller system SlugCon^{TM} jointly developed by ABB and BP for terrain induced slugging attenuation. This control system as shown in Figure 2-19 was based on both feedforward and feedback algorithm using both inlet and outlet pressure as controlled variable and pipeline choke valve as the manipulated variable. The system was deployed at BP Hod field and improvement in the stability of the flow in the field pipeline was observed. The control system was also reported to help achieve small disturbances in the separator, smoother compressors operation and a considerable reduction in the pipeline inlet pressure ensued and this could translate into increased production. However, since the system was configured close to the well upstream the pipeline, the possibility of flow instabilities in form of hydrodynamic slugs along the pipeline can not be ruled out. Also the possibility of having a delay due to measurement transmission across a 13 km pipeline can not be overruled. This could be the reason occasional slugging was still observed in Havre and Dalsmo [127] when this system was deployed.

Many of the existing methods for slug control used riserbase measurements, upstream measurement or combination of both and downstream measurements. However, the infrential slug control method of Cao et al. [143] attenuate slugging using only topside measurement such as the riser outlet pressure, the topside separator pressure,the three-phase separator pressure, level of liquid in the topside separator, gas outlet flow rate of the topside separator, liquid outlet flow rate of the topside separator, riser outlet mass flow rate from a Coriolis flow meter, riser outlet density from a Coriolis flow meter, hard count of a Gamma meter located at the riser outlet, and soft count of a Gamma meter located at the riser outlet. This technique has been field tested experimentally and numerically field trial has also been conducted and about 10% increase in production has been reported.

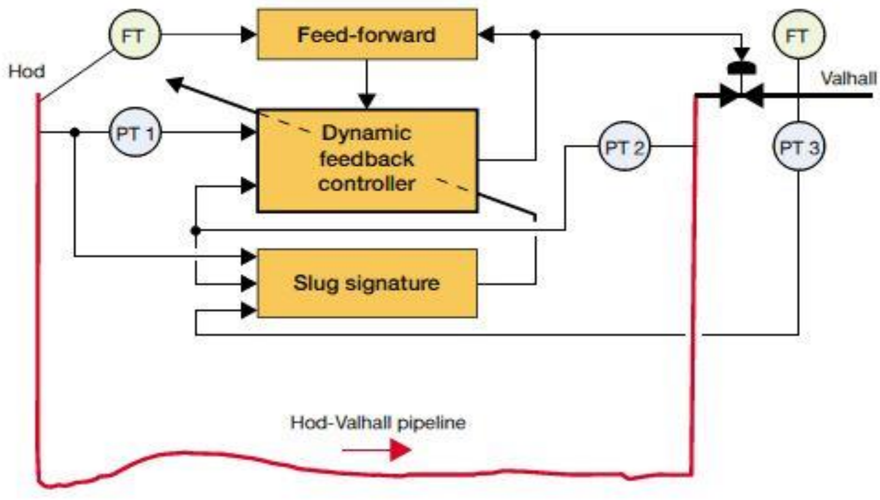


Figure 2-19 SlugCon^{TM} control system [126]

2.5.1.3 Other techniques

Song and Kouba [144] proposed subsea separation as a method for severe slugging elimination. The multiphase fluid is separated into its constituent single phases, liquid and gas at the subsea and the individual phases is transported using different pipelines. This method is advantageous in the sense that no back pressure is introduced to the system, thus the production is not negatively impacted. However there is possibility of liquid carryover into the gas line and gas blowby into the liquid line thereby providing opportunity for slugging in the liquid and gas lines. Also the cost of separator, two separate flow lines and pumps to transport the fluids to the receiving facility can be very significant most especially when the separation is done near the well head and the transport line runs into several kilometres.

Hassanein and Fairhurst [81] also proposed the use of emulsion forming agent to make a homogenous mixture out of the multiphase fluid as a method for severe slug prevention however no detailed information on the technique was provided.

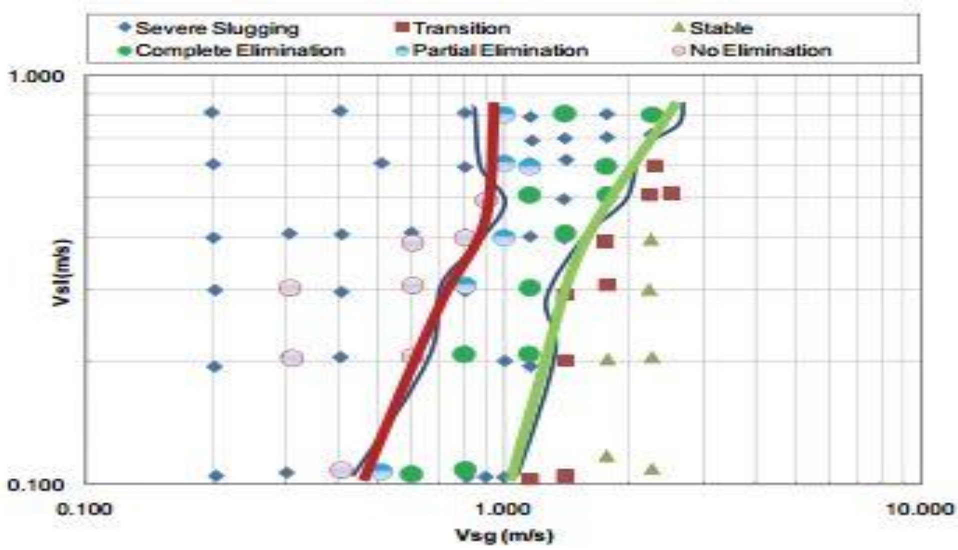


Figure 2-20 Surfactants severe slugging attenuation [145]

Sarica et al. [145] carried out an experimental campaign on the use of surfactants as a severe slugging attenuation technique and propose method for quantifying its elimination potential. Interestingly, surfactant was observed to attenuate slugging at different levels for different flow conditions as shown in Figure 2-20. While it shows potential for total slug elimination at some flow rates, at others it shows partial attenuation and at low flow rates it was unable to attenuate slugging. Apart from additional cost of injecting the foaming agent, there are other issues that are to be resolved concerning this method. Such issues include the optimum dosage rate of the surfactant, the possible effect of the surfactant on the multiphase fluid and challenges the foaming agent could pose to the separation facility.

2.5.2 Hydrodynamic slug control

Before now significant efforts have been concentrated on control of severe/terrain induced slugs. The reason for this is not farfetched. Hydrodynamic slugs have previously been viewed as high frequency short slugs which could be accommodated by the system or tamed using slug catchers. However it was reported that Bonga field, a West African field suffered from flow assurance issue due to hydrodynamic slugging despite the fact that the conventional strategy for severe slug control has been put in place [146].

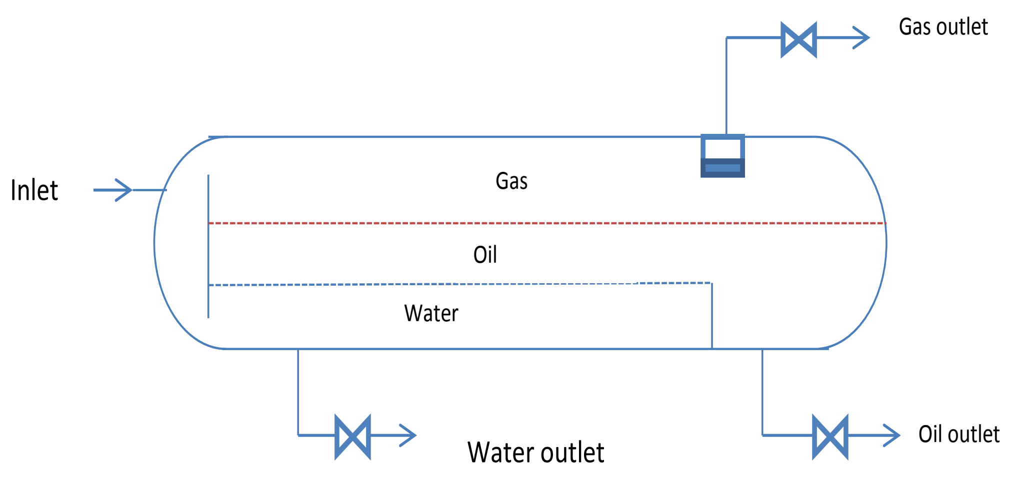


Figure 2-21 Diagram of a simplified horizontal slug catcher

Slug catcher is one of the passive methods for slug attenuation. They are vessels usually installed upstream the separators to provide buffer volume for the slugs. Figure 2-21 shows a typical horizontal slug catcher. These vessels are usually oversized for fear of slugging problems and are not economically friendly [30; 44] .

Miyoshi et al. [103] developed a model for slug catcher design and reported that various variables critical to performance could be quantified. Though this model could be used to achieve some level of proper sizing, the practice of oversizing slug catcher is still in place. As production activities keep moving deep offshore and the space constraint becomes more and more critical, the use of slug catcher could therefore become less attractive. This method is also believed to be unable to handle gas surges associated with slugging [13; 138].

Kovalev et al. [138] proposed a technique for pipeline slugging attenuation which they claimed has the potential for taming hydrodynamic slugging. The device was called Vessel-Less S^3 and is shown in Figure 2-22.

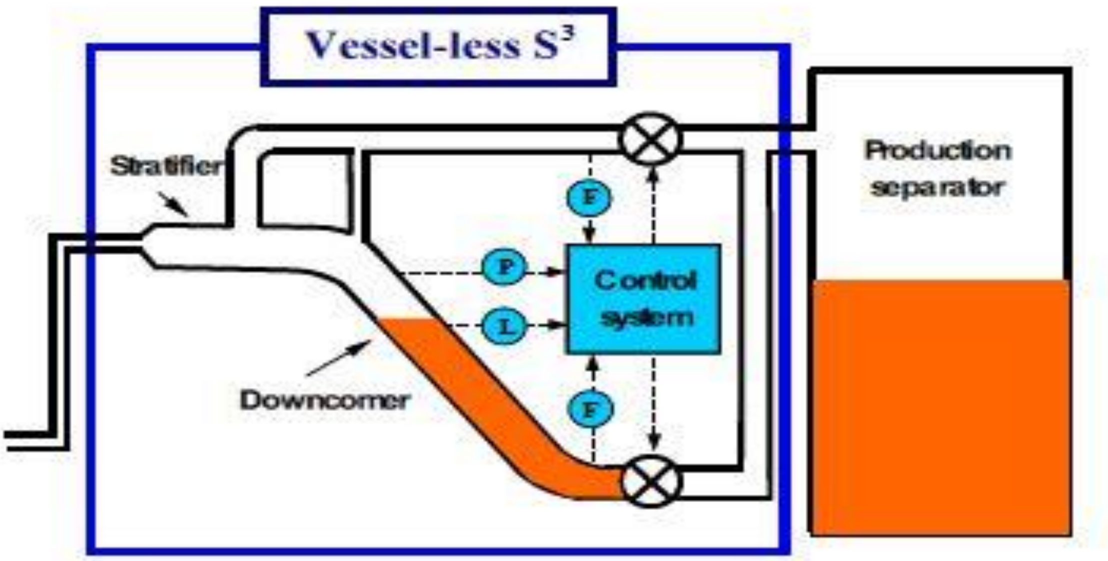


Figure 2-22 Vessel-Less S^3 [138]

It was an advanced version of the earlier proposed device S^3 which was considered less cost-efficient solution for slug control. To address this cost efficiency issue, the Vessel-Less S^3 was developed. This was achieved by reducing the volume of the vessel required for the device through the use of a stratifier and T-junctions as secondary separator. Although the volume was claimed to have been reduced but the addition of stratifier, T- junctions to a downcomer which is also a tilted vessel can constitute additional cost. Also the effectiveness of the T-junctions depends critically on the stratifier and no systematic procedure for the sizing of the volume of this device has been reported.

Krima et al. [147] proposed gas injection as an effective method for hydrodynamic slug control using OLGA. Different control strategies were studied and reported that with the aid of riser-top choking the volume of gas required to attenuate hydrodynamic slugs is reduced. Inyiama [148] employed active feedback control strategy using riserbase pressure as a controlled variable and riser top choke valve as manipulated variable with OLGA to control hydrodynamic slug. The results of his investigation show that the riser slugging was suppressed and the choke valve opening was improved from 5% to 12.65%. However, the contribution of slug tracking model used on the feedback control strategy was not accounted for.

Xing [48] and Xing et al. [117] employed experimental and computational fluid dynamics (CFD) methods to investigate the use of wavy pipe for hydrodynamic slug control. The device acts like a mixer which allowed gas penetration into the slug body thereby reducing the density and effectively attenuate the slug flow. However, the slug flow was observed to redevelop few meters downstream the device.

It was deduced from the literatures that hydrodynamic slug flow in pipeline-riser systems can indeed be very problematic and its attenuation is desired. It is therefore expedient to gain better understanding of hydrodynamic slug flow in pipeline-riser system and develop appropriate strategies for its control.

2.6 The use of gas vessels in pipeline systems

Gas pressure vessels have been previously used in various industries for different applications. A brief review of such applications in single phase water pipelines and slug multiphase flow is attempted in this section.

2.6.1 The use of gas vessel in single phase water pipelines

Gas pressure vessels of various designs have been extensively used in the water industry to protect pipelines from pressure transients caused by some operating conditions such as opening and closing of valves, starting and stopping of pumps. This application is usually referred to as surge suppressors or arrestors/dampeners.

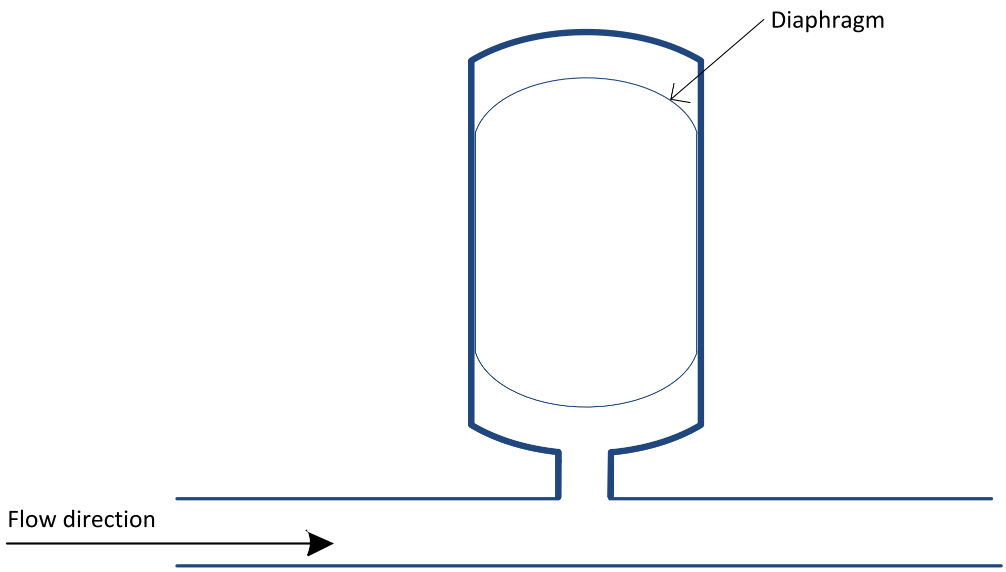


Figure 2-23 A diagrammatic representation of simplified surge suppressor

Young [149] categorised these surge arrestors into bladder surge tank (BST) and hydropneumatic surge tanks (HST). The major difference between these vessels lies in the design. In BST design, a bladder physically separates the precharged gas from the working fluid while the HST is without a physical device inside it but with a level control system and compressor which helps to control the gas liquid interphase. However, the operation mechanism for both vessels is same. The compression and expansion properties of gas are the principle upon which the surge arrestor is based.

For example, when pressure surge occurs as a result of pump shutoff or valve closure, the fluid is transported into the HST or BST, where it compresses the precharged gas in the vessel until the pressure in the pipeline returns to steady state. The reverse mode is also possible where the gas in the vessel expands and the fluid released into the pipeline to counter pressure surge [149; 150]. A typical example of gas vessel used as a surge suppressor is shown in Figure 2-23.

Although gas vessel has been used to control pressure transient in water pipeline, it is important to observe that the phenomenon leading to such pressure transient is different from the intermittent multiphase slug flow. Also, the gas vessel is designed such that an external influencer such as compressor and level controller or internal influencer such as piston/diaphragm helps to control the volume of gas in the vessel. It is therefore unclear whether the gas vessel concept with or without an influencer will be able to attenuate slug flow. This gap will be explored in this work.

2.6.2 The use of gas vessel in slug flow study

In a quest to experimentally produce slug behaviour close to the field situation in the laboratory, many investigators have previously used gas vessel as additional pipe length in the study of slug flow in pipeline-riser systems. These vessels are usually placed near the pipeline inlet and are operated such that variable pipeline length can be created by filling part of the vessel with water or operating liquids [125; 151-154].

Jansen et al. [125] investigated the elimination of severe slugging using choking and gas lifts experimentally in a 12.1m long pipeline-riser system of 2.54 cm diameter (9.1m long pipeline connected to a 3m high riser). The gas vessel was used to generate additional 10m pipe length equivalent. Choking was reported to effectively eliminate or attenuate severe slugging but with attendant increase in system pressure. Although gas injection was also able to stabilise the flow in the system, large amount of gas is required to achieve which makes it less attractive cost wise.

Malekzadeh et al. [151-154] in their experimental studies of various aspects of severe slug flow in pipeline-riser systems of 65m, 50.8mm horizontal pipeline linked to a 35m long pipeline with internal diameter of 50.8mm inclined at -2.54^{o} leading to a 15.5m, 45mm vertical riser employed gas vessel to simulate various additional pipe length of 197m and 123 m which are 400litres and 250 litres volume equivalent respectively. However, none of these works was done on hydrodynamic slug flow. Other authors such as Danielson et al. [95] have also explored the concept of extra volume to simulate long pipeline with large pipe diameter using LedaFlow simulator. However, the focus was on slug behaviour and not slug control. Although the extra volume concept has been explored to alter the characteristics when placed near the entrance of the pipeline, it is not clear whether the vessel can provide slug attenuation when turned upside down. This would be explored in this study.

2.7 Summary

A review of the advances in slug flow phenomenon and the various attenuation techniques were also attempted. Slug formation mechanisms and stability analysis were reviewed.

A number of mitigation techniques such as the use of wavy pipes, pipe diameter modification, riser base gas injection, gas re-injection, the use of slug catcher, manual and active choking of the riser top valves, use of flow conditionals, and foaming agents have been discussed.

The use of gas vessel in slug studies and other industries were also reviewed. Gas vessel placed near the entrance of a pipeline-riser system has previously been used to simulate additional pipe volume. This effectively will alter the slug flow characteristics due to increased compressibility in the pipeline-riser system

The use of gas vessels in form of surge arrestors in single phase water pipeline has also been reviewed.

Despite the advances made in severe slug prediction and control, it appears hydrodynamic slug control has not received much attention. Efforts have been concentrated on hydrodynamic slug prediction but its control has not been well researched. This could be attributed to the general belief that it is a short high frequency slugs which can be tamed using slug catcher. Also the understanding of the mechanism of hydrodynamic slugs and its contribution to riser slugging has not been well understood till date.

However, the observation from the work of Brill et al. [16] that hydrodynamic slug could be severe, the problematic nature of hydrodynamic slug reported in Guzman and Fairuzov [17] and the complex slugging resulting from hydrodynamic-severe slug interaction reported for a ConocoPhillips field in the North Sea by Danielson et al. [18] are sufficient reasons for a renewed interest in control of hydrodynamic slugs.

There is therefore a need to gain better understanding of the mechanism of hydrodynamic slug contribution to riser slugging and the optimization of slug control techniques.

This work is dedicated to addressing these gaps. The next chapter will address the methods adopted in addressing the aim and objectives of this work.

3 METHODOLOGY

3.1 Introduction

This chapter describes the method adopted to achieve the objectives set out in section 1.2. The numerical tools and simulations conducted as well as the industrial pipeline-riser system investigated are described. The Cranfield University multiphase experimental facilities were used for the experimental studies. The experimental procedures are well explained. The chapter begins with the justification for the methods, after which the numerical tools were presented followed by detailed experimental facility and procedures. The chapter overview is shown in Figure 3-1.

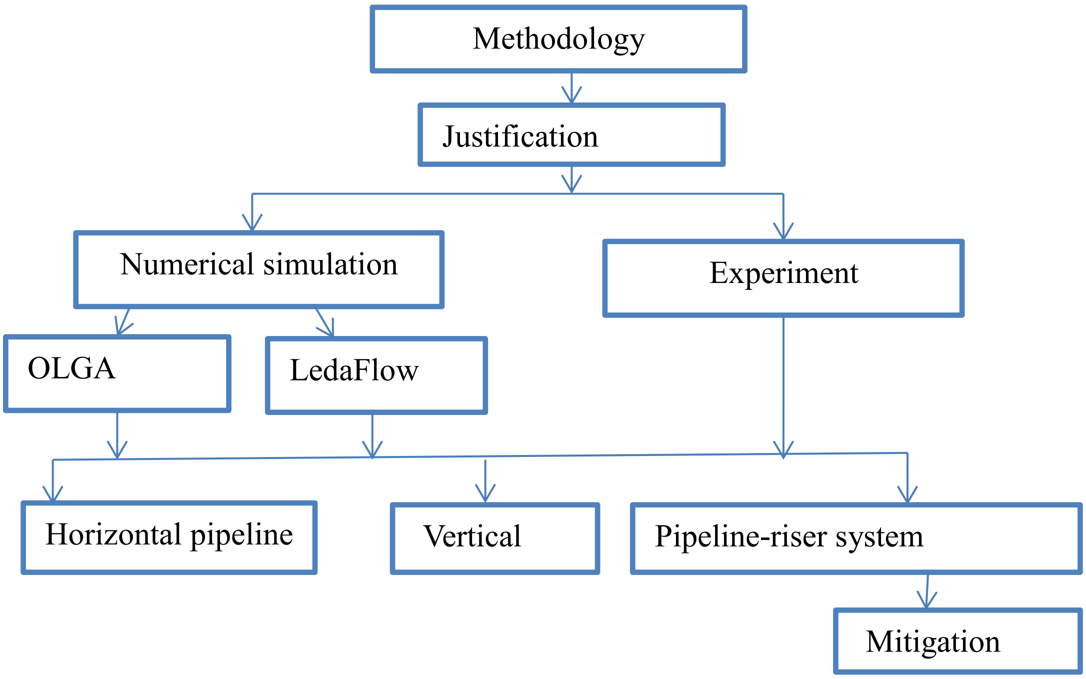


Figure 3-1 Diagram showing methodology structure

3.2 Justification for methodology

Multiphase flow and indeed slug flow has been studied widely using both experimental and computational methods, a detailed review of which have been provided in chapter two. Apart from experimental method and the use of one dimensional (1D) industrial multiphase codes for numerical simulation in this study, computational fluid dynamics (CFD) technique could have been employed. A preliminary study was conducted on a pipe of 0.078m internal diameter and 30m length using FLUENT software- a CFD tool (detailed in Appendix A). For this very short pipeline, a single simulation run was observed to take average of four days to complete. Although considerable insight was gained into slug flow initiation, growth, stability and collapse in horizontal pipes using this method, however due to computational cost it would be impractical to model a full industrial system, hence the choice of the methods used in this study. The methods adopted for this study are not just well established; they are also economically attractive and provide a springboard for the researcher to have a practical feel of the industry.

3.3 Numerical investigation of hydrodynamic slug flow

Numerical tools provide an advantage of investigating industrial systems which are of larger sizes compared to the available experimental facilities. In order to meet the first objective of this study, two industrial software packages OLGA and LedaFlow have been used to gain a good understanding of hydrodynamic slug flow in pipeline-riser system. This understanding is needed for the development of appropriate strategy for the slug attenuation. Extensive numerical studies were conducted on a large size pipeline-riser system. This was a 3.7 km long horizontal pipeline leading to a 0.13 km vertical riser; both pipeline and riser are of 17” internal diameter as shown in Figure 3-2. Other geometries used in this work are shown in Appendix B.

The unit cell model of both softwares (OLGA and LedaFlow) were explored for the prediction of slugging also the slug tracking model of OLGA and slug capturing model of LedaFlow were employed . Slug envelopes were developed for these geometries and compared for all the models described in section 2.4.

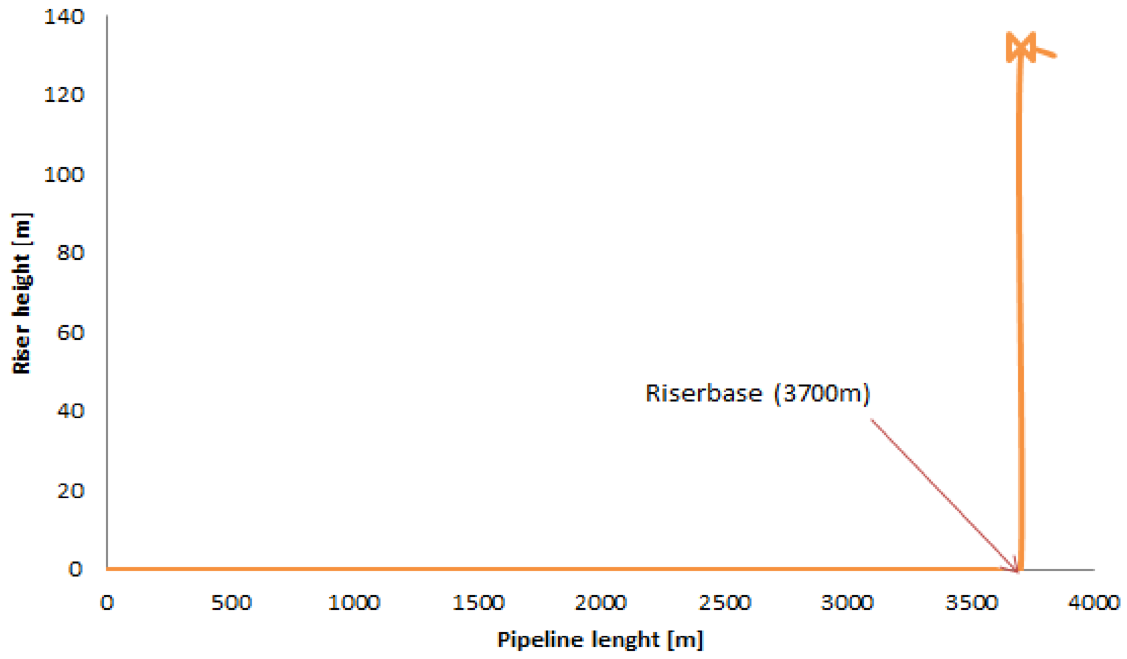


Figure 3-2 Geometry of pipeline-riser system

3.3.1 Pre-processing

The pre-processing describes the activities carried out before the actual numerical solution of the problem. One of the pre-processing activities is the creation of fluid file. For any simulation study in both OLGA and LedaFlow, fluid property file must be specified. The information about the properties and amount of the fluid for a given range of temperature and pressure are housed in this file. More details on the fluid properties, pipe materials properties are shown in Appendix B.

Meshing or discretisation is another important pre-simulation process. The geometry of the problem needs to be prepared in form in which the solver would be able to solve the problem. This form is usually referred to as grid/mesh. They are connected discrete points which represent the flow domain. The geometry shown in Figure 3-2 was modelled in OLGA and LedaFlow. The discretised geometry of the pipeline-riser system for OLGA for example is shown in Figures 3-3.

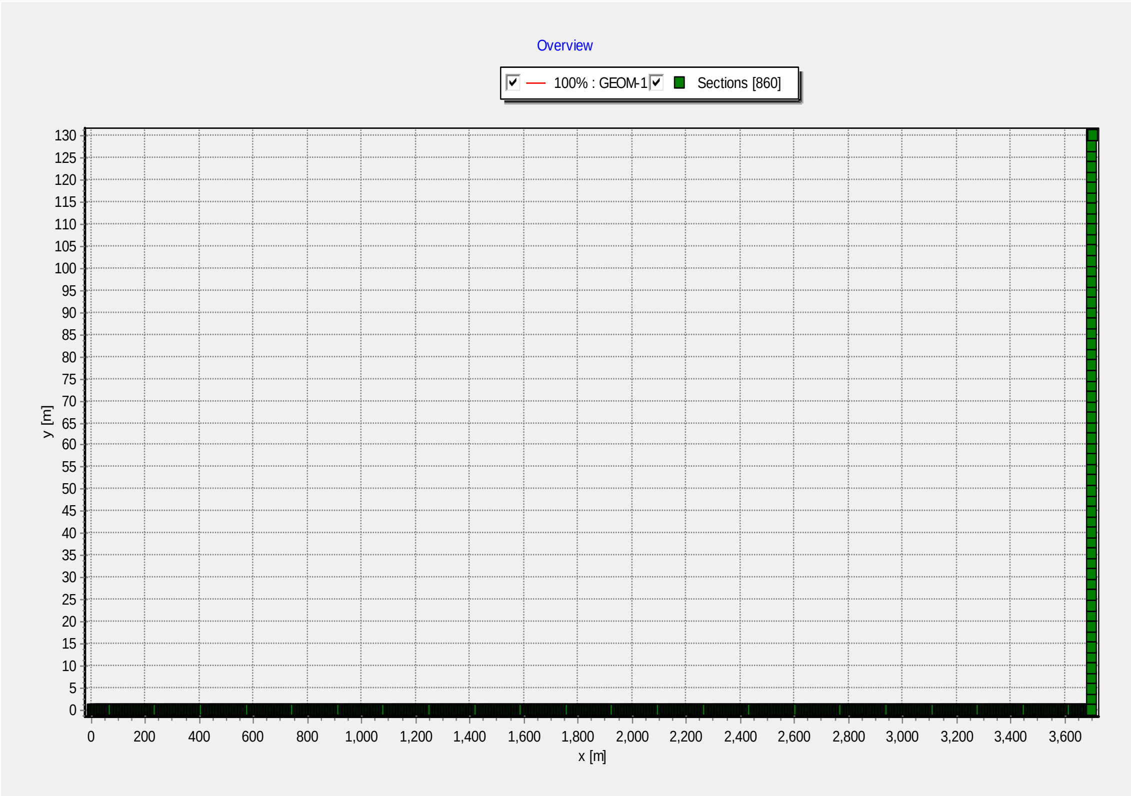


Figure 3-3 Discretised geometry of pipeline-riser system

Apart from the fluid files, geometry and meshing preparation, the boundary conditions must also be specified before a simulation can be carried out. The outlet Temperature was kept at 40^{o} C while the pressure was kept constant at 27.95 bar for horizontal pipeline study, 22.5 bar for the pipeline-riser system and vertical pipes. Once these activities are completed the simulation is then carried out to solve the problem.

3.3.2 Simulation procedure

The solution of the problem prepared in the pre-processing section was achieved by simulating it using appropriate models.

The accuracy and convergence of the solution depend largely on the mesh. The mesh size is also a very crucial factor in determining the computational time which is a major issue in numerical simulations. Therefore, mesh sensitivity studies were carried out to identify the optimum mesh size required to obtain solution which is not mesh dependent and at lowest possible computational cost. The mesh sensitivity study showed that the mesh with 1800 cell was optimum and was chosen for this study. Details of the study can be found in Appendix B.

The numerical simulation of the pipeline-riser, pure horizontal and vertical pipe were carried out for various flow conditions using the various models (Unit cell, slug tracking and slug capturing). A total number of about 872 simulations were done and a good number of the results fall within the slug region.

3.3.3 Post processing

The flow regime indicators in both softwares were used to judge the presence or absence of slugging for the unit cell model while the fluctuation of the flow variables like pressure, mas flow rate and so on were used for the slug tracking and slug capturing. The superficial velocities were used to generate the flow envelopes which were analysed to understand the behaviour of hydrodynamic slug flow in pipeline-riser system. These are presented in Chapter four.

3.4 Experimental study

The experimental campaign serves to meet the first objective partially and predominantly the second, third and fourth objectives. The Cranfield University Process system engineering laboratory houses a number of experimental facilities. Three of these facilities were employed in this study. They are: the 2” and 4” three- phase pipeline-riser system and the 2” two- phase (Air/Water) horizontal rig. The three phase rig was used to carry out studies that pertain to pipeline-riser system was also adapted for vertical pipe study while the horizontal two phase rig was used for horizontal pipeline studies.

3.4.1 The three-phase pipeline-riser system

The 2” rig part of the existing three-phase, air- water - oil facility in the Cranfield University shown as blue colour in Figure 3-4 was modified to accommodate the intermittent absorber for the hydrodynamic slug part of this work as shown in Figure 3-5.

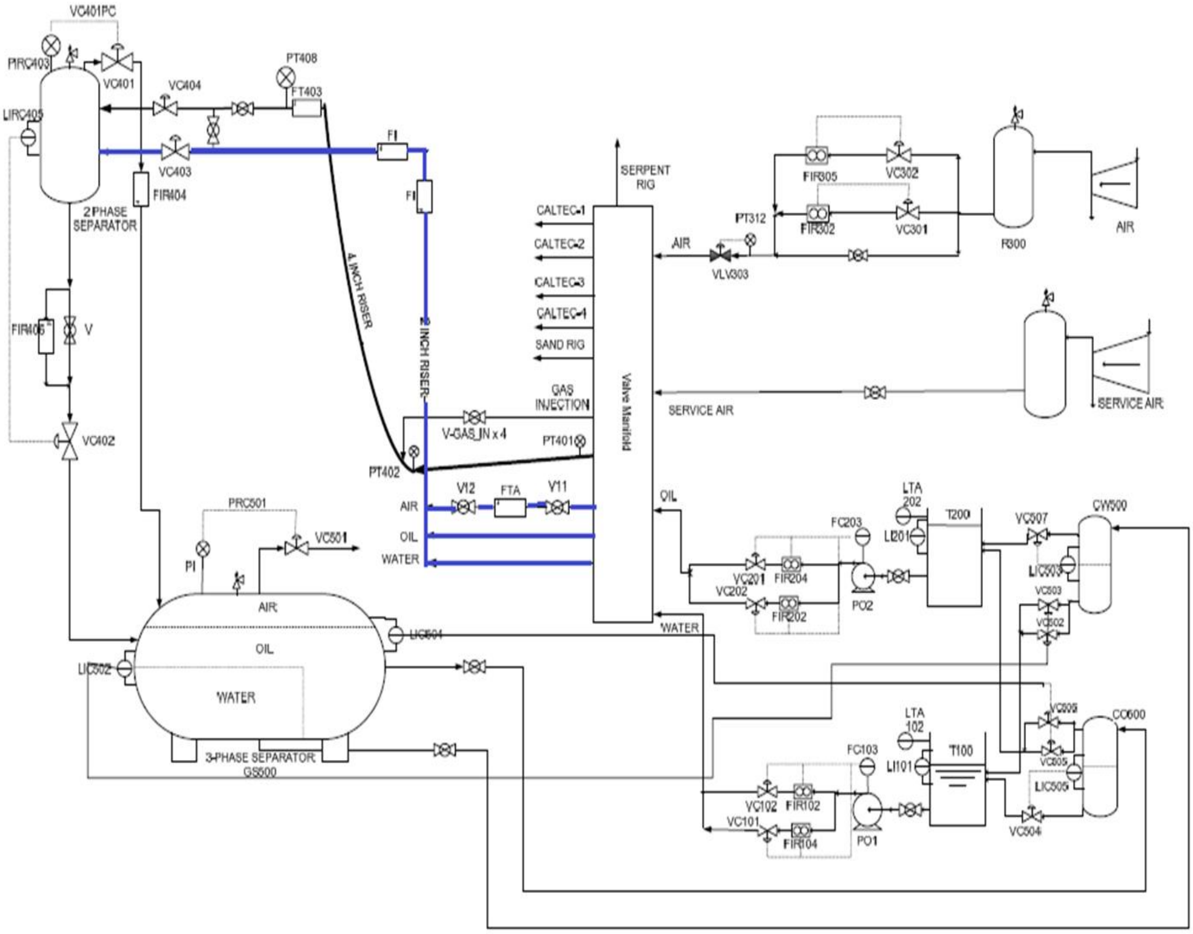


Figure 3-4 Cranfield University multiphase Experimental facility [155]

The three-phase 4” test facility of Cranfield University is purpose built for severe slugging investigation. Both rigs are fully automated high pressure test experimental rig comprising of three main sections. The metering section where controlled and measured rate of working fluids are supplied into the test section which comprises of the pipeline-riser system and the test separator, then finally leading to the third section where separation of the multiphase working fluids takes place in a horizontal three -phase separator. The various fluids are cleaned in their respective coalescers before transported back into their storage tanks and the air is released into the atmosphere. The schematic of this experimental facility is shown in Figure 3-4.

The working fluids (air and water) are supplied and metered at the metering and supply section. The air is supplied through an air cooler and filter which serves to remove moisture, droplets and particles from the air, so clean and dry air is delivered into the system. An Atlas Copco compressors used in the supply of compressed air into the test rig has a capacity of 400 SCM/h at a pressure up to 10 barg. Two Rosemount Mass Probar flow meters of 0.5inch and 1 inch were used to measure airflow rates up to 120 Sm^3/h and 4250 Sm^3/h respectively.

Water is supplied into the system from a 12 m^3 tank with the help of a centrifugal pump of 40 m^3/h maximum capacity. The water flow rate is measured by an inch Rosemount 8742 magnetic flow meter and a 3 inch Foxboro Coriolis meter for flow up to 1kg/s and 10 kg/s respectively.

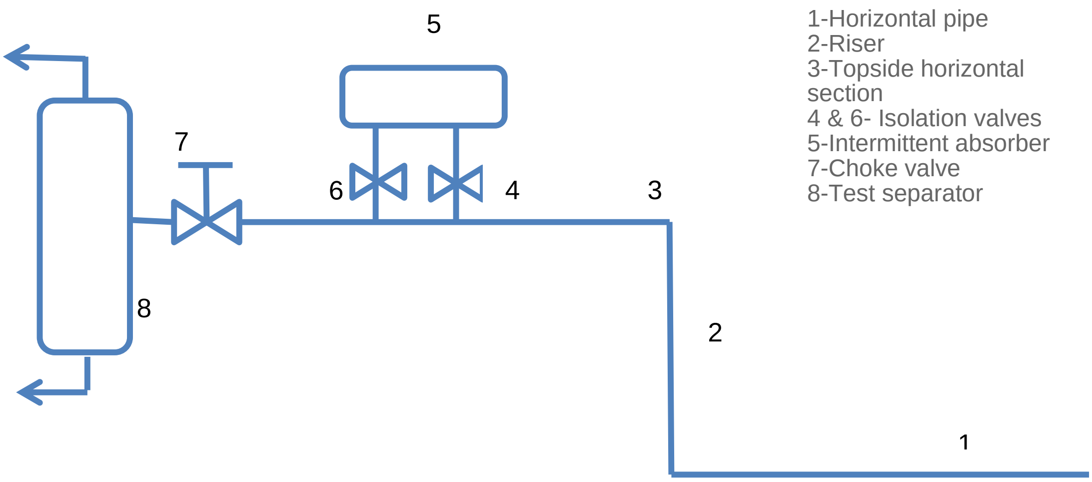


Figure 3-5 Schematic of the 2" multiphase experimental facility

The facility is powered and controlled by the Delta V system of Emerson Process Management system which is a field bus based Supervisory, control and Data Acquisition (SCADA)) system. The pressure at test section was measured by pressure transducer range 0-6 barg and uncertainty ±0.25% of full scale. The temperature at the gas metering section was measured by thermocouples of range 0-100 °C and uncertainty ±1% of full scale

Figure 3-5 shows the test area used for the hydrodynamic slug study. It was the 2” loop pipeline-riser system which comprise of the 40m long purely horizontal pipe (1), the 11m high vertical riser (2), about 3m horizontal topside section (3), the intermittent absorber (5) the upstream and downstream isolation valves (4 and 6 respectively), topside choke valve (7) and the test separator (8) .The test separator is a 1.2m high and 0.5m diameter vertical two phase separator where the fluids from the pipeline-riser systems are discharged.

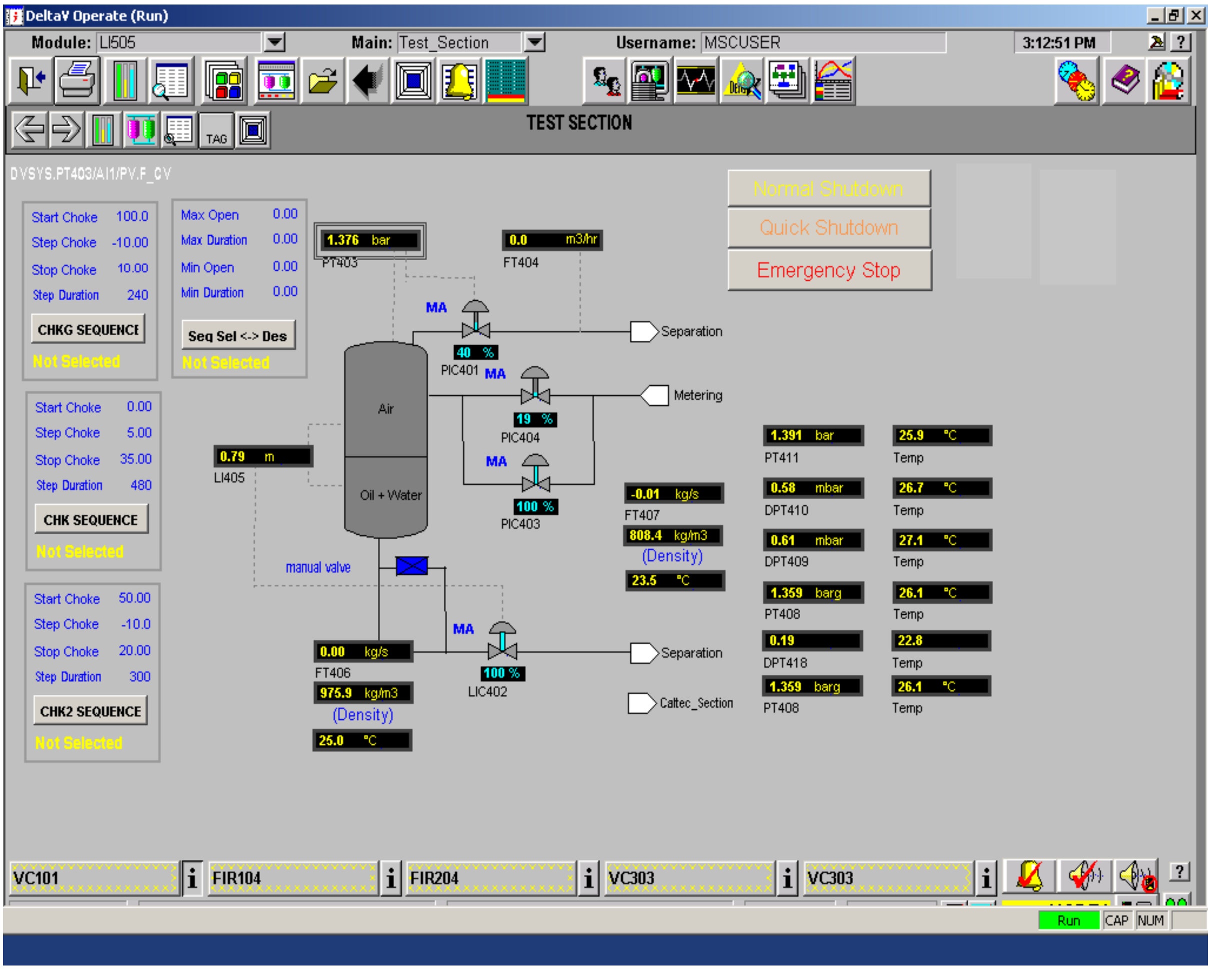


Figure 3-6 A typical DeltaV GUI

The 4” pipeline-riser system test area was used for the severe slugging. This is 55m long pipeline system which is inclined to -2^{o} from the horizontal followed by a10.5m high 4” catenary riser.
The air water mixture from the test area is discharged into the horizontal three-phase separator where they are separated. The liquid level and the separator pressure are automatically controlled by level and pressure controllers respectively. The separated air is discharged into the atmosphere and the water is pumped back to the water tank via a coalescer.

A Delta V SCADA system is used to remotely operate the rig and perform the experimental procedure including pressurising and depressurising the system, control, shut down and data acquisition. A typical DeltaV GUI is shown in Figure 3.6. More details on the Cranfield University multiphase experimental facility has been well documented in [155]

3.4.2 The two-phase horizontal experimental rig

The hydrodynamic slug flow in horizontal pipeline was studied using the 2” air/water two-phase test rig in the Process system engineering laboratory. The schematic of this facility is shown in Figure 3-7.

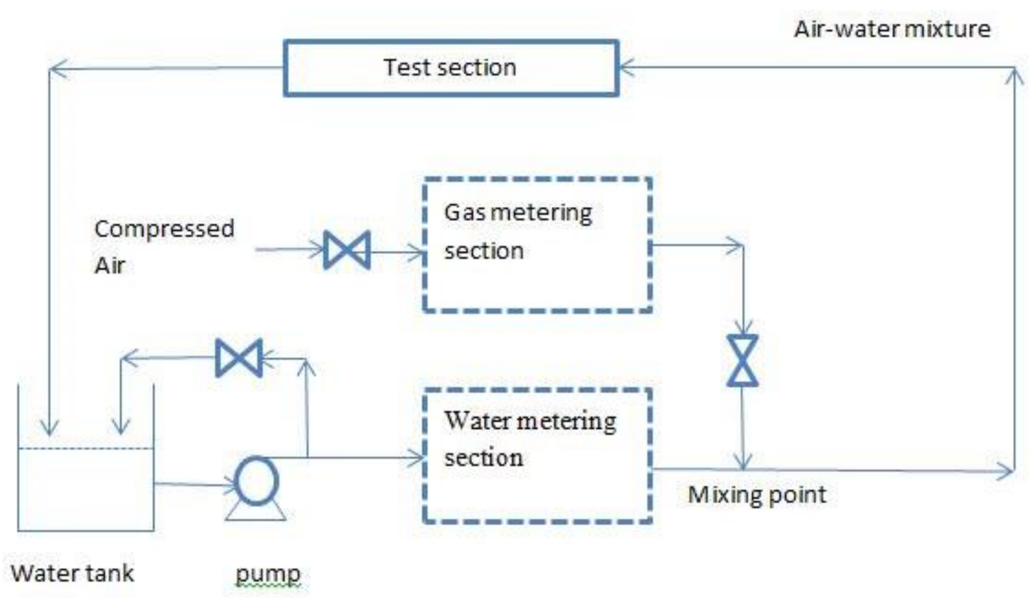


Figure 3-7 Schematic of two-phase horizontal rig

The air was supplied directly from the Cranfield University central compressors and flowed to the metering section through a needle valve.

The water was supplied into the horizontal pipe from a 4.4m^3 water tank. A centrifugal pump with a maximum capacity of 40m^3/h and 5 barg discharge pressure was used to supply the water into the flow line with a bypass line. With the help of isolation valves, the water can either flow into the metering section or return into the tank through the bypass.

An electromagnetic flow meter shown in Figure 3-8 was used for water metring. It has measurement range of 0-4.524m^3/h and uncertainty of ±1% of full scale while the gas turbine air flow meter shown in Figure 3-9 has capacity of 1-60m^3/h and also uncertainty of ±1% of full scale. The pressures at the gas metering section and upstream test section were measured by pressure transducers range 0-6 barg and uncertainty ±0.25% of full scale. The temperature at the gas metering section was measured by thermocouples of range 0-100 °C and uncertainty ±1% of full scale.

The water and air were mixed together at the mixing point located 15m upstream the test section.

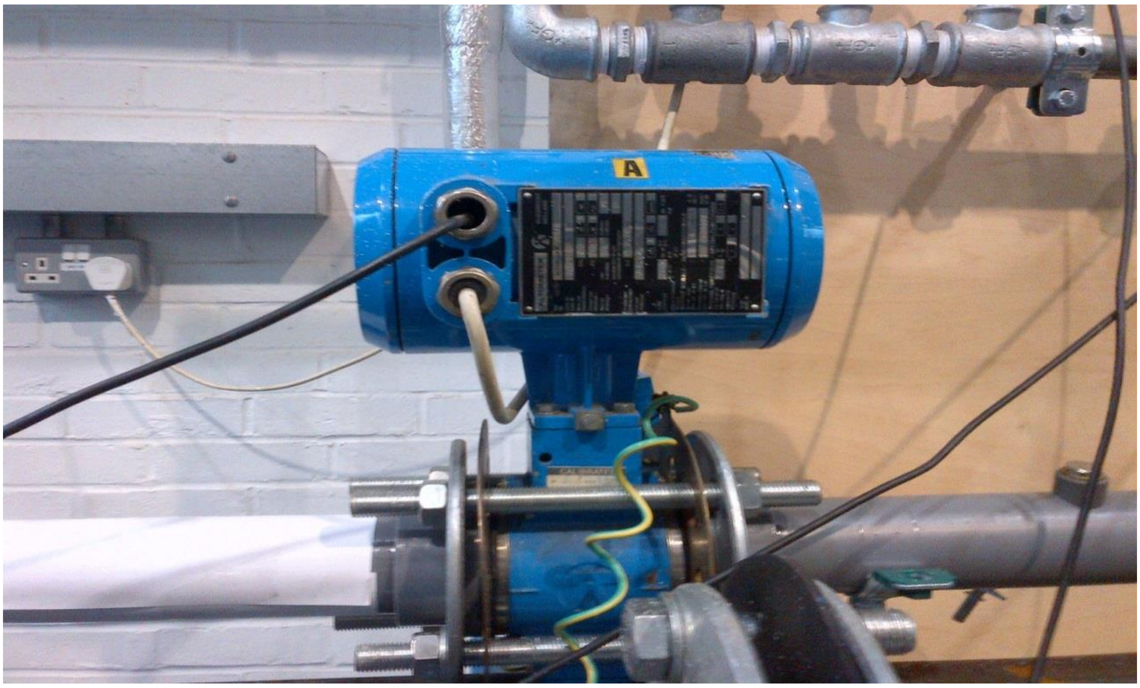


Figure 3-8 Electromagnetic flow meter

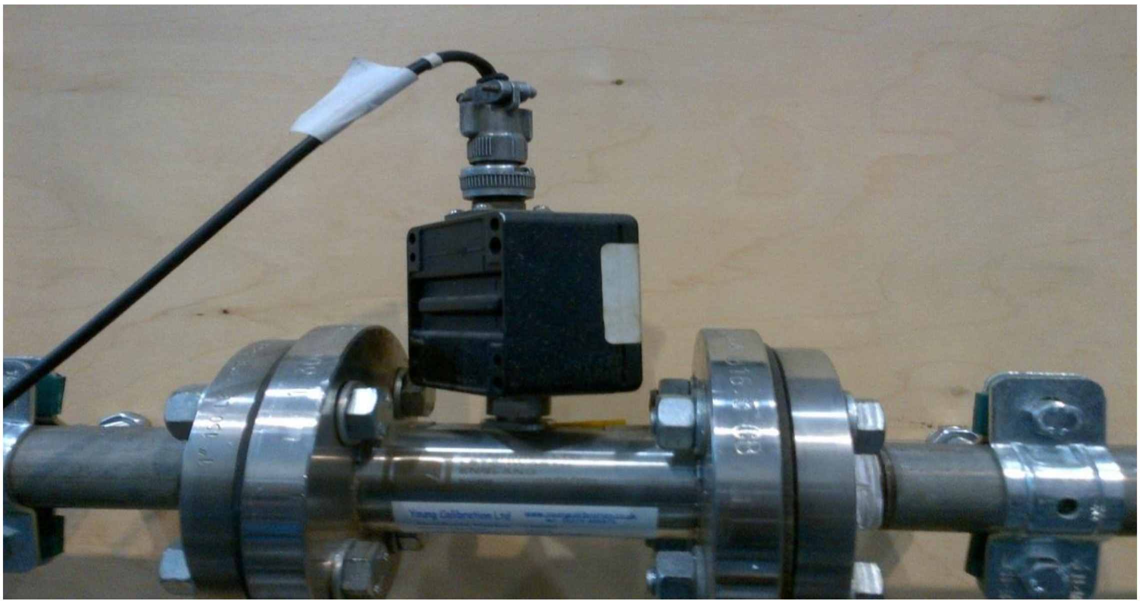


Figure 3-9 Gas flow meter

Figure 3-10 Pseudo spiral tube

The test section is a pseudo spiral tube constructed by joining various pipe bends in twisted form as shown in Figure 3.10**.** The behaviour of the water/air two-phase mixture was observed immediately upstream the test section, at the test section and downstream the test section. The air mixture then flowed back to the water tank. Although other valuable information could be gathered from the experimental rig, the flow regime map was of primary interest. This was obtained through visual observation, the pressure response upstream the test section and superficial velocities plotted to obtain the slug flow envelope in pure horizontal pipeline.

3.5 The experimental procedure

In order to run the experiment for the three phase rig, the 2’’ pipeline-riser system was isolated from the rest of the facility using the appropriate valves. The compressors and pumps are then switched on. The system is then pressurised before the various experimental conditions were tested for the cases with or without the intermittent absorber. The DeltaV system is used to set the various flow conditions and data acquisition.

This same rig was adapted for vertical pipe studies; here the gas was introduced at the riser base instead of travelling with the water through the horizontal section of the pipeline-riser system.

For the severe slugging studies, similar procedures were followed for the rig operation. The 4” pipeline-riser system was isolated from the rest of the experimental facility using various isolation valves. Two sets of experiments were conducted. The first set of tests was done with the 4” pipeline-riser system isolated from the intermittent absorber and the second with the absorber coupled. This isolation valve installed on the arm of the splitter connecting the two systems as shown in Figure 3-12 made it possible to have these two sets of experimental mode.

For the two-phase horizontal rig, the experimental procedure is manual and the data acquisition system is Labview®. The manual valves are also positioned in right order and the manual control valves are manipulated to derive various experimental flow conditions.

3.6 Approach to slug attenuation

3.6.1 Parameter variation technique

The parameter variation technique basically employs the principle of changing a part to change the whole. The ability of the risertop choking to alter the system behaviour when varied was explored. The effect of such variation on slug flow in the pipeline-riser system was investigated using the bifurcation map.

3.6.2 The intermittent absorber

The intermittent absorber was designed and built as a horizontal vessel installed on the riser top upstream of the two-phase test separator. The vessel is made of stainless steel pipe of a 6 inch nominal diameter and has a total volume of 0.0284 m^3. This volume is greater than that of the riser which is about

0.0234 m^3. This was believed to be able to cater for the worst case slug which could of the magnitude greater or equal riser volume. The vessel is isolated from the pipeline-riser system with aid of two isolating valves thereby allowing for experiments where the vessel is not necessary. These valves also help to achieve three various operating mode with the single absorber. The first design is achieved when the two isolation valves are opened, the second when the upstream valve is opened and the downstream is closed and the third is achieved when the upstream valve is closed and downstream valve is opened. Figure 3-11 shows the schematic diagram of the intermittent absorber and a detailed schematic of the intermittent absorber is shown in Appendix B. The extra volume provided by the absorber is expected to be able to provide slug flow attenuation by altering the behaviour of slug from the pipeline-riser system.

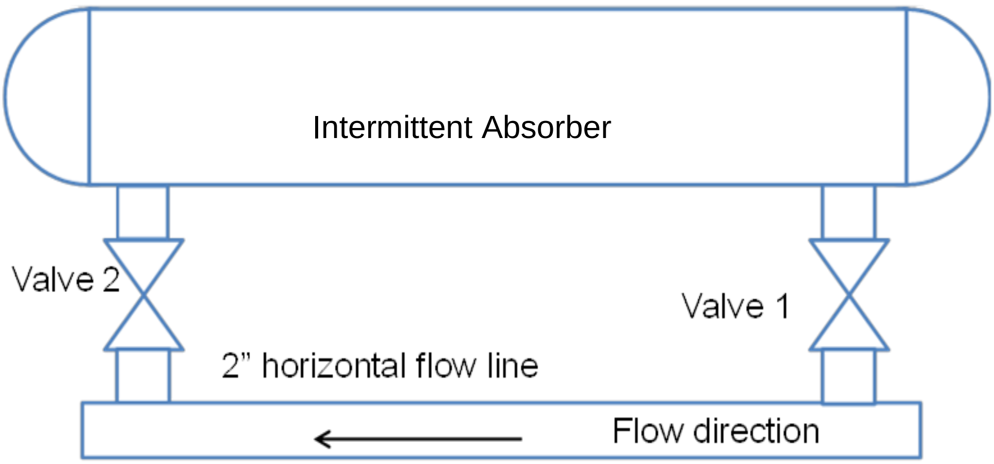


Figure 3-11 The intermittent absorber

3.6.3 The intermittent absorber coupled with 4" pipeline-riser system

The 2" pipeline-riser system extensively discussed in section 3.4 is used here as an intermittent absorber for the 4" pipeline-riser system. This was done for severe slugging attenuation investigation.

Figure 3-12 Intermittent absorber coupled with 4" pipeline-riser system

Although the 2" system is purpose built for hydrodynamic slug studies, a horizontal Y splitter connecting the 4" pipeline-riser to the 2" pipeline-riser system was used to couple it to 4" system. This connection is shown in Figure 3-12. The extra volume provided by the 2" pipeline-riser system is expected to be able to modify the severe slugging flow in 4" pipeline-riser system eventually delivered to the two-phase separator.

3.7 Limitation of methods

Numerical tools provide an advantage of investigating industrial systems which are of larger sizes compared to the available experimental facilities. They also provide cost advantage. However, the tools used in this study are in 1D and slug formation process is a 3D phenomenon. This notwithstanding the predictive capability of these tools is generally acceptable and they have been widely used in the industry. Also the primary aim of this study is not on the slug formation process but slug attenuation.

Although the experimental facilities were able to achieve the objectives of this work, instrumentation on the absorber would have provided better understanding of the slug attenuation mechanism of the device. However, the procedure and the methods for proving the concepts are sufficient for the scope of this study.

3.8 Summary

The methodology used for this study has been described in this chapter. The numerical modelling approach, simulation procedure, experimental facilities and procedures as well as the limitation of methods were all documented. The following chapters describe and discuss the results.

4 HYDRODYNAMIC SLUG FLOW IN PIPELINE-RISER SYSTEMS

4.1 Introduction

This chapter is dedicated to gaining insight into the behaviour of hydrodynamic slug flow in pipeline-riser systems and the impact of geometry interaction on slug flow. The understanding of this behaviour is very important in the development of effective slug control strategy. Previous studies have provided significant understanding on the flow of hydrodynamic slug in horizontal pipes [64; 68; 71; 156-159] and behaviour of severe slug flow in pipeline-riser system [29; 47; 48; 50; 160]. However, only few studies exist on hydrodynamic slug flow in pipeline-riser system [17; 30]. There is therefore the need to understand the behaviour of this type of slug in pipeline-riser system before appropriate control strategy can be deployed.

The well-established flow pattern map was employed in this study with special interest in the slug flow regime. Slug envelopes were produced using two multiphase commercial codes, OLGA and LedaFlow. Flow regimes in OLGA and LedaFlow are identified in terms of numeric values that correspond to the different flow regimes namely Stratified Flow = 1, Annular Flow = 2, Slug Flow = 3 and Bubbly Flow = 4.

Experimental studies were also conducted to validate the numerical studies. The methodology adopted for the study is detailed in Chapter three. The numerical simulation of hydrodynamic slug flow is presented first followed by experimental study for its validation.

4.2 Numerical simulation of hydrodynamic slug flow

The slug envelopes obtained from horizontal pipeline, vertical pipeline, pipeline with riser downstream are discussed and comparisons of the systems have been made. Comparisons were also made between the envelopes obtained for various models.

4.2.1 Slug flow envelopes for pure horizontal Pipeline

The first configuration described in section 3.3 was investigated. That is, the pure horizontal 3.7km, 17'' internal diameter pipeline. A total number of 332 data points were studied covering superficial velocities ranging from 0.039 to 34.99 m/s for gas and 0.18 and 8.25 m/s for liquid.

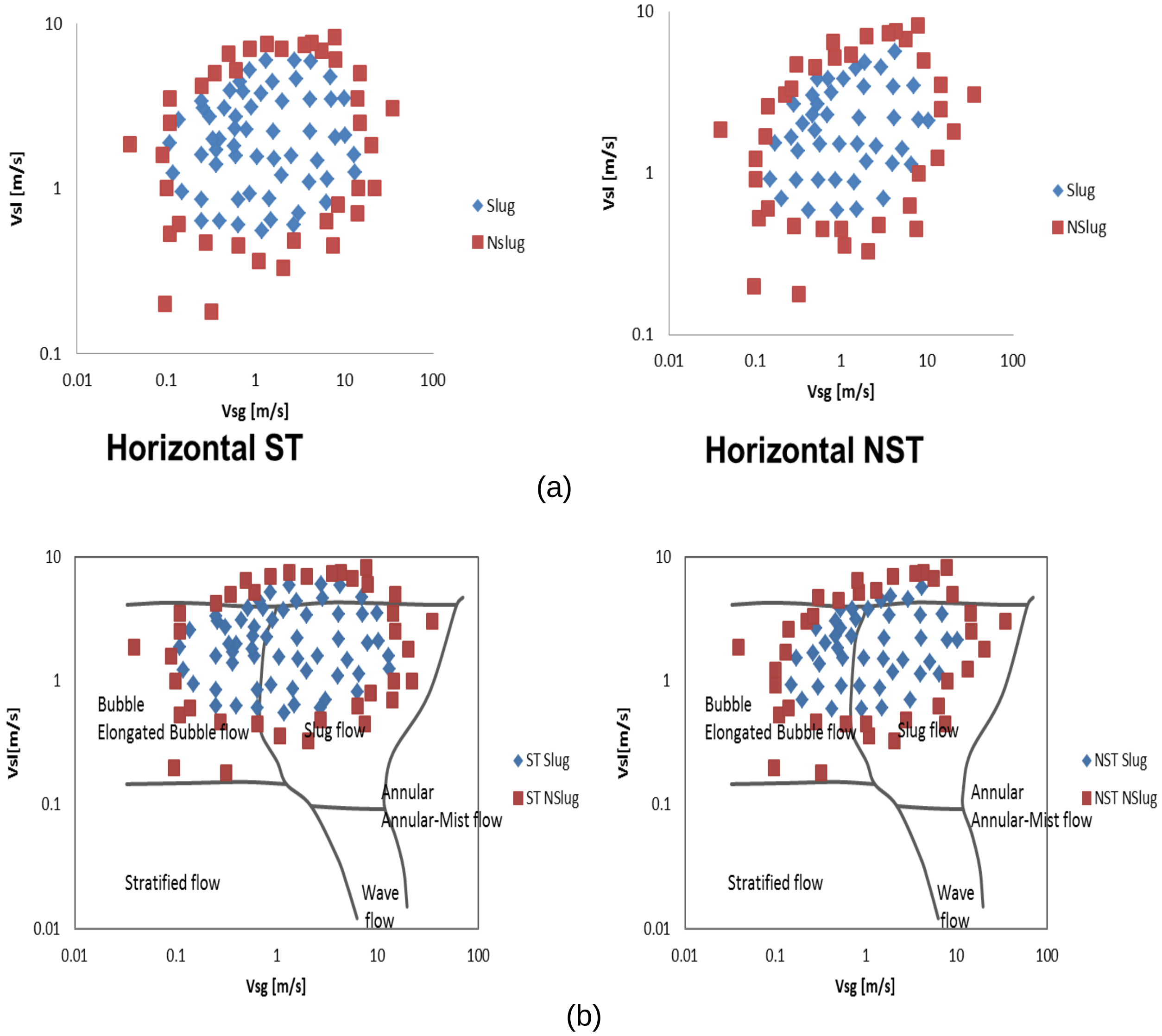


Figure 4-1 (a) OLGA hydrodynamic slug envelopes for horizontal pipe (b) OLGA prediction compared with [24]

Figure 4-1(a) shows the hydrodynamic slug flow regime obtained from OLGA models (slug tracking model and the unit cell model designated as ST and NST). As can be seen from the map, at high liquid and considerably high gas superficial velocities, hydrodynamic slugs were formed. This is typical of hydrodynamic slug flow as earlier discussed in the literatures [19; 24]. From Figure 4-1(a), the envelope obtained from the slug tracking model is bigger than that of the unit cell model. Slugs were still observed at gas superficial greater than 10m/s in ST whereas beyond none were observed in NST. This implies that the unit cell model under predicts hydrodynamic slug region.

Figure 4-1(b) shows the hydrodynamic slug flow regime obtained from OLGA models compared with Mandhane et al. [24] map. The Figure shows that considerable amount of data fall predicted by OLGA for slug fall within the slug region of [24]. However some region predicted as slug by OLGA fall within the non-slug region and vice versa. This could be as a result of the effect of the difference in pipe diameter.

Figure 4-2 (a) shows the slug envelopes for the horizontal pipeline as predicted by LedaFlow models (slug capturing and unit cell model designated as SC and NSC). The regions reported to be void of slugging by unit cell model were reported to suffer slugging by the slug capturing model. This is similar to the observation between unit cell model and the OLGA slug tracking model slug envelopes prediction. It was observed that up to superficial gas flow rate of 9 m/s, slugs were observed for SC whereas none was observed at this condition for NSC. It appears that unit cell model under predicts slug envelope compared to both slug tracking and slug capturing models.

Figure 4-2(b) shows the hydrodynamic slug flow regime obtained from LedaFlow models compared with Mandhane et al. [24] map. The Figure shows similar trend like Figure 4-1 (b) where considerable amount of data fall predicted for slug fall within the slug region of [24] and some region predicted as slug fall within the non-slug region and vice versa. This could be as a result of the effect of the difference in pipe diameter.

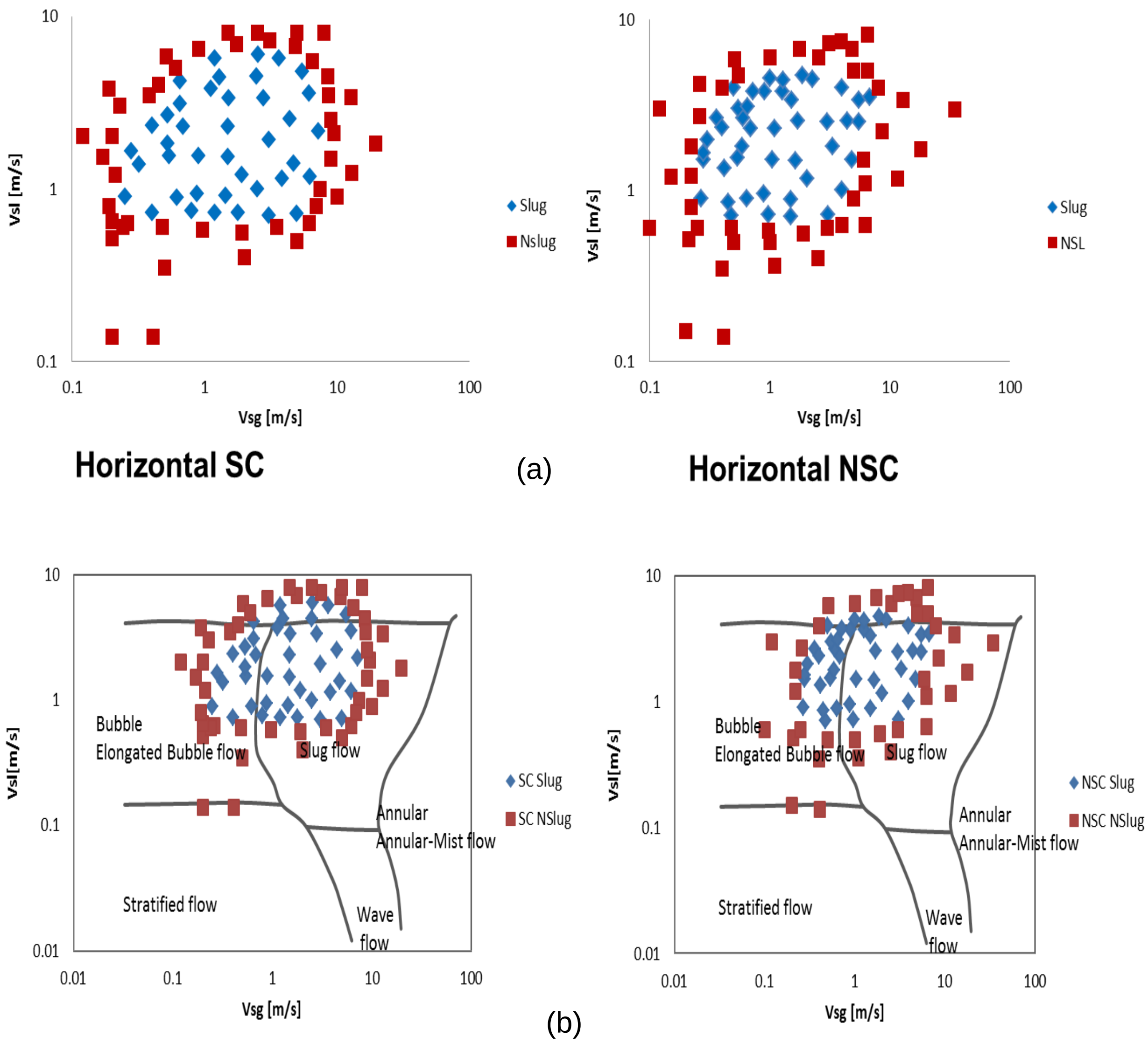


Figure 4-2 (a) LedaFlow hydrodynamic slug envelope for horizontal pipeline (b) LedaFlow prediction compared with [24]

4.2.2 Slug flow envelope for pure vertical pipe

The slug flow envelope predicted by OLGA model is shown in Figure 4-3 (a). It appears that the base of the envelope is wider and taper towards the top. This implies that in a vertical pipeline, slugs are formed at low flow rates and medium flow rates than are likely to occur at high flow rates. Though the envelope seems tilted compared to what was reported in the literatures for example Barnea [25].

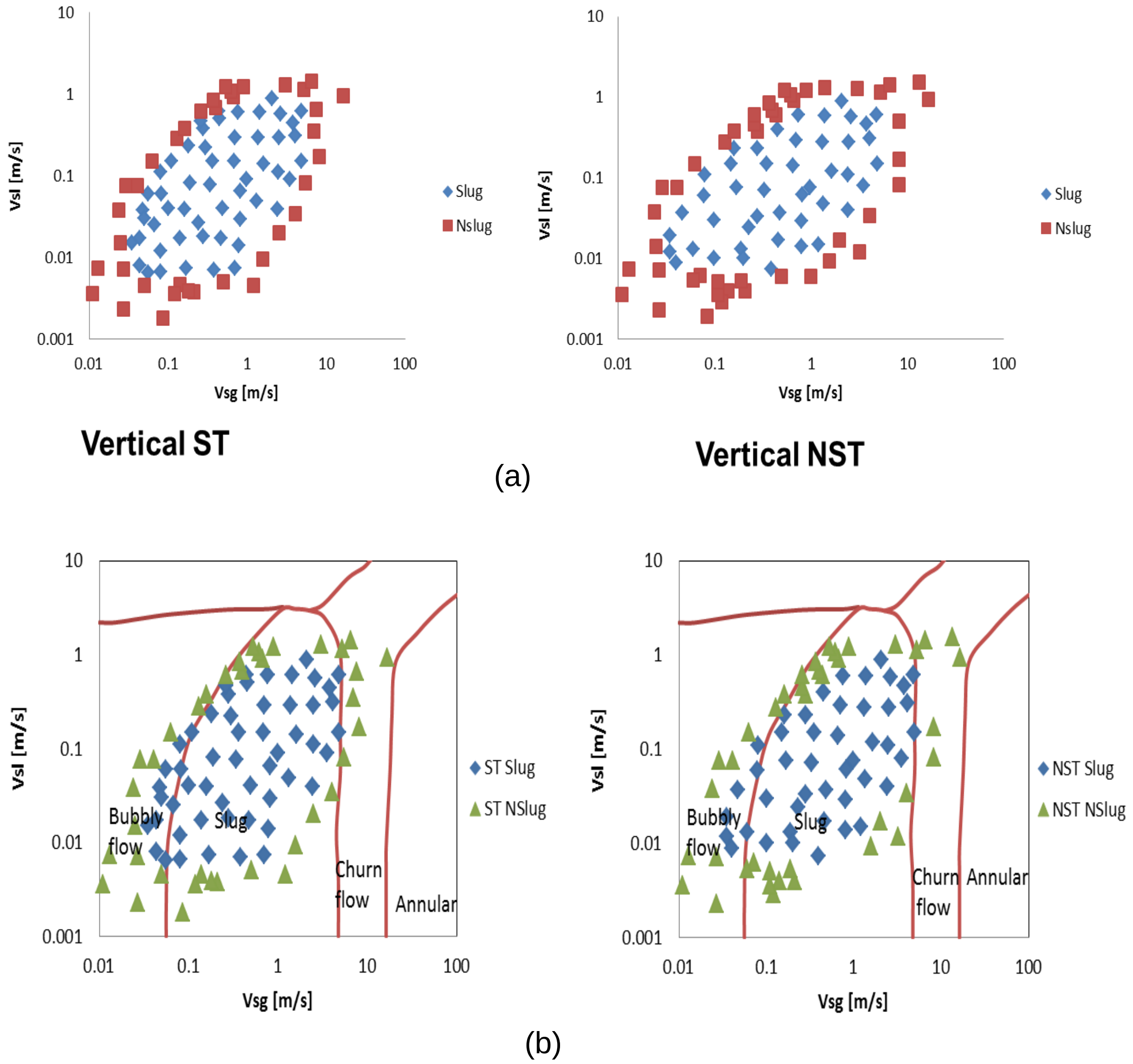


Figure 4-3 (a) OLGA slug envelope for vertical pipeline (b) OLGA prediction compared with [25]

Figure 4-3(b) shows the slug flow regime obtained from OLGA models for vertical pipe compared with Barnea [25] map. The Figure shows that considerable amount of data fall predicted by OLGA for slug fall within the slug region of [25]. However some region predicted as slug by OLGA fall within the non-slug region and vice versa. This could be as a result of the effect of the difference in pipe diameter.

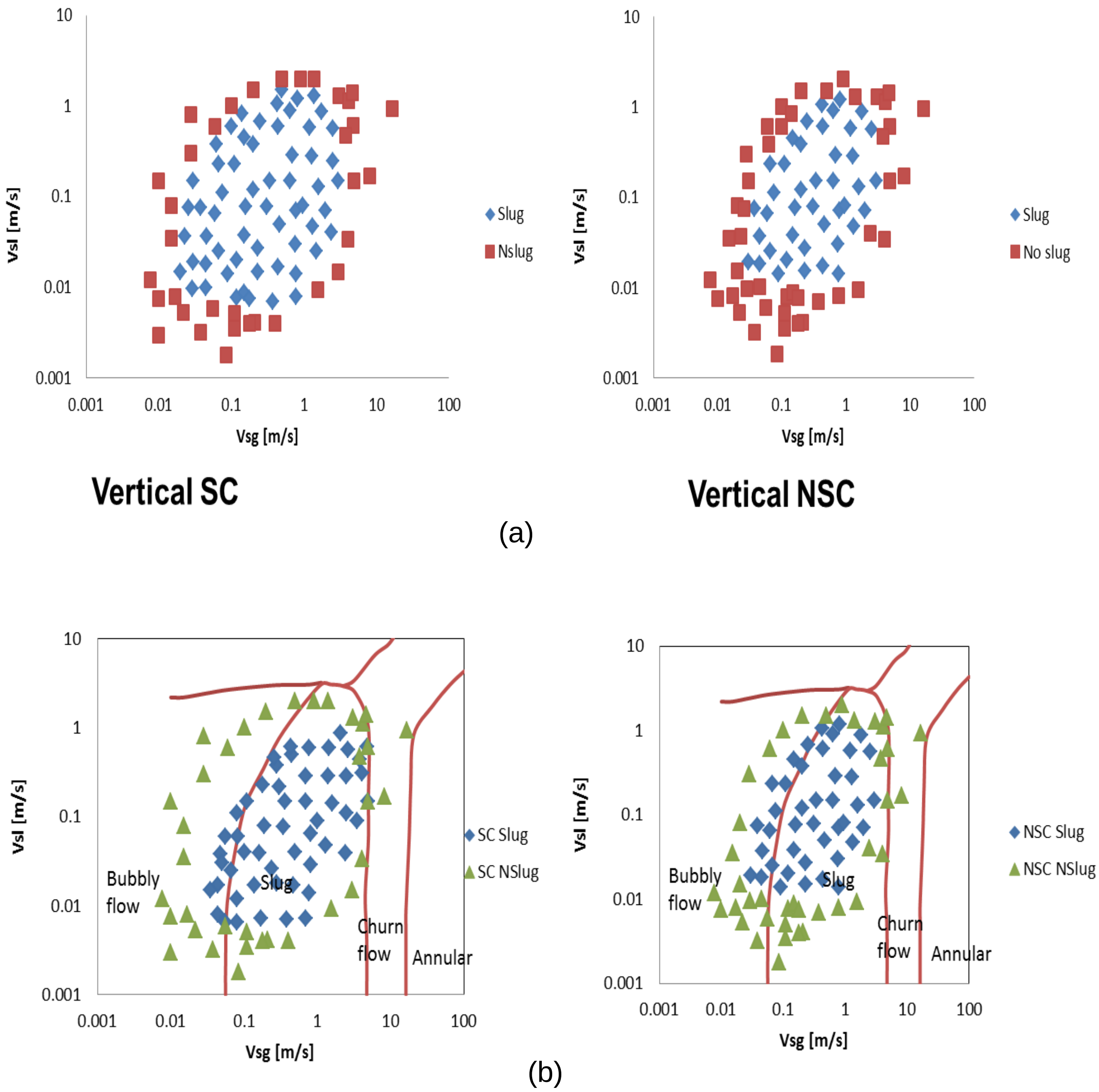


Figure 4-4 (a) LedaFlow slug envelope for vertical pipeline (b) LedaFlow prediction compared with [25]

The trend observed in Figure 4-4 (a) is similar to that observed in Figure 4-3 (a). Although the unit cell model and the slug tracking model in OLGA predict almost at the same level for the vertical pipe, in LedaFlow the unit cell model and the slug capturing predict at different levels. The region predicted by slug capturing model appears to be larger than that of unit cell model. The trend observed in Figure 4-4 (b) is also similar to that observed in Figure 4-3(b).

4.2.3 Slug flow envelope for pipeline-riser system

The pipeline-riser system described in section 3.3 was studied for hydrodynamic slugging for superficial velocities ranging from 0.01 to 44.28 m/s and 0.02 to 8.23 m/s for gas and liquid respectively. A total of 192 data points were studied. It was observed that at high flow rate the hydrodynamic slug was dominating the slugging in the pipeline-riser system. But at low flow rate the slug formation dynamics changed and the riser system dominates the slug formation mechanism. The riser slugging has been studied and reported by many authors [29; 44; 161; 162].

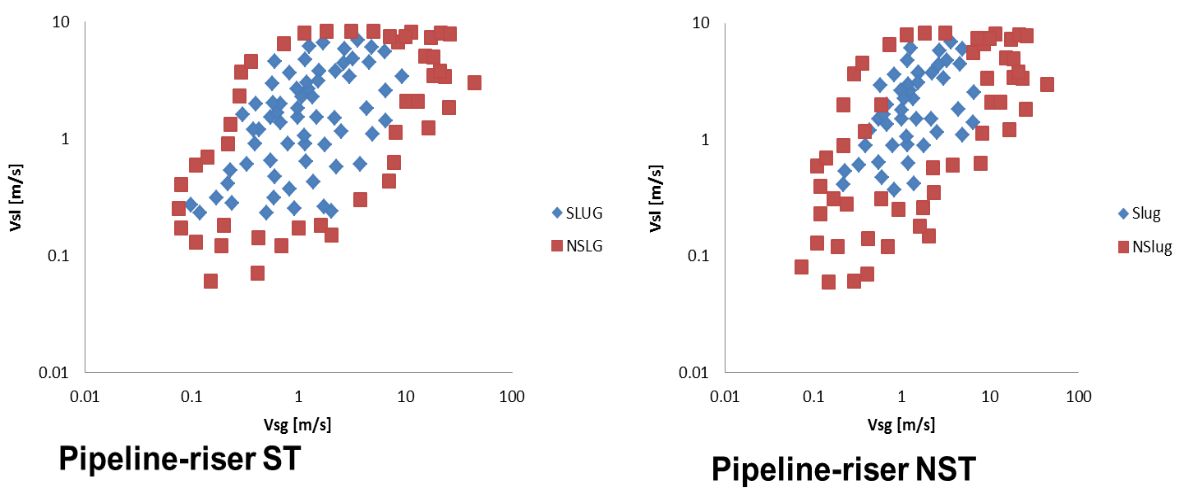


Figure 4-5 OLGA slug flow envelope for pipeline-riser system

Figure 4-5 shows the slug flow envelope developed for this pipeline riser system using OLGA. Considerable number of data points investigated fall within the slug flow regime while the rest fall within the non-slug regime.

Figure 4-6 shows the slug enveloped obtained with LedaFlow. The envelope obtained from the slug capturing model is similar to the envelope described for OLGA prediction in Figure 4-5. However it appears that for the unit cell model (NSC), slug predicted at considerable low flow rates disappeared.

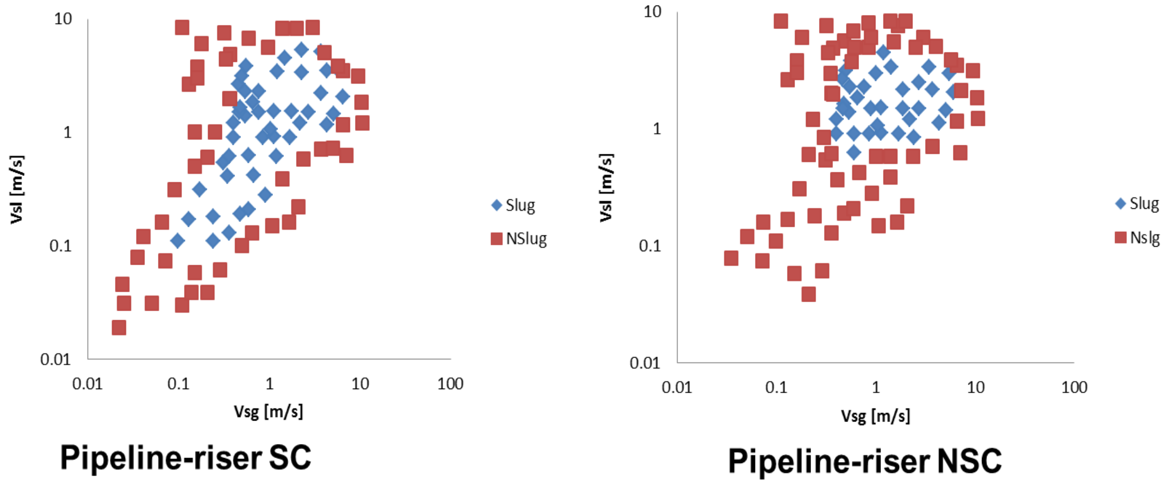


Figure 4-6 LedaFlow slug flow envelope for pipeline-riser system

4.3 **Hydrodynamic slug flow behaviour in pipeline-riser system**

This section seeks to obtain full qualitative picture of hydrodynamic slug flow behaviour in a pipeline-riser system. To achieve this, comparisons were made between the horizontal and vertical envelopes, horizontal and pipeline-riser system, vertical and pipeline-riser system and amongst all these three systems.

Figures 4-7 and 4-8 show the comparison between the horizontal and vertical slug envelopes for OLGA (ST and NST) and LedaFlow (SC and NSC) predictions respectively. It is shown that at low flow rates slug flow occurs in vertical pipes whereas relatively higher flow rate is needed to experience slug in horizontal pipe. This is in consonance with previous works for example Schmidt [40] and Schmidt et al. [30] .

The comparison of the horizontal, vertical and pipeline-riser envelopes shows that at low flow rates, the region where slugs were not experienced in horizontal pipeline suffer slugs in both vertical pipe and pipeline riser systems as can be seen in Figures 4-7, 4-8, 4-9 and 4-10. This can be traced to the fact that the mechanisms for hydrodynamic slug formation in horizontal and slug flow in vertical pipes are not same. In horizontal pipelines sufficient liquid level is needed for the interfacial waves to grow and block the pipe cross section [159; 163] whereas in vertical pipe, at low gas and liquid flow rates slug flow will occur when gas bubble usually referred to as Taylor bubble is formed and large enough to block the pipe cross section and hinder the flow of the heavier fluid (liquid slug). This usually leads to the instability in riser pipe [30] .

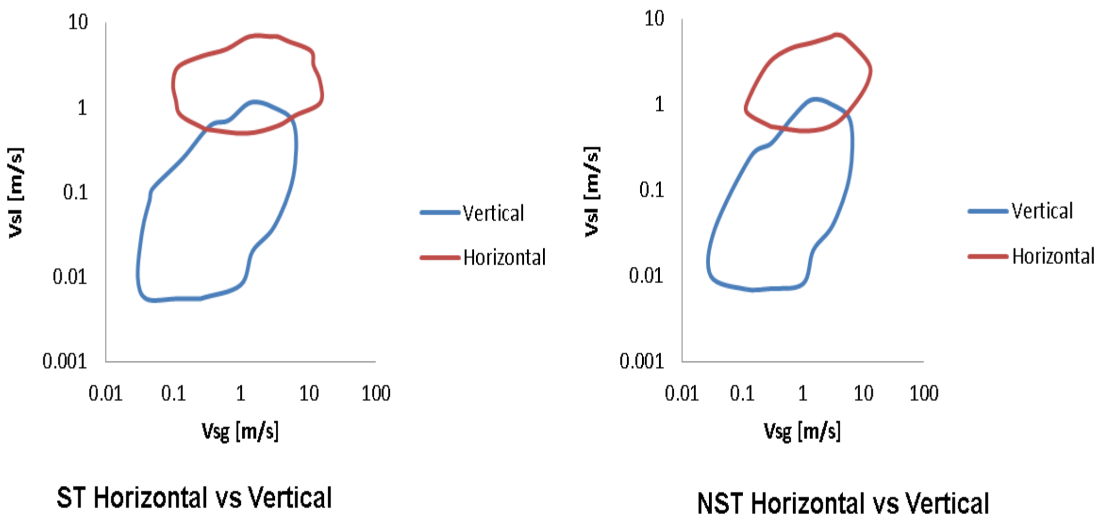
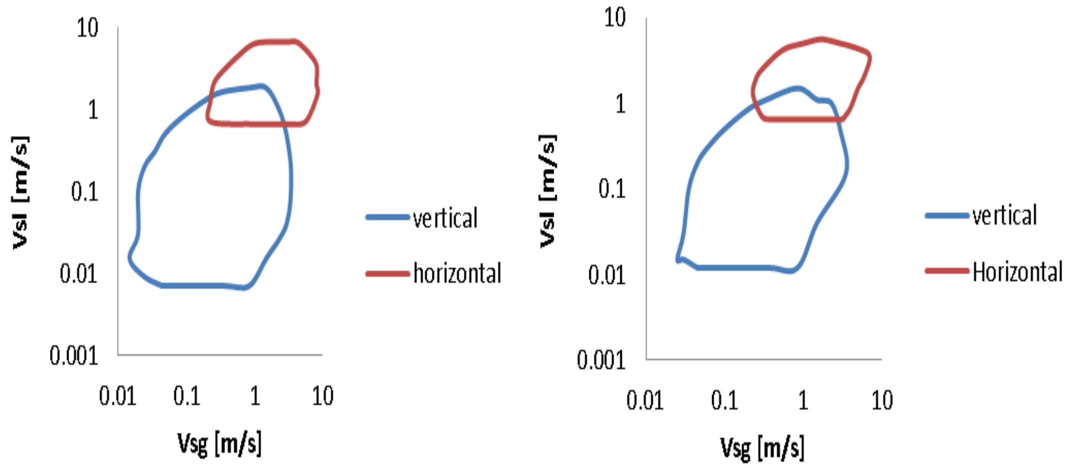


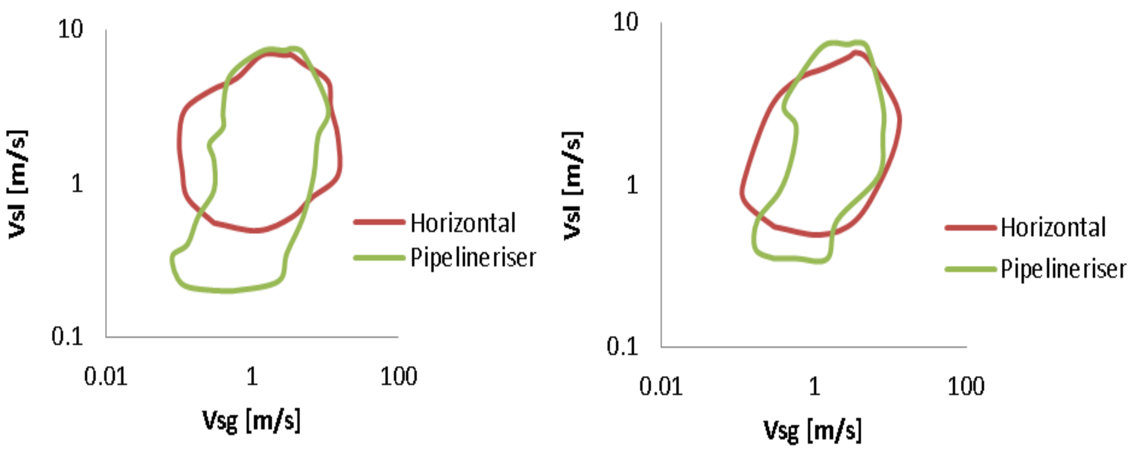
Figure 4-7 OLGA horizontal and vertical pipeline slug envelopes



SC Horizontal vs Vertical

NSC Horizontal vs Vertical

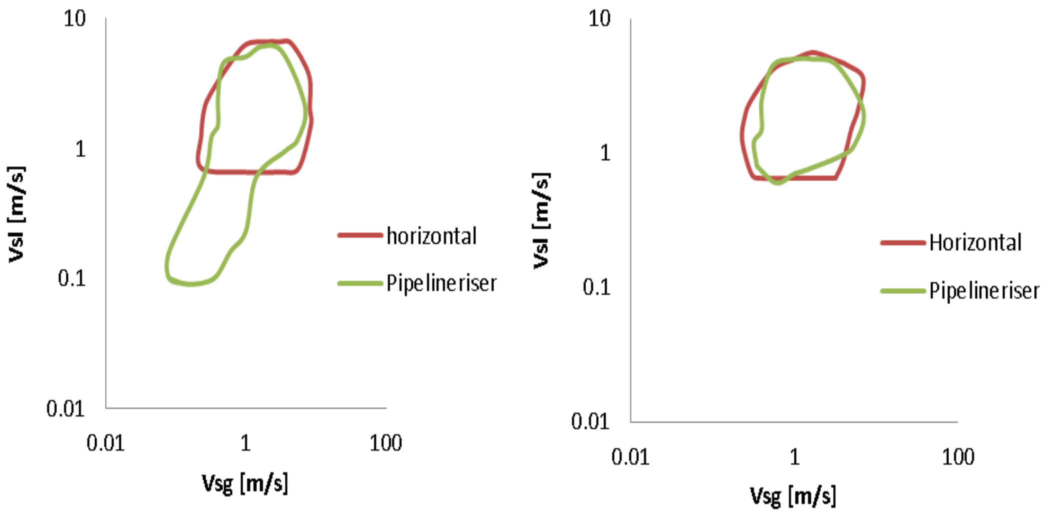
Figure 4-8 LedaFlow horizontal and vertical pipeline slug envelopes



ST Horizontal vs Pipelineriser

NST Horizontal vs Pipelineriser

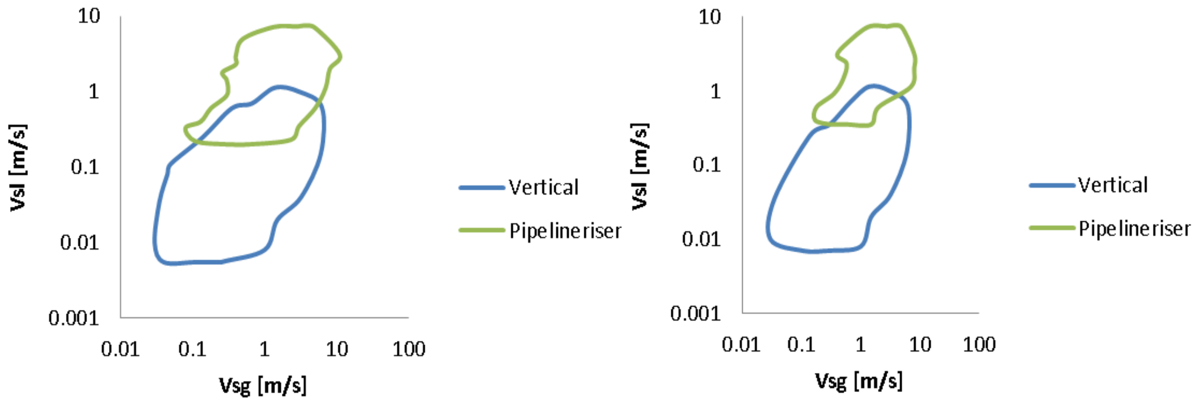
Figure 4-9 OLGA Slug envelopes for horizontal and pipeline riser system



SC Horizontal vs Pipelineriser

NSC Horizontal vs Pipeline-riser

Figure 4-10 LedaFlow Slug envelopes for horizontal and pipeline riser system



ST Vertical vs Pipelineriser

NST Vertical vs Pipelineriser

Figure 4-11 OLGA Slug flow regions for vertical and pipeline riser system

Figures 4-9 and 4-10 show the comparison between the horizontal and pipeline-riser system slug envelopes for OLGA and LedaFlow predictions respectively. It is shown that the slug occurring at high flow rates in the pipeline-riser is due to slugs in the horizontal pipeline. The slug formed in the upstream horizontal pipeline is transported through the riser pipe under the same conditions where slug is absent for the vertical pipe. This implies that at high flow rates, the slug flow rate in the vertical riser are due to the slug flow from horizontal pipe upstream the riser pipe [44].This type of behaviour was reported for a gas-liquid flow in large pipeline-riser system where the effect of upstream configurations was investigated [164].

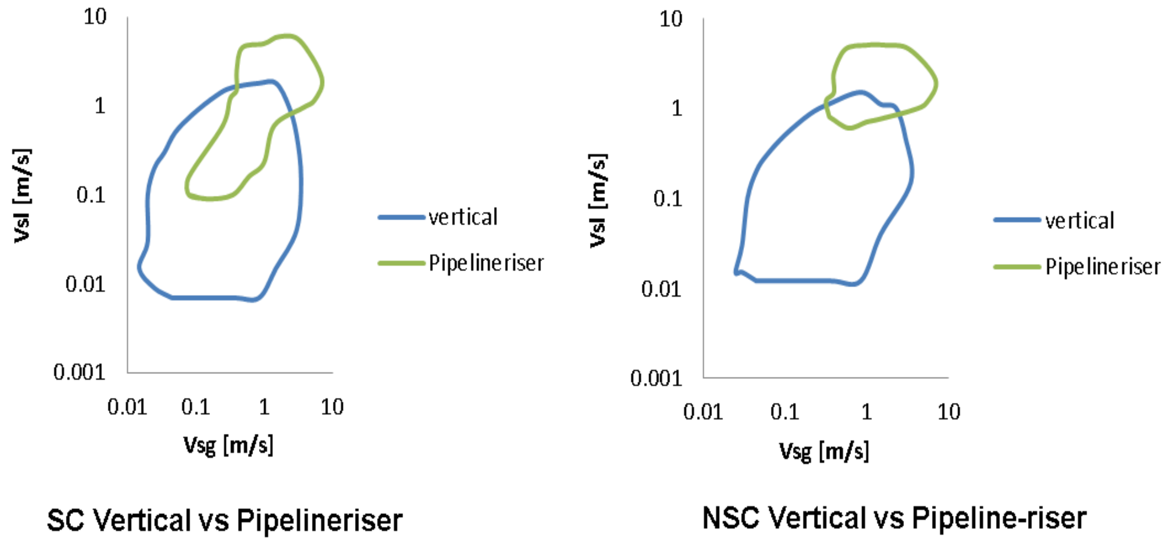


Figure 4-12 LedaFlow Slug flow regions for vertical and pipeline riser system

Figures 4-11 and 4-12 show the comparison between the vertical and pipeline-riser system slug envelopes for OLGA and LedaFlow predictions respectively. These Figures showed that, there is significant reduction in the area prone to slugging in a vertical pipe compared to the pipeline-riser system. This could be due to the interaction between the pipeline and riser. This suggests the upstream horizontal pipeline has significant effect on the slug flow in the pipeline-riser system [164].

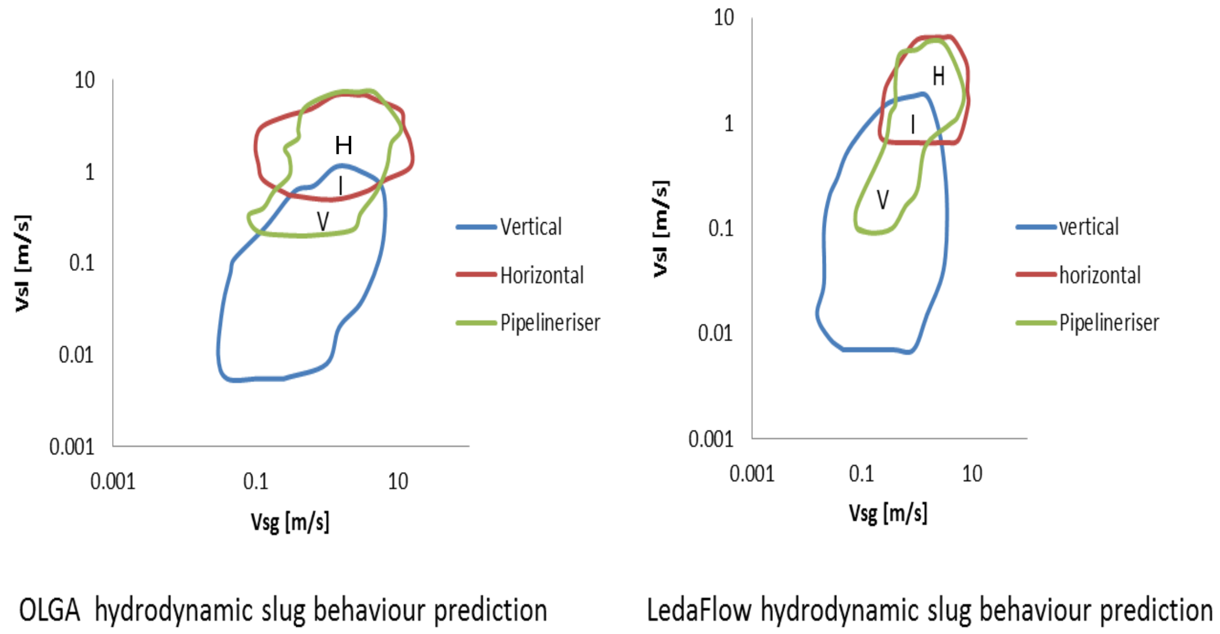


Figure 4-13 Hydrodynamic slug behaviour in pipeline-riser system

Figures 4-13 shows the combination of all the slug envelopes and a clearer picture of the hydrodynamic slug behaviour in pipeline-riser ensued. Both software tools predict three regions designated as head/horizontal (H), intersection/neck (I), and vertical/handle (V).

The region H shows the region due to hydrodynamic slugs contributed from the horizontal pipeline. This region occurs at high flow rates and could have the characteristics of typical normal slug flow.

The intersection region (I) is the area where the horizontal and vertical envelopes intersect. It appears that both hydrodynamic slugs from the horizontal and slugs in the vertical pipes contribute to the slug behaviour in this region. This region could be complex and difficult to control as there would be interplay between different mechanisms.

Region V is the portion of the envelope below both H and I. It occurs at low flow rates. This is believed to be the region influenced by the vertical section of the pipeline-riser system, though it is narrower than the original portion of the vertical slug envelope. Region V was not originally present in a pure horizontal pipeline but appears in the pipeline-riser system which shows the contribution of the vertical section to the pipeline riser slugging. This shows clearly that both the horizontal and vertical pipes which constitute a pipeline riser system mutually affect the slug behaviour. The larger part of the slug region in the pipeline-riser system seems to be due to the contribution from the horizontal pipe. Therefore the dynamics of the upstream pipeline cannot be neglected in the design of pipeline-riser system [30].

4.3.1 Hydrodynamic slug flow in H-region

From Figure 4-13, it is observed that the area designated as H region of the pipeline-riser slug envelope falls within the slug region of pure horizontal pipe. This region appears not to suffer slugging in the pure vertical region. It is therefore important to clarify if the overall dynamics of the pipeline-riser system is indeed determined by the horizontal pipe or not.

Table 4.1 Properties of case study in the H region

Total mass flow [kg/s]	600
Gas mass fraction[-]	0.01
Oil mass fraction [-]	0.239
Water mass fraction [-]	0.751
Inlet Temperature [^{0}C]	90
Outlet Temperature [^{0}C]	40
PR outlet Pressure [bar]	22.5
Horiz outlet Pressure [bar]	27.95

A representative case in this region has been studied to observe the behaviour of slug in these systems. The evolution and dissipation of slug was studied in the pure horizontal pipeline and the pipeline-riser system using this case and the property of the case are summarised in Table 4.1. This representative flow condition corresponds to 2.48m/s and 4.50 m/s superficial velocities of gas and liquid respectively.

For a pure vertical pipe, this case did not experience any slugging as can be seen in Figures 4-20 when compared with the behaviour at the riser outlet. However, both the horizontal and pipeline-riser system were observed to suffer from slugging as shown in Figures 4-15, 4-16,4-17,4-18, and 4-19.

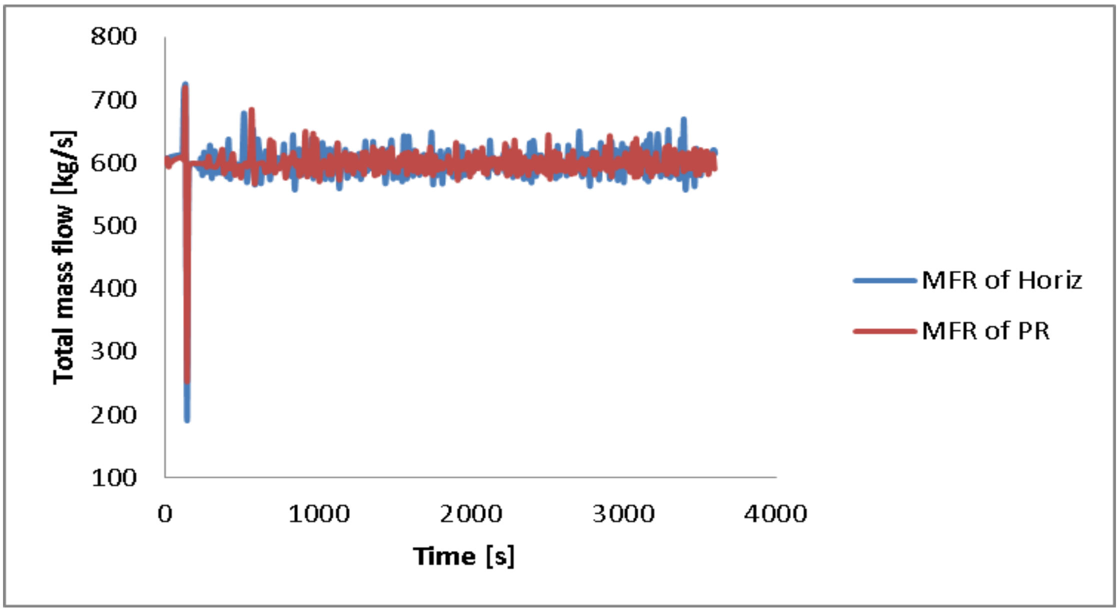


Figure 4-14 Total mass flow rate at 1 km from inlet

Figure 4-14 shows the trend plot of the total mass flow rates at 1km for pipeline-riser system (PR) and the pure horizontal pipeline (Horiz). It was observed that at 1 km from the inlet of the pipeline, the pure horizontal case has developed interfacial waves of peak in the 684 kg region. Similar waves were observed to have been formed in the pipeline-riser system. The highest peak of fluctuation recorded at this point for the pipeline-riser system was about 684kg/s apart from the initial surge which peaked at 708/s kg.

Figure 4-15 shows the trend plot of total mass flow rates of the pipeline-riser system (PR) and the pure horizontal pipeline (Horiz) at 2km from the inlet. For the pure horizontal pipeline, the waves have grown to form slugs and the flow fluctuating between 154 and 846 kg/s. Again similar trend was observed for the pipeline-riser system but with slightly lesser fluctuation around 183 and 808 kg/s.

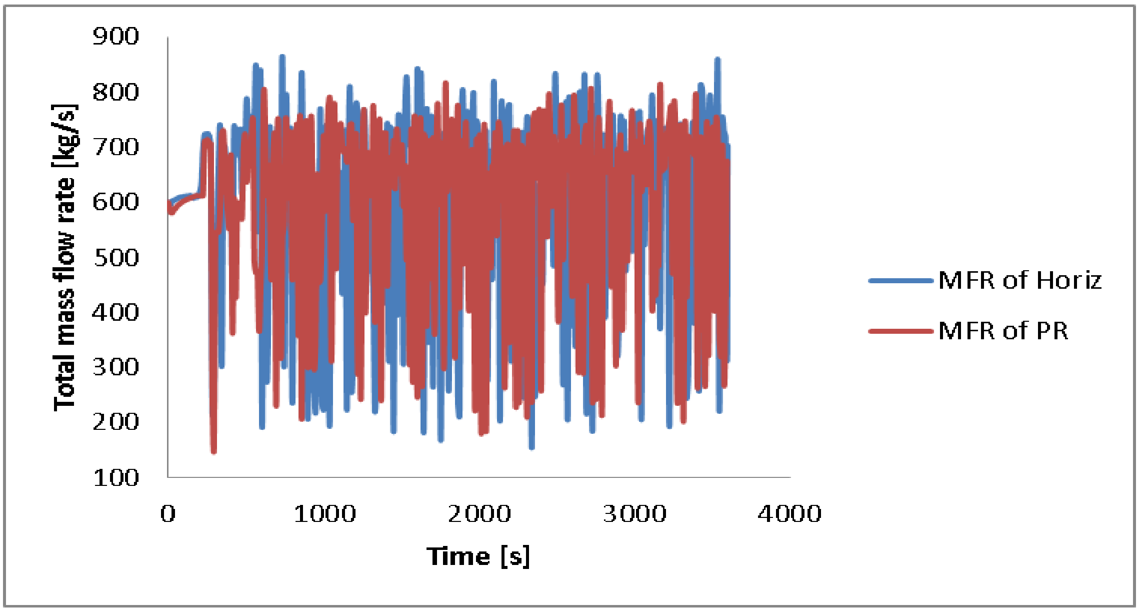


Figure 4-15 Total mass flow rate at 2km from inlet

The initiation and development of slugs have been studied previously by many authors [57; 61; 64; 159; 165]. Ujang et al. [64] for example reported that in a 37m and 0.078m internal diameter pipe, slugs were initiated in the region of 3m from the inlet and the slug further developed downstream the pipe. This is similar to the trend observed in Figures 4-15 and 4-16. Though they reported a reduction in slug frequency downstream the pipe from point of initiation, it appears that this is not the case in this study. This can be traced to the fact that there is enough liquid to enhance the slug growth and that the slug frequency has become independent of the distance from the inlet [166].

Figure 4-16 shows the trend plot of total mass flow rates of the pipeline-riser system (PR) and the pure horizontal pipeline (Horiz) at 3km from the inlet. As can be seen the slugs have further grown when compared with Figure 4-15.

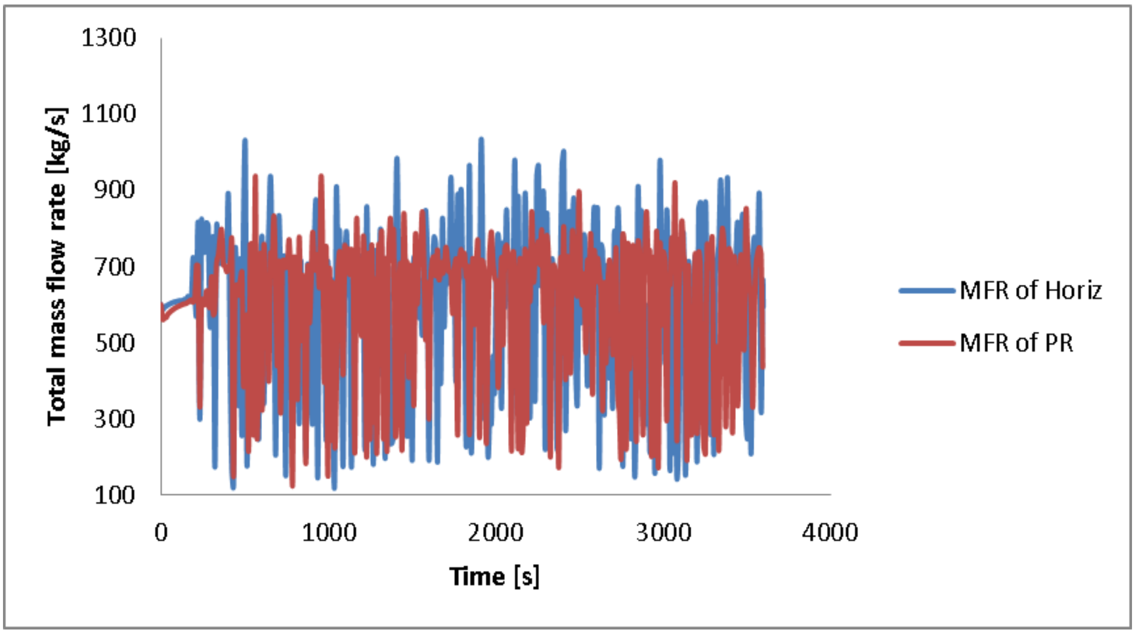


Figure 4-16 Total mass flow rate at 3km from inlet

The pure horizontal pipe has further increased in flow fluctuation ranging from 150 and 1035kg/s while those in the pipeline-riser system fluctuate between 124 and 937kg/s. Again the frequency of the slugs was not observed to change. This suggests that the liquid available in the pipelines are sufficient to offset the difference between the rate of liquid joining the slugs at the front and the rate of liquid leaving the slug at the back of the slugs [28; 43].

The constant frequency also suggests that the slug length in this region does not change. The average slug length was observed to be about 200 m which is greater than the riser height 130 m. This agrees with the observation of Brill et al. [16] who reported that hydrodynamic slug could be severe with length greater than the riser.

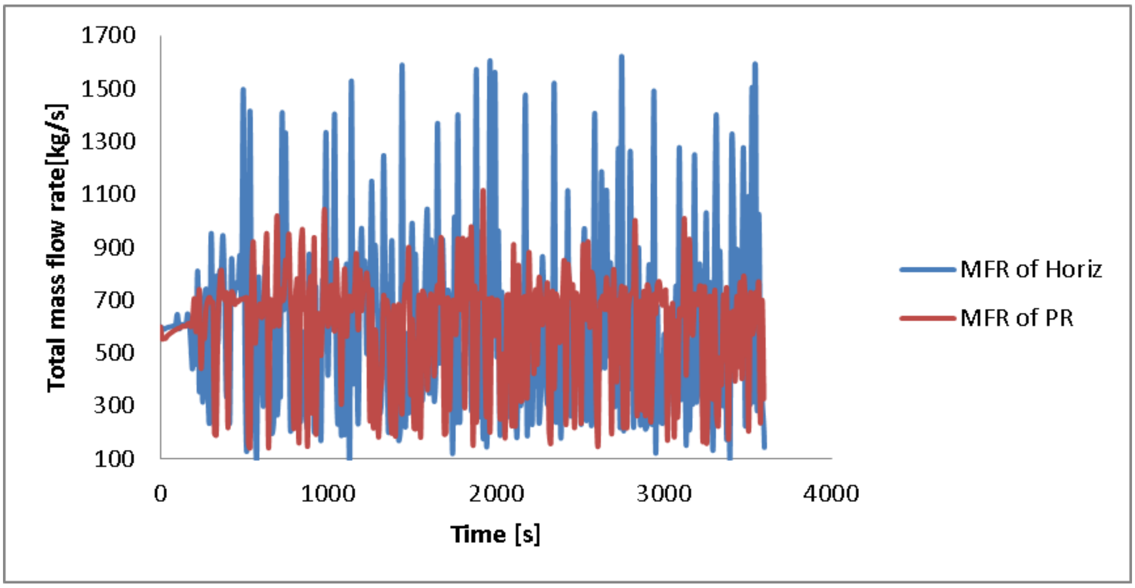


Figure 4-17 Total mass flow rate at 3.7km from inlet

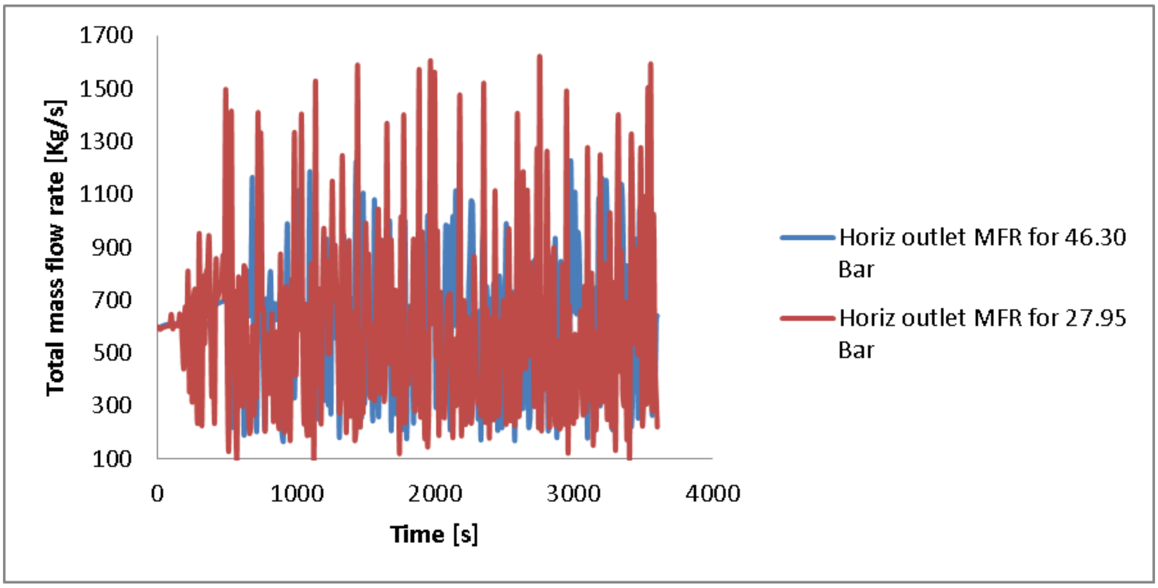


Figure 4-18 Effect of outlet Pressure condition on slug formation and behaviour

The total mass flow trend for the outlet of the pure horizontal pipeline and the riserbase of the pipeline-riser system (3.7 km from the inlet) is shown in Figure 4-17. The pure horizontal pipeline experienced serious fluctuation ranging from 128 to 1620 kg/s whereas the flow in pipeline-riser system fluctuates between

142 and 1113kg/s. This quantitative difference in the behaviour of the slug at this point can be traced to the outlet boundary condition at the pure horizontal pipe and the riser base.

A study on the effect of pressure was conducted to ascertain the reducing effect of pressure on the hydrodynamic slug. This effect is shown in Figure 4-18. The average riser base pressure for the pipeline-riser system is 46.3 bar compared to the 27.95 bar used for the pure horizontal pipeline.

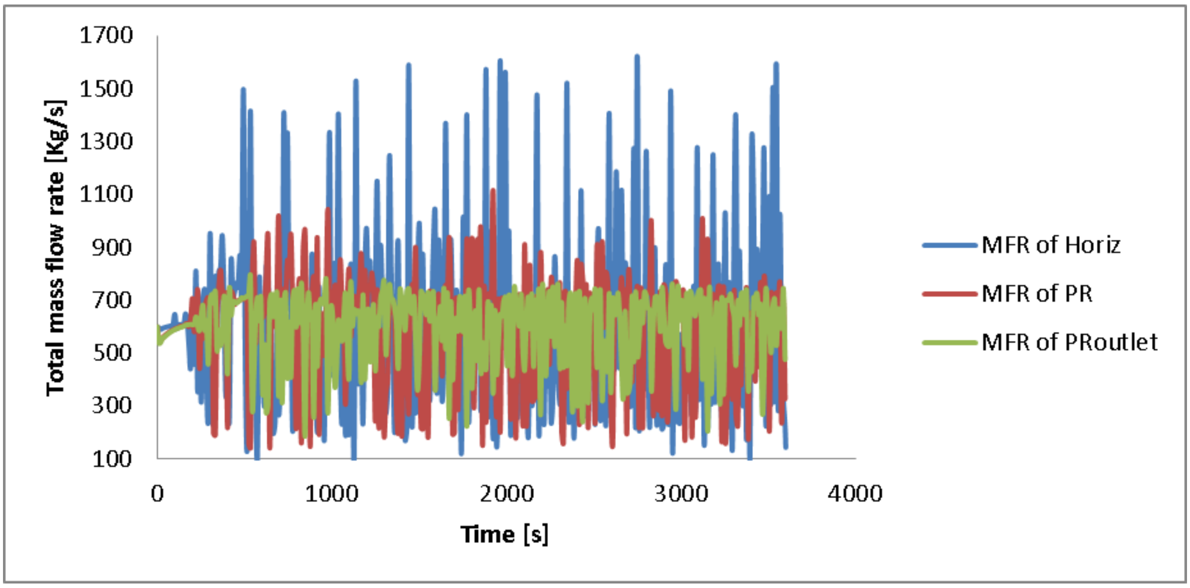


Figure 4-19 Comparison between riser outlet, riserbase and horizontal outlet total mass flow rates

When the same average riser base pressure was used for the pure horizontal pipeline, it was observed that the amplitudes of the fluctuation at lower pressure (27.95bar) are higher than that of higher pressure. It can thus be said that higher pressure inhibits the formation of hydrodynamic slugs or reduce the severity of hydrodynamic slugs. This is in consonance with the observation of Yeung et al.[167] where it was reported that increasing the back pressure can help to mitigate slugging. Schmidt et al. [44] has also reported that higher pressure serves to reduce the region of hydrodynamic slugs.

Figure 4-19 shows a comparison between the total mass flow trend plot at the riser base, riser outlet and the pure horizontal outlet. Schmidt et al. [44] reported that hydrodynamic slugs flows through the riser pipe ‘’nearly unchanged’’, a comparison of the flow fluctuations at the riserbase and the riser outlet of the pipeline-riser system shows that the riserbase flow fluctuations range between 142 and 1113kg/s whereas that of the riser outlet was between 185 and 747kg/s. Having established that the difference between the fluctuations at the riser base and the outlet of the pure horizontal pipeline can be traced to the pressure difference, similar conclusion can be drawn between the riser outlet and the pure horizontal outlet.

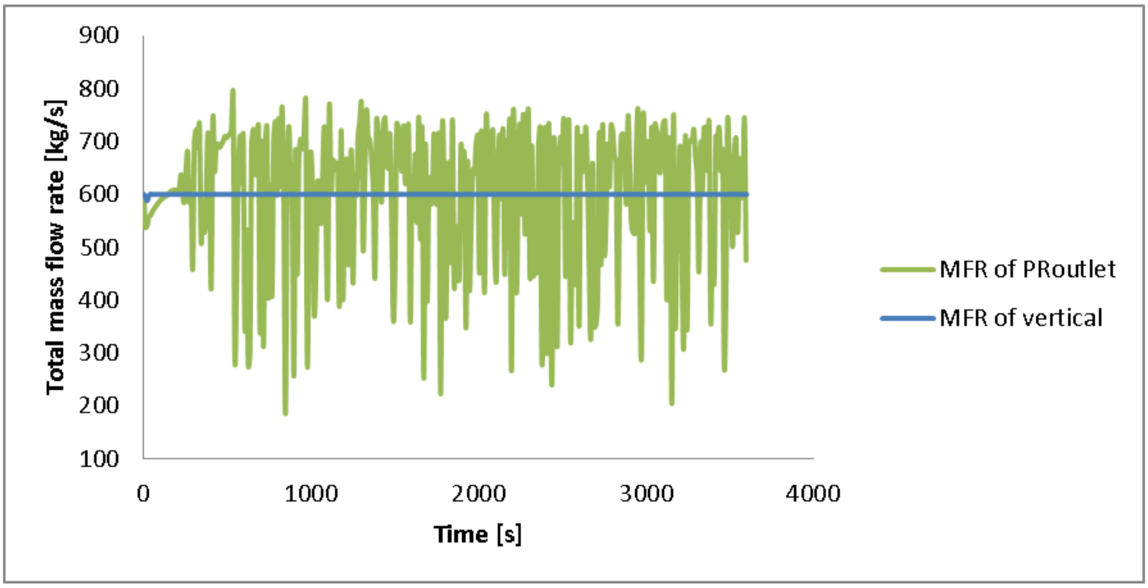


Figure 4-20 Comparison of total mass flow rate for pure vertical and pipeline-riser system

Figure 4-20 shows the riser outlet and the pure vertical total mass flow rates trend plots. It was observed that for the pure vertical pipe, there is no slugging compared with the pipeline-riser outlet which shows slugging. The difference between their behaviour can be traced to the contribution from the horizontal section of the pipeline-riser system. This is in consonance with the previous studies which reported that the slug formed in the horizontal section upstream riser pipe is responsible for the slugs observed in the riser pipe [30; 44; 164].

4.3.2 Hydrodynamic slug flow in I-region

From Figure 4-13, it is shown that the area designated as I region of the pipeline-riser slug envelope falls within the slug region of both pure horizontal pipe and vertical pipe. Again there is need to ascertain the contributions of the constituents pipes making up the pipeline-riser system. A representative case of shown in Table 4.2 which corresponds to 0.25 m/s and 0.90 m/s superficial velocities of gas and liquid respectively in this region has been studied to observe the behaviour of slug in these systems.

The evolution and dissipation of slug was studied in the pure horizontal pipeline and the pipeline-riser system using this case and the property of the case are summarised in Table 4.2.

Table 4.2 Properties of case study in the I-region

Total mass flow [kg/s]	120
Gas mass fraction[-]	0.007
Oil mass fraction [-]	0.239
Water mass fraction [-]	0.754
Inlet Temperature [^{0}C]	90
Outlet Temperature [^{0}C]	40
PR outlet Pressure [bar]	22.5
Horiz outlet Pressure [bar]	27.95
Vert outlet pressure [bar]	22.5

Figure 4-21 shows the trend plot of the total mass flow rates at 1km for pipeline-riser system (PR) and the pure horizontal pipeline (Horiz). It was observed that at 1 km from the inlet of the pipeline, the pure horizontal case has developed interfacial waves of peak in the 135 kg/s region. Similar waves were observed to have been formed in the pipeline-riser system but appear to have higher amplitude towering to over 190kg/s. This behaviour could be traced to the liquid contribution from the riser pipe.

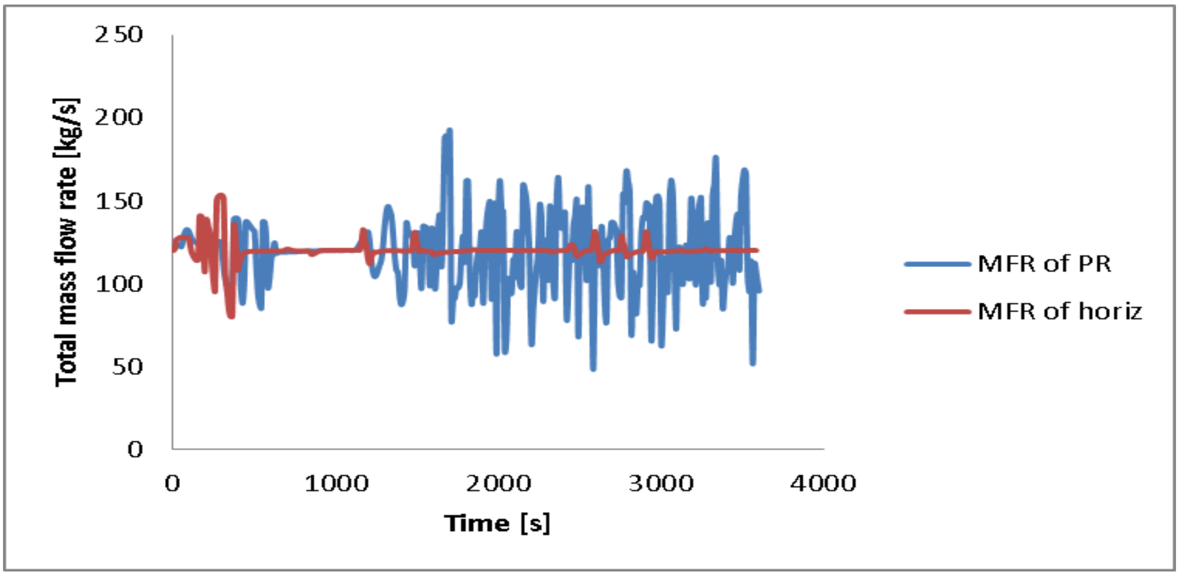


Figure 4-21 Total mass flow rate at 1 km from inlet

Figure 4-22 shows the trend plot of total mass flow rates of the pipeline-riser system (PR) and the pure horizontal pipeline (Horiz) at 2km from the inlet. For the pure horizontal pipeline, the waves have grown to form slugs and the flow fluctuating between 46 and 150 kg/s.

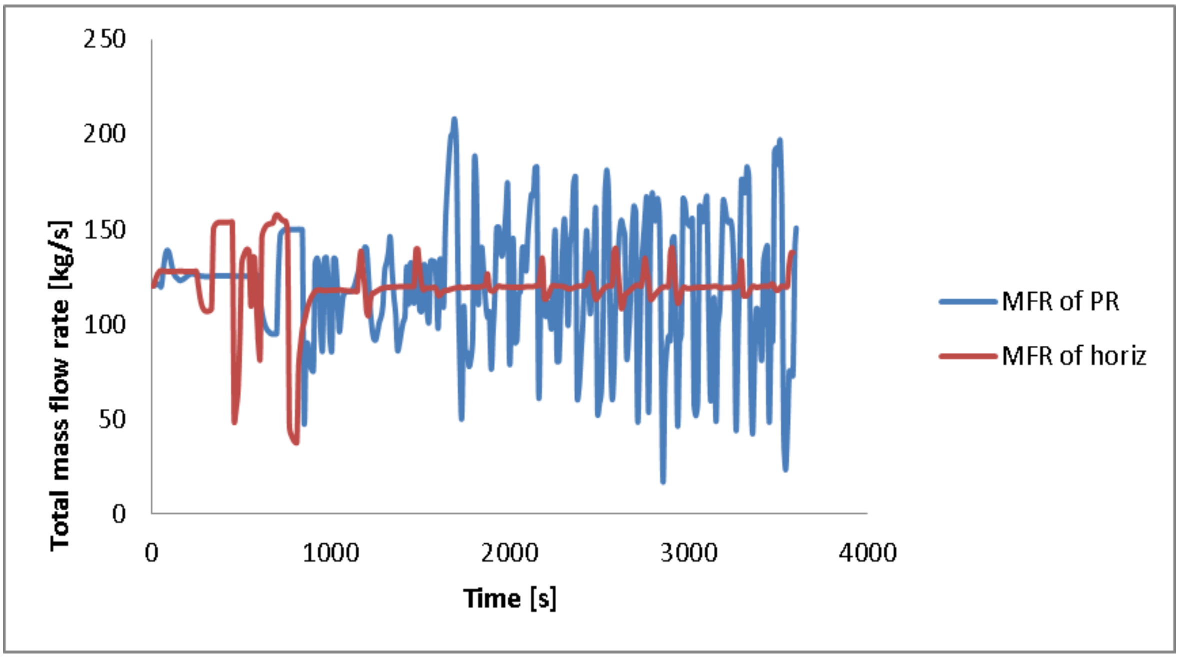


Figure 4-22 Total mass flow rate at 2km from inlet

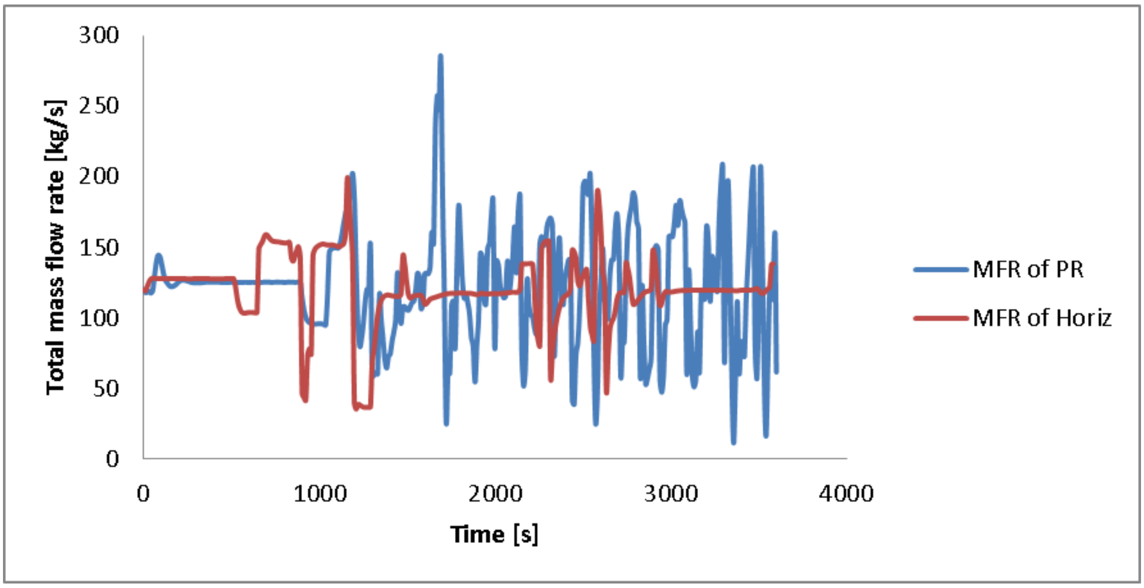


Figure 4-23 Total mass flow rate at 3km from inlet

Again similar trend was observed for the pipeline-riser system but with higher fluctuation around 17 and 208 kg/s. It appears that the frequency has also increased further. This could be traced to the fact that more liquid is available from the riser pipe due to liquid fall back. This is believed to enhance the wave growth and the initiation of more slugs as the distance towards the riserbase reduces from the inlet.

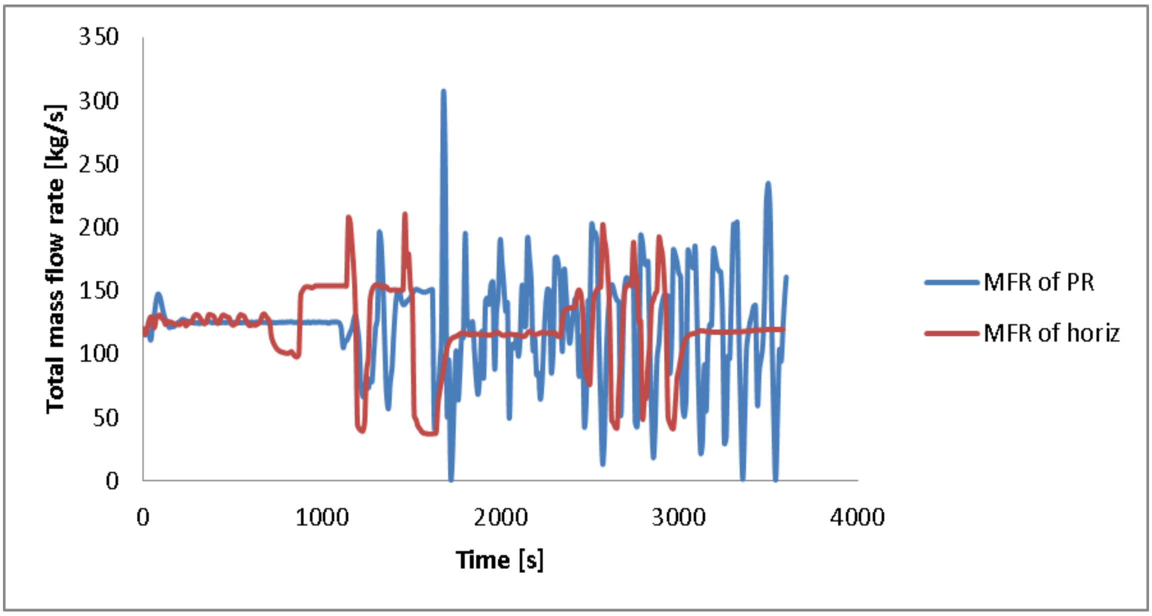


Figure 4-24 Total mass flow rate at 3.7km from inlet

Figure 4-23 shows the trend plot of total mass flow rates of the pipeline-riser system (PR) and the pure horizontal pipeline (Horiz) at 3km from the inlet. As can be seen the slugs have further grown when compared with Figure 4-22. The pure horizontal pipe has further increase in flow fluctuation ranging from 39 and 198 kg/s while those in the pipeline-riser system fluctuate between 11 and 284kg/s. However the frequency of the slugs was observed to have reduced compared with Figure 4-22. This could be due to release of some of the liquid for slug production in the riser pipe. It could also be that the slug has combined to form longer slugs [77]. The reduction in slug frequency downstream the pipe inlet has been previously reported for a 37m and 0.078m internal diameter pipe where slugs were initiated in the region of 3m from the inlet and developed further downstream with reduced frequency [64].

The total mass flow trend for the outlet of the pure horizontal pipeline and the riser base of the pipeline-riser system (3.7 km from the inlet) is shown in Figure 4-24. It appears that growth of slugs continued through the pure horizontal pipeline. The fluctuation lies within 39 and 210 kg/s range. This type of behaviour has been reported in Scott [77], and Zoeteweij [168]. Zoeteweij [168] observed that this type of slug that keeps growing till the end of the pipeline is characterised by continuous change in length and can be difficult to predict and control. However this view was not substantiated with any control study.

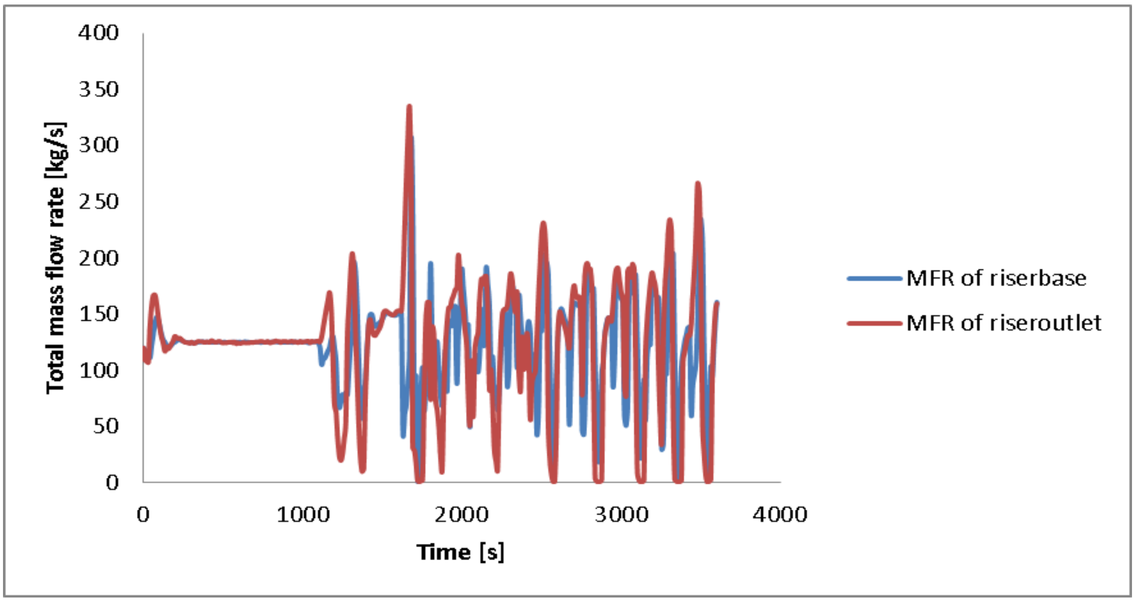


Figure 4-25 Comparison between riser outlet and riser base total mass flow rates

Figure 4-25 shows a comparison between the total mass flow trend plot at the riser base and riser outlet. Again it appears there is growth in the amplitude of the fluctuation from 1.35 to 334kg/s compared with 3 and 304kg/s at the riserbase. This shows again the contribution from the vertical riser pipe. From Figure 4-26, it is shown that apart from the initial surge which towered at 160kg/s, the pure vertical pipe suffered a continuous fluctuation in flow between 109 and 133kg/s. It can therefore be said concerning I- region that both the vertical pipe, and horizontal pipeline constituting the pipeline-riser systems suffer slugging and contribute to the overall slug behaviour of the slug flow in the system. Also the slug formed in this region keeps growing throughout the pipeline-riser system. The slug length was observed to grow from 5D to 949D. An average slug length of about 205 m was also observed and up to 409.6 m long slug was observed at the outlet. This is far greater than the riser height.

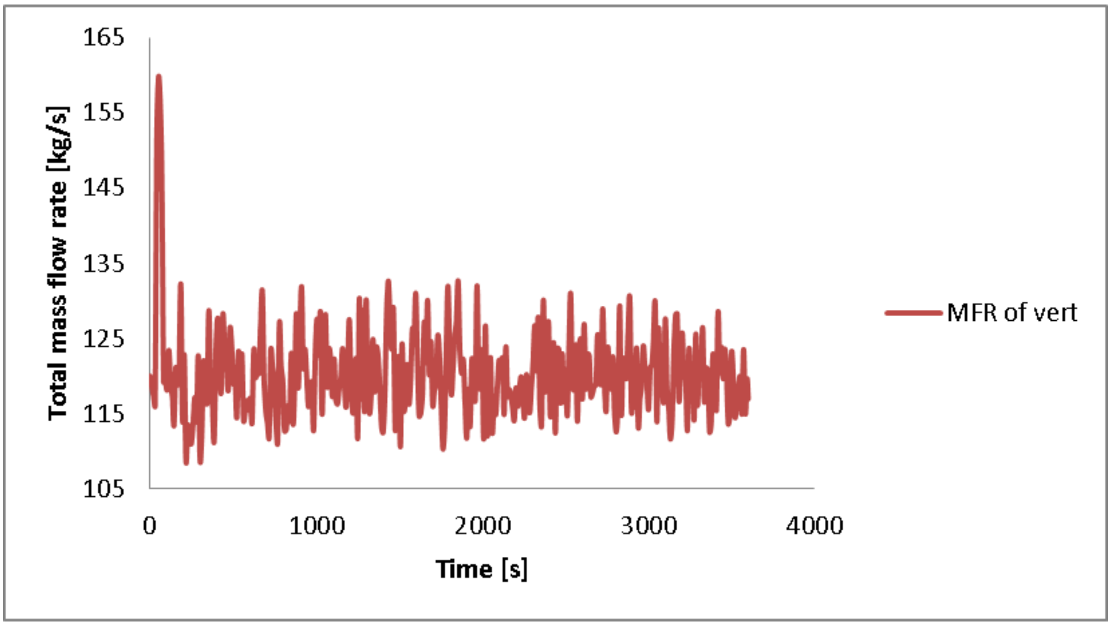


Figure 4-26 Total mass flow at the pure vertical pipe outlet

4.3.3 Hydrodynamic slug flow in V-region

From Figure 4-13, it is observed that the area designated as V region of the pipeline-riser slug envelope falls within the slug region of pure vertical pipe. This region is without slug in the pure horizontal envelope. A further investigation was conducted to determine the effect of geometry interaction on slug flow behaviour in this region. The evolution and dissipation of slug was studied in the pure horizontal pipeline and the pipeline-riser system using this case and the property of the case are summarised in Table 4.3. The representative flow condition investigated was equivalent to 0.2 m/s and 0.14 m/s superficial velocities of gas and liquid respectively.

For a pure horizontal case, this case did not experience any slugging as can be seen in Figures 4-27, 4-28, 4-30 and 4-31. However, both the vertical and pipeline-riser system were observed to suffer from slugging.

Table 4.3 Properties of case study in the V-region

Total mass flow [kg/s]	19
Gas mass fraction[-]	0.04
Oil mass fraction [-]	0.239
Water mass fraction [-]	0.721
Inlet Temperature [^{0}C]	90
Outlet Temperature [^{0}C]	40
PR outlet Pressure [bar]	22.5
Horiz outlet Pressure [bar]	27.95

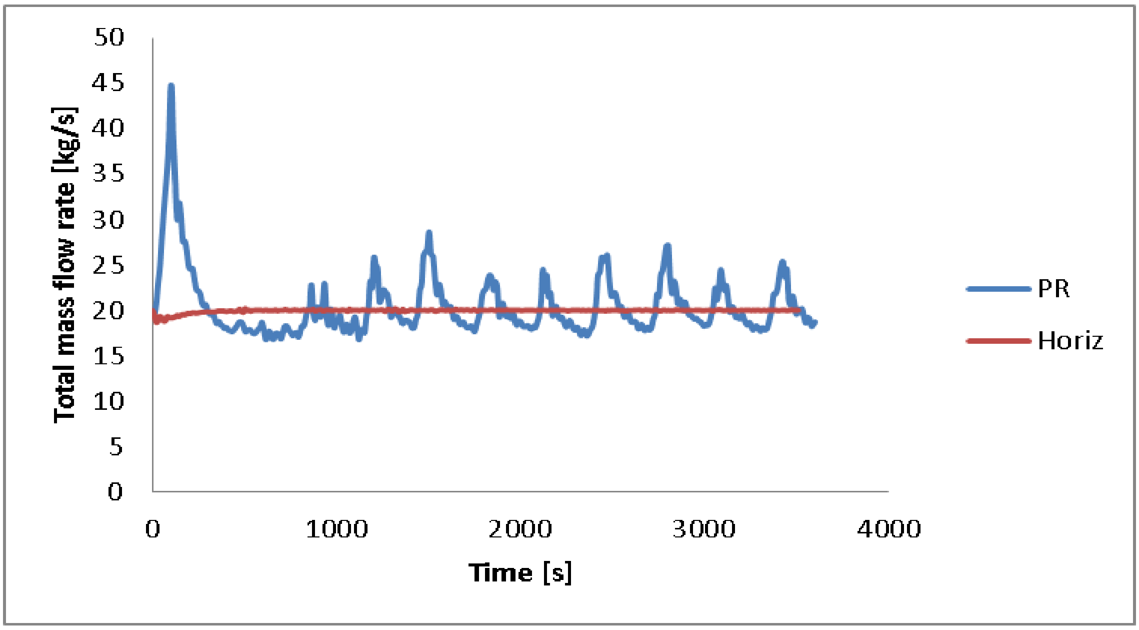


Figure 4-27 Total mass flow rate at 1 km from inlet

Figure 4-27 shows the trend plot of the total mass flow rates at 1km for pipeline-riser system (PR) and the pure horizontal pipeline (Horiz). It was observed that at 1 km from the inlet of the pipeline, the pure horizontal case remains stable at 19 kg/s and without any slug precursor or waves. However for the pipeline-riser system, slug precursors were observed. This can be as a result of liquid fall back from the riser pipe which provides sufficient liquid in the pipeline for slug formation [29; 44]. The highest peak of fluctuation recorded at this point for the pipeline-riser system was about 28kg/s apart from the initial surge which peaked at 45 kg/s.

Figure 4-28 shows the trend plot of total mass flow rates of the pipeline-riser system (PR) and the pure horizontal pipeline at 2km from the inlet. Again for the pure horizontal pipeline, the flow is stable at 19 kg/s without any slug precursor or waves. However the waves observed at 1km for the pipeline-riser system has grown further with the first surge peaking at about 89kg/s and the regular slug precursor at about 38kg/s.

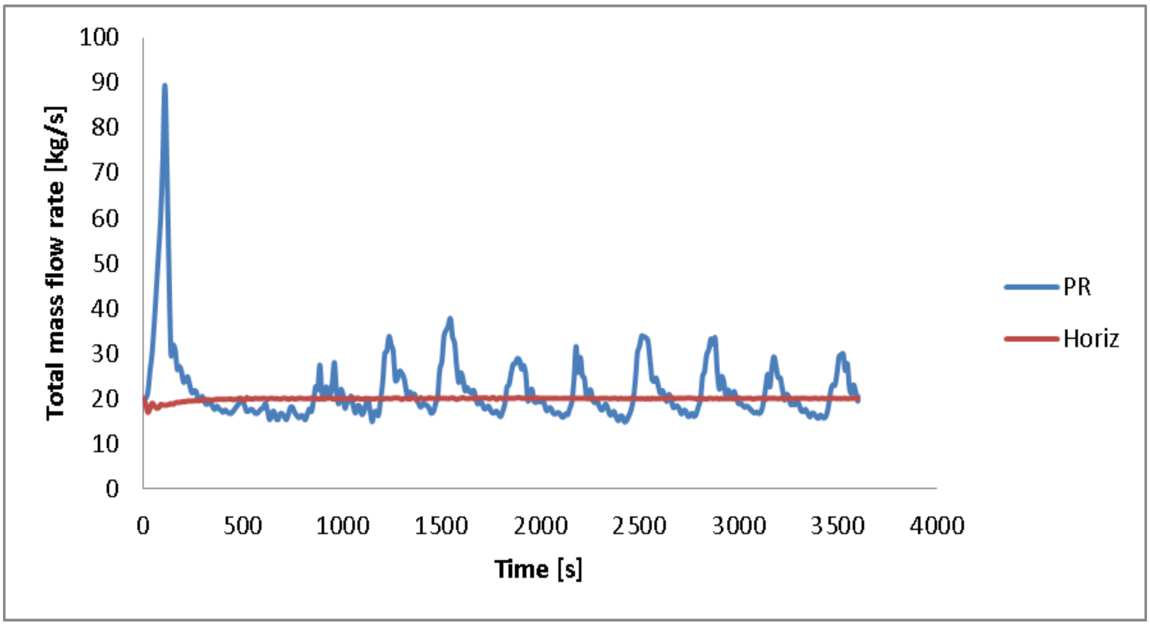


Figure 4-28 Total mass flow rate at 2km from inlet

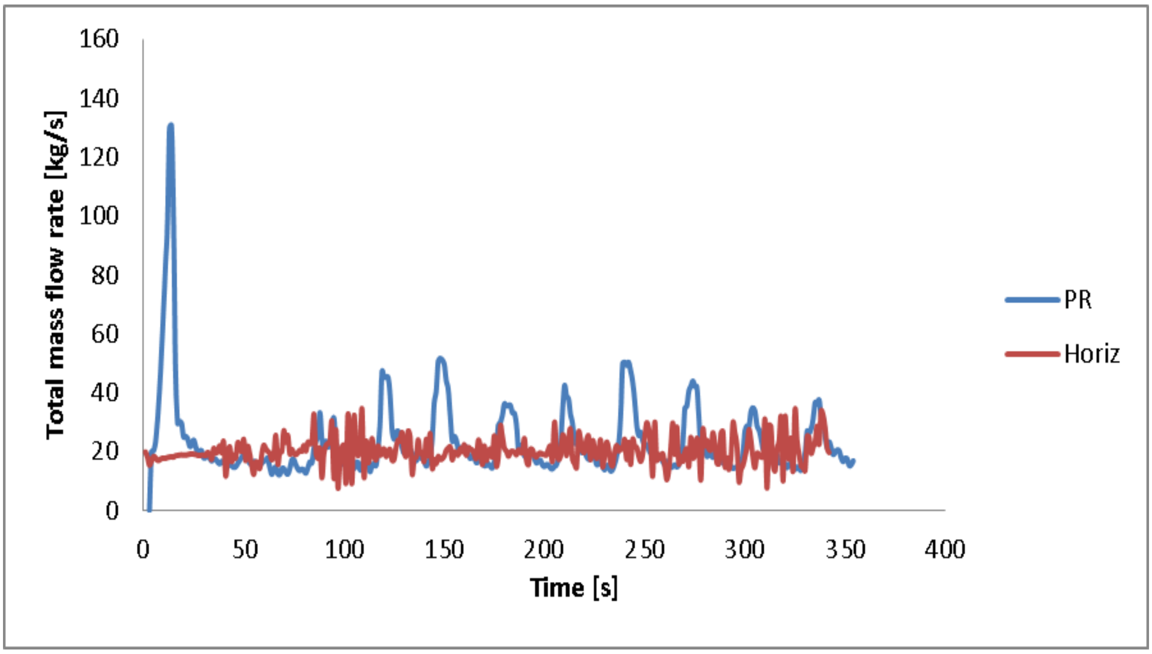


Figure 4-29 Total mass flow rate at 3km from inlet

Figure 4-29 shows the trend plot of total mass flow rates of the pipeline-riser system (PR) and the pure horizontal pipeline (Horiz) at 3km from the inlet. As can be seen the frequency of the slug precursors observed in the pipeline-riser system remain the same while the fluctuation in the total mass flow rate has moved further north. The first surge has now reached about 130 kg/s and the regular slugs peaked at about 50kg/s. Interestingly it was observed that the horizontal pipeline experienced some waves at the interface at this point. However this interfacial waves dissipated before the outlet as can be seen in Figure 4-30. This could be because the available liquid height in the pipeline is not high enough to bridge the pipe for slug formation [169; 170]

The total mass flow trend for the outlet of the pure horizontal pipeline and the riserbase of the pipeline-riser system (3.7 km from the inlet) is shown in Figure 4-30. The pure horizontal pipeline experienced no slug at the outlet whereas at the riser base of the pipeline severe slugging was observed. This can be traced to the combination of the growth of the slug precursors transported from the horizontal part of the pipeline-riser system and the liquid fall back from the riser pipe. Slug growth was observed along the riser pipe. This is evident in the increase in the amplitudes of the fluctuation. The additional growth could be as a result of liquid fall back from the riser pipe and the inability of the incoming input mass flow rate to overcome the hydrostatic head in the riser. This shows a clear contribution from the riser pipe to the slug formation in the pipeline-riser system.

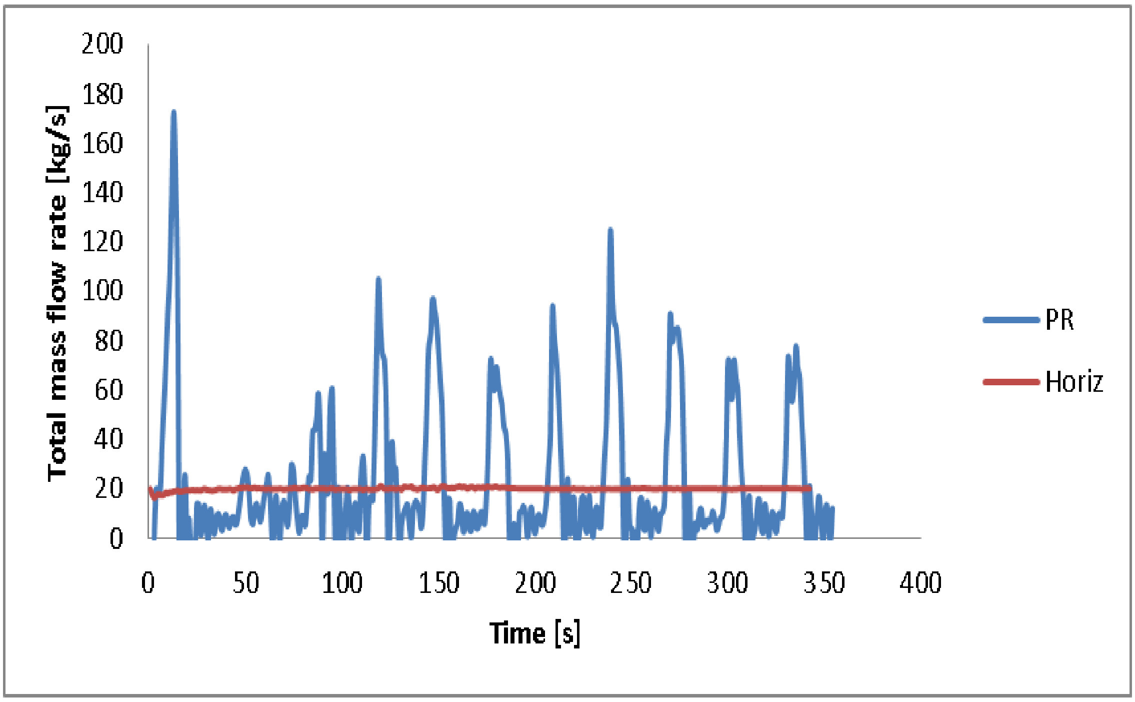


Figure 4-30 Total mass flow rate at 3.7km from inlet

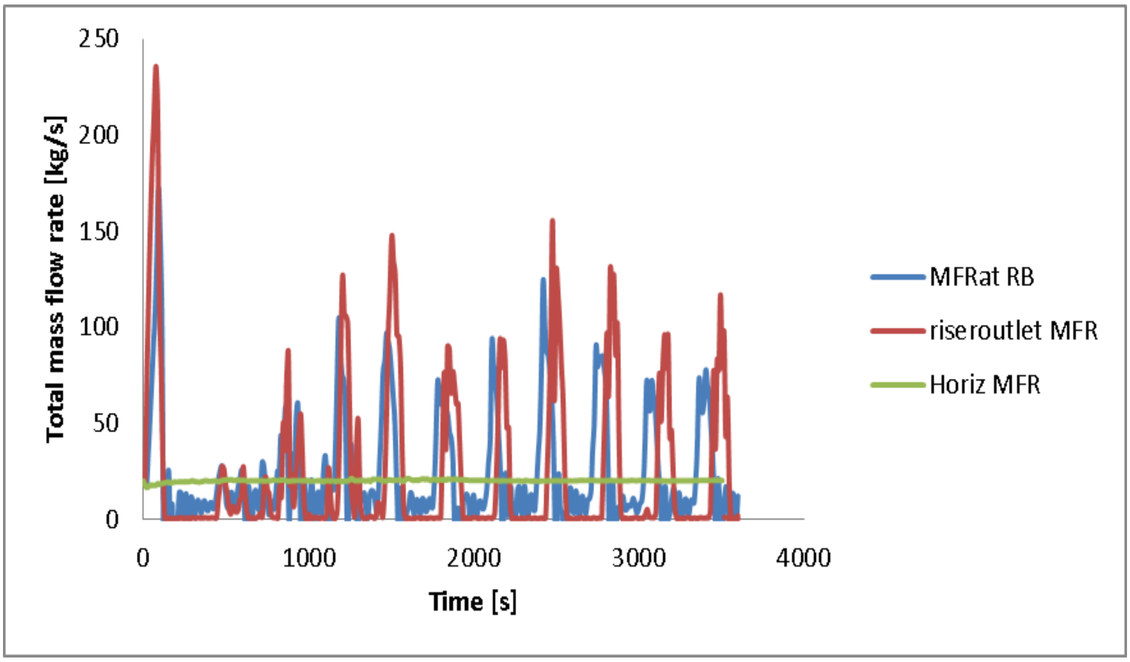


Figure 4-31 Comparison between riseroutlet, riserbase and horizontal outlet total mass flow rates

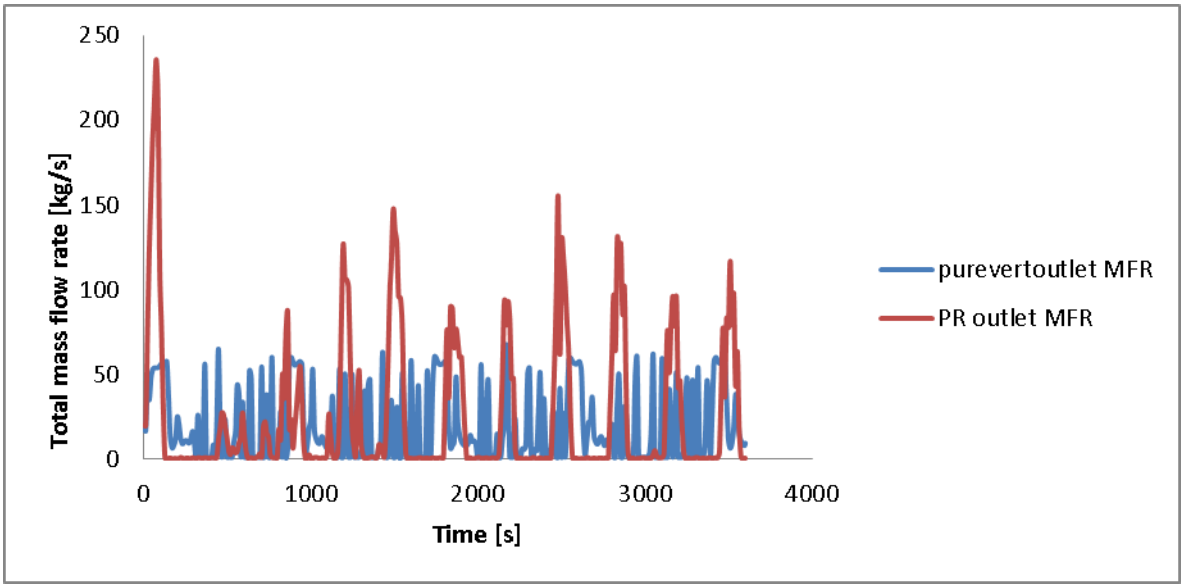


Figure 4-32 Comparison of total mass flow rate for pure vertical and pipeline-riser system

Figure 4-32 shows the riser outlet and the pure vertical total mass flow rates trend plots. It was observed that for the pure vertical pipe, there is slugging of lesser amplitude compared with the pipeline-riser outlet. The difference between their behaviour can be traced to the contribution from the pipeline-riser system configuration.

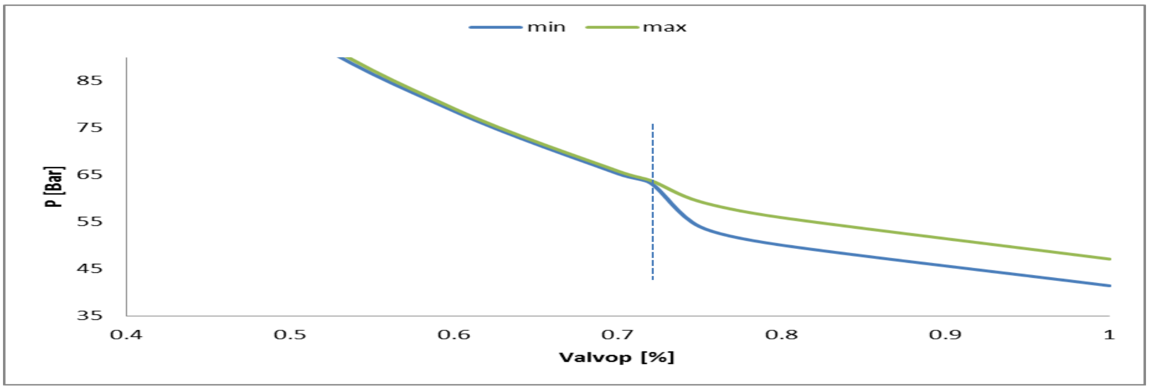
The pipeline-riser however experienced slugging of higher amplitudes. It appears then that the slugging dynamics in the pipeline-riser system is not just as a result of the individual pipelines that constitute it but could be due to some kind of complex mutual coupling effects between them. Since the pure horizontal pipeline suffers no slugging under the same condition which the vertical pipe and the pipeline-riser system experienced slugging. It could be said that for a pipeline-riser system, both horizontal and the vertical sections contribute to the overall dynamics.

4.4 Stabilization of hydrodynamic slug flow in pipeline-riser system using choking method

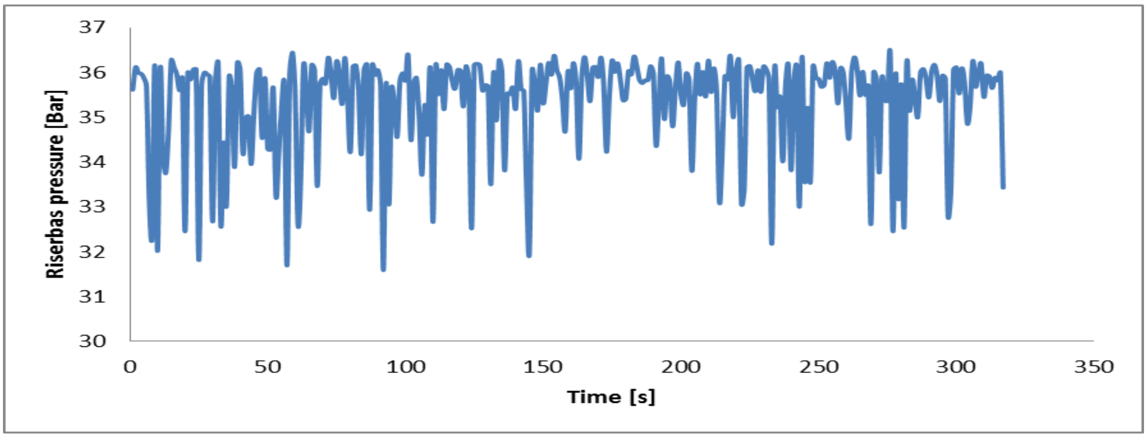
Hydrodynamic slugs have been extensively studied in the previous sections and various types identified. In section 4.3.1 it was reported that increase in the downstream pressure can inhibit the formation of hydrodynamic slug or attenuate it. In this section, this concept is further investigated for each of the representative flow condition in the regions. The risertop choke valve was used to generate the pressure increase. This method has been extensively used in the oil and gas industry to eliminate severe slug. The hydrodynamic slug mitigation potential of this traditional method is investigated. Bifurcation maps are generated for the representative slug flow conditions in these regions to further understand the behaviour of these slug types.

4.4.1 Bifurcation map for H-region

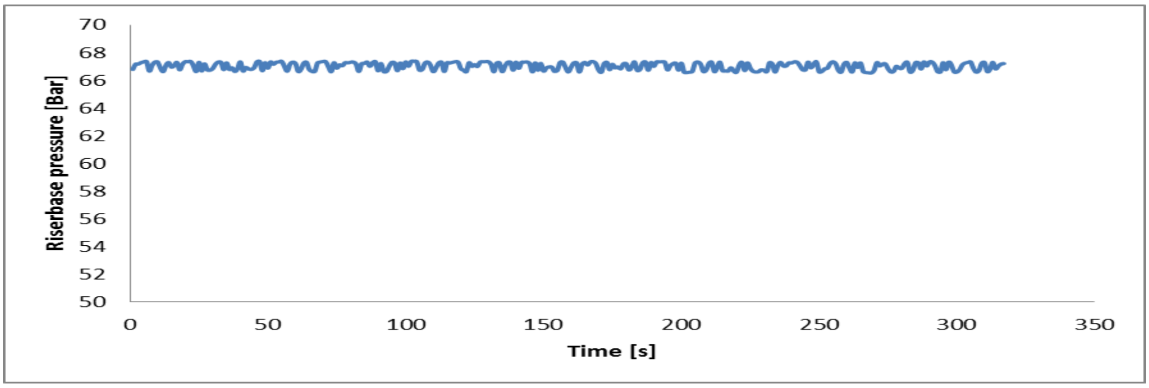
Figure 4.33 (a) shows the riserbase pressure bifurcation map of the industrial pipeline-riser system described in section 3.3. The flow and boundary condition for the representative flow condition is shown in Table 4.1 in section 4.3.1.



(a)



(b)



(c)

Figure 4-33 H-region riserbase pressure (a) bifurcation map of pipeline-riser (b) Riserbase pressure trend plot at 100% valve opening (c) Riserbase pressure trend plot at 60% valve opening

The blue dotted line runs through the bifurcation point which is 72% valve opening and at 63.85 bar. The right hand plane of the line is the unstable region while the left hand plane is the stable region. Figures 4-33 (b) and (c) show the riserbase pressure trend plot at 100% and 60% valve opening respectively. It is shown that at 100% valve opening the system is unstable but at 60% valve opening the valve has supplied sufficient back pressure to stabilise the unstable flow.

4.4.2 Bifurcation map for I-region

The riserbase pressure bifurcation map of the case described in Table 4.2 is shown in Figure 4.34. The stable and unstable region is divided using a dotted blue line and the fluctuation in the unstable region is enclosed by the blue and green lines. The green line connects the maximum pressures as the valve openings are varied while the blue line represents the corresponding minimum pressures. The bifurcation occurs at valve opening of 20% and 45.71 Bar.

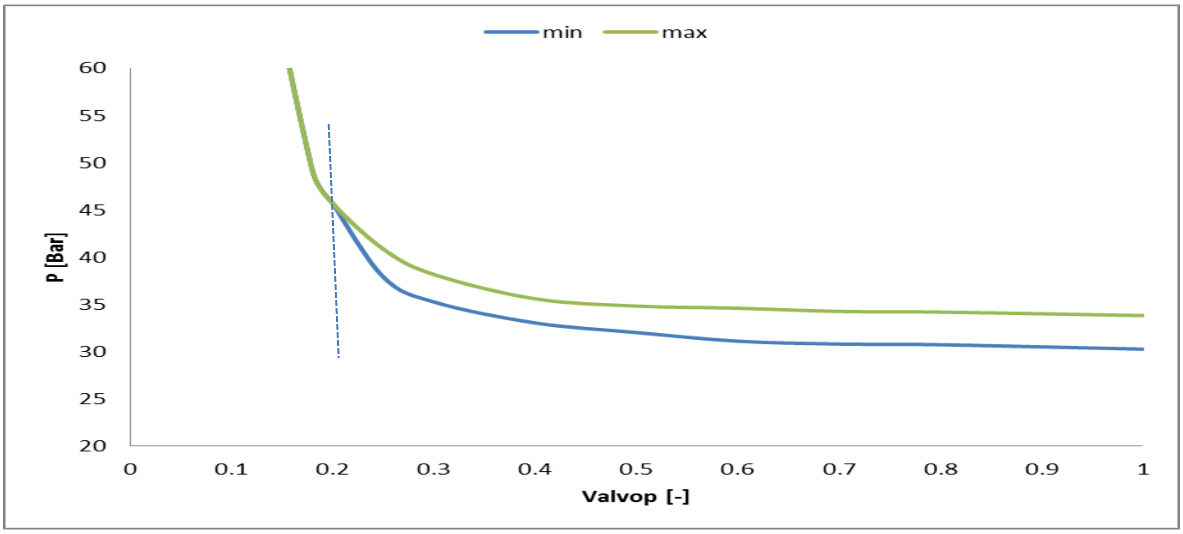


Figure 4-34 Riserbase Pressure bifurcation map of pipeline-riser system in the I-region

4.4.3 Bifurcation map for V-region

Figure 4.35 shows the riserbase bifurcation map of the pipeline-riser system in the V-region.

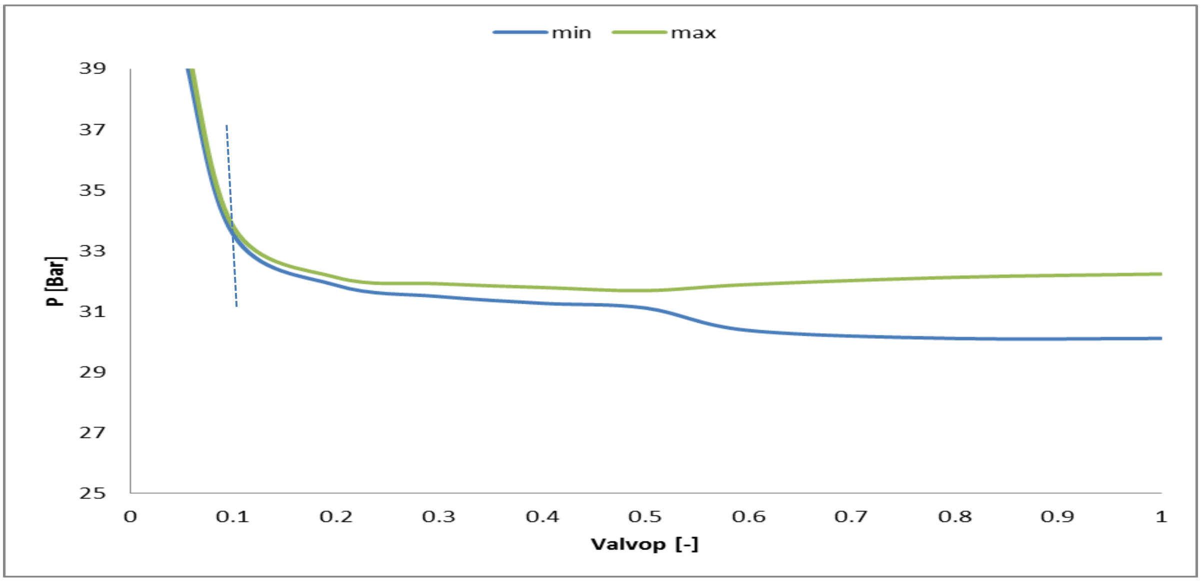


Figure 4-35 Riserbase pressure bifurcation map of pipelineriser system in V-region

The dotted blue line serves to demarcate the stable from unstable region. The green line connects the maximum pressure for all the valve openings while the blue line represents the pressure low peaks for all the valve openings. The bifurcation lies around 10% valve opening and pressure value of 33.7bar. Small amplitude fluctuations were experienced below 50% valve opening. At valve opening above 50%, the system was observed to experience a more chaotic instability. Though the maximum pressure fluctuation experienced is in the neighbourhood of 2 Bar, the valve opening required to stabilise the system in this region is very small compared with other regions 72% and 20% for H-region and I-region respectively. This shows a degree of instability in this region compared with other regions. It is widely known that severe slugging occurs at a low flow rate but with the help of an inclined pipeline upstream the riser pipe [29]. However in this study a pure upstream horizontal pipe was used. This suggests that whether an inclined pipe precedes a riser pipe or not, severe slugging can still occur. This view has been reported in earlier works [171] . It has been shown that significant choking was needed to stabilise the unstable hydrodynamic slug flow which unfortunately could mean less production. It is therefore important to develop an approach to stabilising the slug flow at larger valve opening.

4.5 Experimental study on hydrodynamic slug flow behaviour in pipeline-riser system

The experimental campaign described in section 3.4 was used to validate the observed behaviour hydrodynamic slug flow in pipeline-riser system. Slug flow maps were generated for pure horizontal pipeline, pure vertical pipe and pipeline-riser system. The slug regions are also compared as done in numerical studies to obtain the total picture of hydrodynamic slug flow in pipeline–riser system.

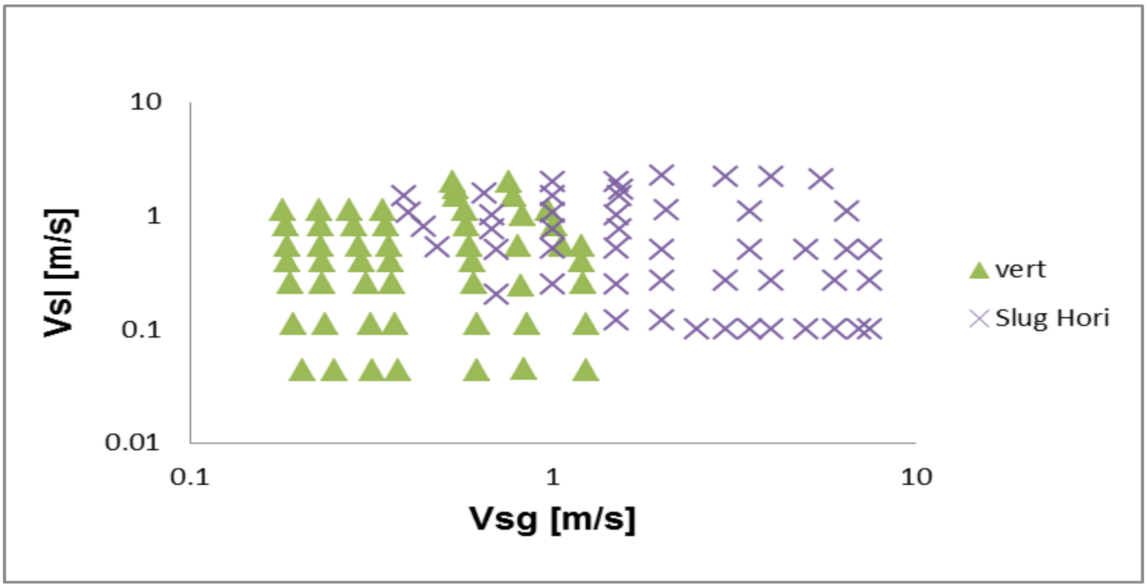


Figure 4-36 Comparison of slug flow maps for pure horizontal and vertical pipelines

Figure 4-36 shows the comparison between the horizontal and vertical slug maps. It is shown that a region of intersection occurs between the two envelopes at high flow rate for vertical envelope and low flow rates for horizontal pipe. It also appears clearly that at low flow rates, the region where slugs were not experienced in horizontal pipeline suffer slugging in vertical pipe. This validates what was observed for the numerical studies as shown in Figures 4-7 and 4-8 and previous flow regime maps [24; 25].

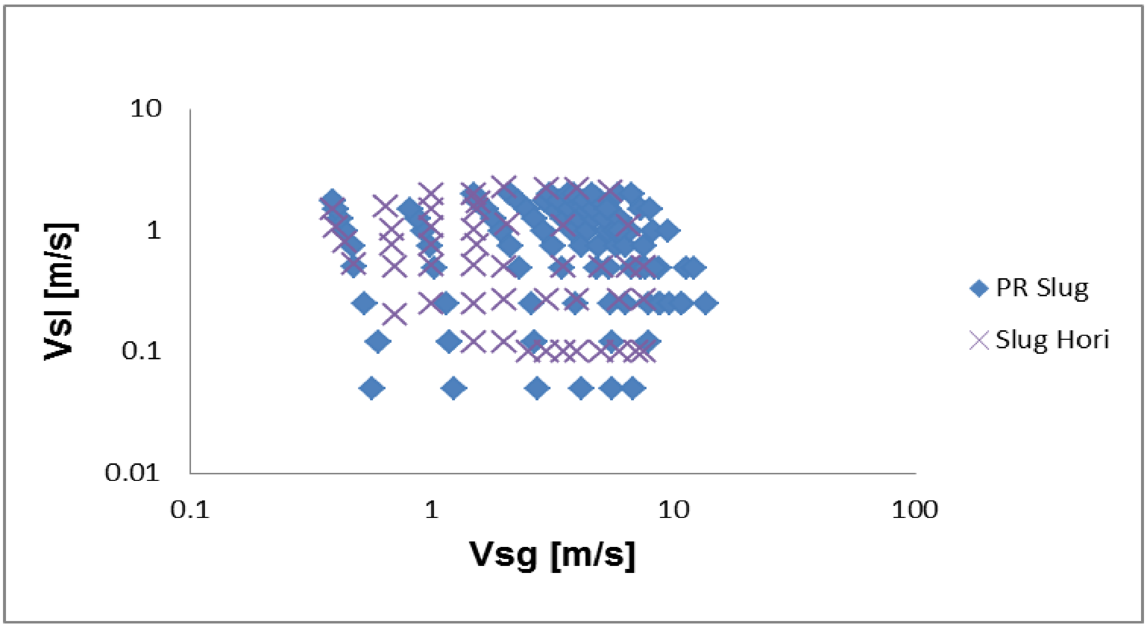


Figure 4-37 Comparison of slug flow map for pure horizontal pipeline and pipeline-riser

Figure 4-37 shows the comparison between the horizontal and pipeline-riser system slug maps .It is shown that the slug occurring at high flow rates in the pipeline-riser is due to slugs in the horizontal pipeline. This is also in consonance with what was observed for numerical study as shown in Figures 4-9 and 4-10.

Figure 4-38 shows the comparison between the vertical and pipeline-riser system slug maps. It is shown that the slug occurring at low flow rates in the pipeline-riser is due to slug in vertical pipeline. This is similar to what was observed in the numerical studies as reported in Figures 4-11 and 4-12.

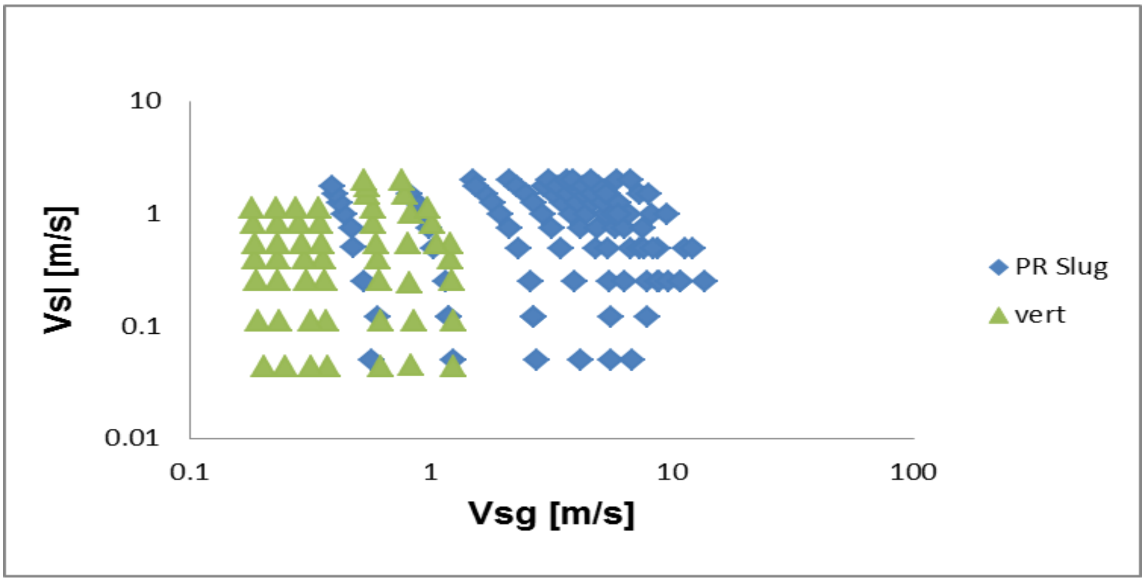


Figure 4-38 Comparison of slug flow map for pure vertical pipe and Pipeline-riser system

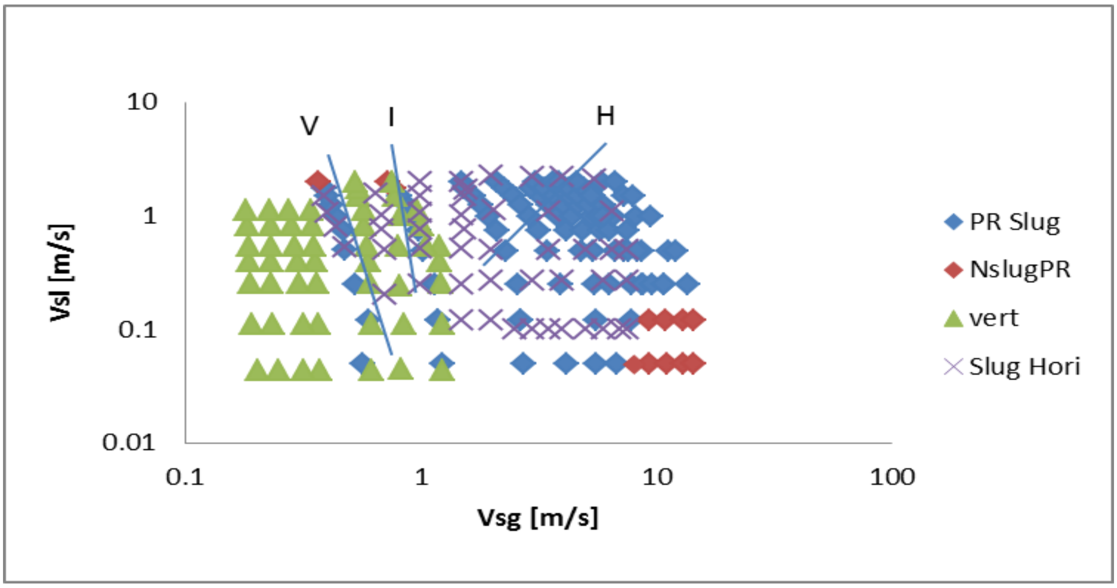


Figure 4-39 Comparison of slug flow map for pure horizontal, vertical pipes and Pipeline-riser system

Figure 4-39 shows the combination of all the slug flow maps. The HIV regions identified in the numerical simulation study as shown in Figure 4-13 are also observed here. However, there was quantitative difference between Figure 4-13 and 4-39. This could be traced to the difference in pipe diameter. Jepson and Taylor [172] investigated the impact of diameter pipe size on slug flow and transition. It was observed that for a large pipe diameter (12"), the transition between wave flow and slug flow occurred at higher liquid flow rate compared with small pipe diameter reported in [24]. The riserbase pressure response plots of the representative flow conditions in these regions are used to further analyse the behaviour of slug in these regions in the next sub-sections.

4.5.1 Experimental hydrodynamic slug flow in the H-region

The slug flow in the H-region occurs at relatively high liquid and gas flow rates. These slugs are of short length and relatively high frequency hydrodynamic slugs formed in the horizontal pipeline and transported into the vertical riser.

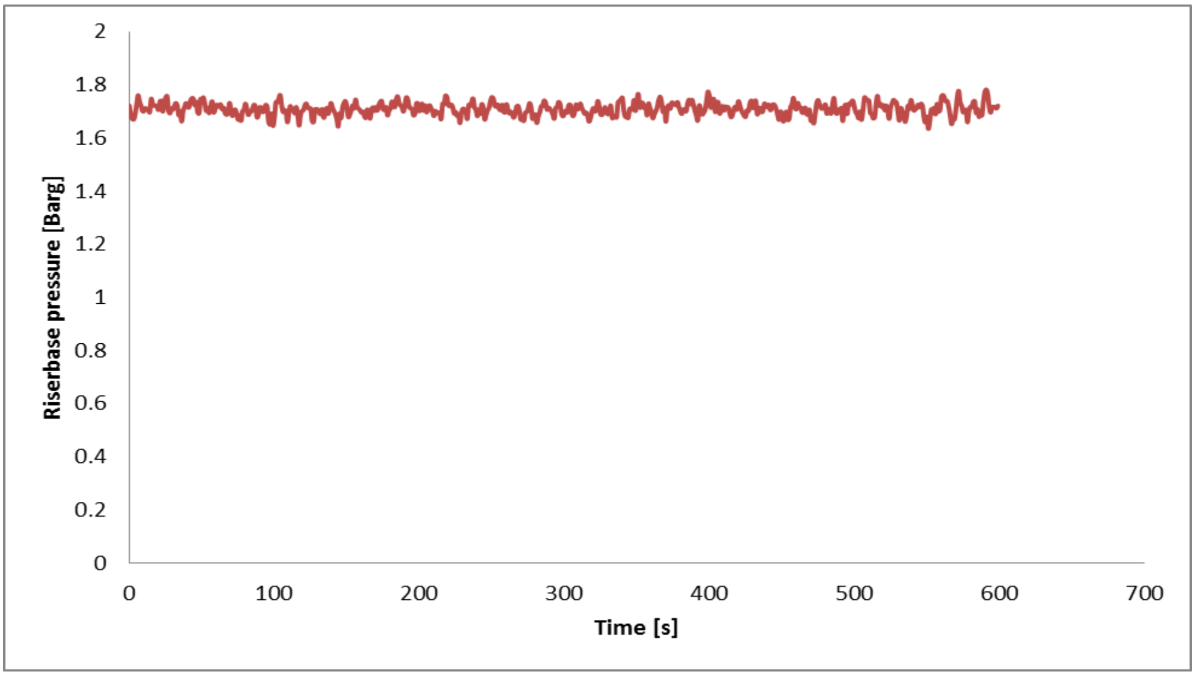


Figure 4-40 Experimental riserbase pressure response for H-region

The riser base pressure fluctuations are of small amplitude in the neighbourhood of 0.2 bar in our experiment. The riserbase pressure response of a representative flow condition of 30 Sm3/hr and 2 kg/s (1.95m/s and 1.0m/s superficial velocities) of air and water respectively is shown in Figure 4-40.

4.5.2 Experimental hydrodynamic slug flow in the I-region

The slug flow in the I-region occurs at moderate liquid and gas flow rates. Hydrodynamic slugs are formed in the horizontal pipeline upstream the vertical riser and are transported through the riser growing. The slugs formed in the horizontal pipes are of considerably longer length and lower frequency compared with those in H-region. Although the slug flow in this region behaves like severe slugging type 2 and 3 described in Malekzadeh et al. [50], it was observed that there was no period when the riser was full of liquid. However different liquid heights were observed in the riser which gives rise to different liquid production period as shown in Figure 4-38. The riser base pressure fluctuations are of considerable amplitude magnitude in the neighbourhood of 0.5 Barg. The riserbase pressure response of a representative flow condition of 7 Sm^3/hr and 0.5 kg/s (0.71m/s and 0.25m/s superficial velocities) of air and water respectively is shown in Figure 4-41.

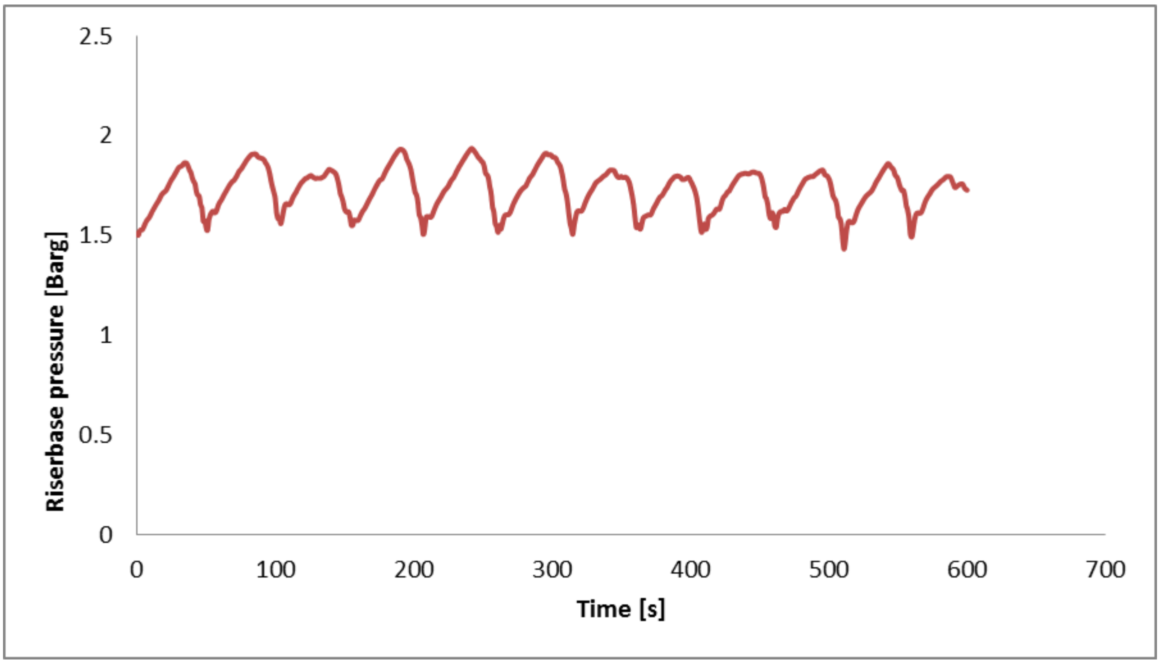


Figure 4-41 Experimental riserbase pressure response for I-region

4.5.3 Experimental hydrodynamic slug flow in the V-region

The slug flow in the V-region occurs at low liquid and gas flow rates. Hydrodynamic slug precursors are formed in the horizontal pipeline upstream the vertical riser but do not block the pipeline like a full slug flow. The period of flow of these wavelike precursors in the horizontal pipeline is characterised by gas flow in the riser pipe with liquid fall back to the riser base. This continual liquid fall back blocks the riser base and hinders free flow of gas into the riser allowing the arrival of more slug precursors. An increase in the riser liquid level ensued.

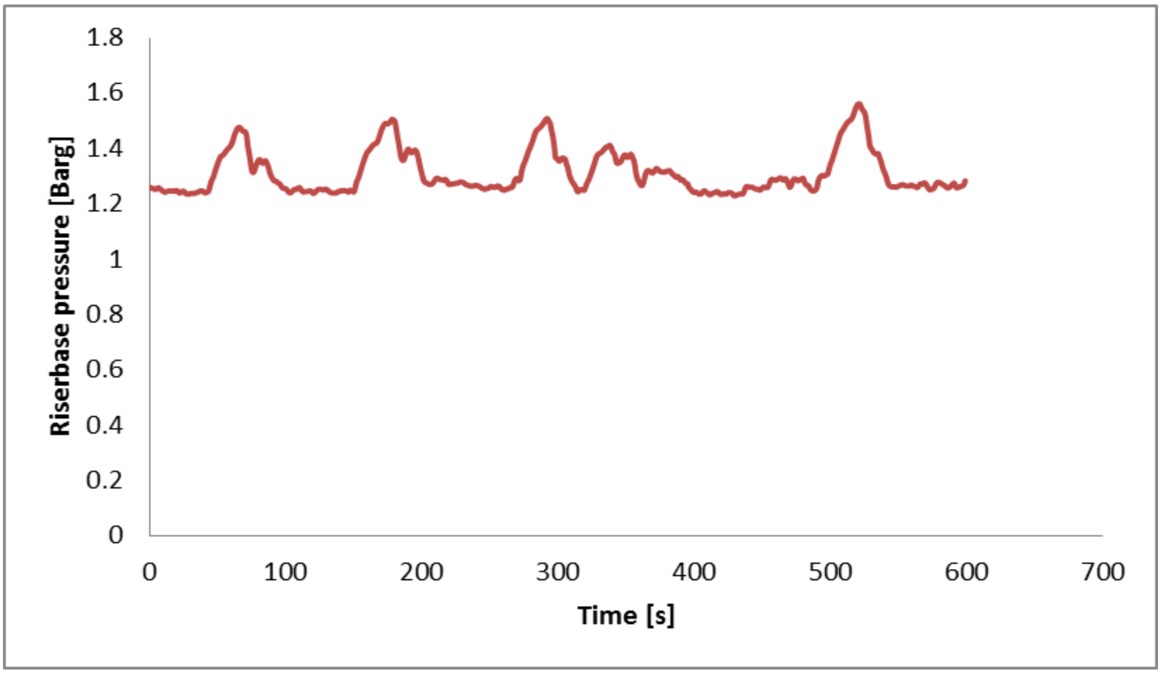


Figure 4-42 Experimental riserbase pressure response for V-region

Before the liquid level gets to the riser top, the gas penetrates the riser and a large Taylor Bubble penetrates the liquid column. The slug is thus produced and the cycle begins. Although the slug flow in this region has characteristic features of severe slugging, it was observed that there was no period when the riser was full of liquid. This reason for these distinct characteristics is traceable to the geometry of the pipeline-riser system. Previous researchers of severe slugging including Schmidt et al. [29] and Schmidt et al. [44] have employed pipeline-riser system with inclined pipeline immediately upstream the riser pipe. This configuration allows for natural accumulation of liquid at the riser base unlike the geometry used in our experiment where a straight horizontal pipeline is connected to a vertical riser pipe. The riser base pressure fluctuations are of considerable amplitude magnitude in the neighbourhood of 0.33 bar. The riserbase pressure response of a representative flow condition of 15 Sm^3/hr and 0.1 kg/s (1.23 m/s and 0.05m/s superficial velocities) of air and water respectively is shown in Figure 4-42.

4.6 Summary

The importance of geometry interaction on flow pattern map has necessitated this study. Slug envelopes were produced using two multiphase commercial codes, OLGA and LedaFlow and three distinct slug regions: region due to horizontal pipeline slugging (H) where slugs formed in the horizontal pipeline are transported through the riser pipe nearly unchanged, region due to both horizontal and vertical pipes slug contributions (I) where the slugs formed in the horizontal pipe keeps growing even through the riser pipe and region due to vertical pipe slugging (V) were slug formation was predominantly due to the vertical pipe. The slugs in I and V regions are severe slugging-like. These regions have been described and the results from experimental studies conducted validate the observed behaviours in both software packages. The understanding derived from this study can be pivotal to the design and operation of pipeline-riser system where hydrodynamic slug is expected. Although both software packages predicted slug flow for a large vertical pipe, as opposed to churn flow that has been reported by several authors including Ali [173] , the code developers might want to consider differentiating slug and churn flow regime in subsequent versions. However, churn flow has generally been classified as an intermittent flow, therefore the results may still be considered valid.

The results also show that choking can indeed be used to mitigate hydrodynamic slug flow in all the regions but at considerable cost. The valve must be choked down at various degrees depending on the regions (flow conditions). There is need to seek a better way of stabilizing hydrodynamic slug flow bearing in mind the distinct behaviours of the identified regions. Finding such methods is addressed in subsequent chapters.

5 SLUG FLOW STABILIZATION AT LARGE VALVE OPENING FOR PRODUCTION MAXIMIZATION

5.1 Introduction

Slugging in oil and gas pipelines is a cardinal problem for all oil and gas producers. It is characterized by large pressure and production fluctuations. In chapter four, it has been established that choking can be used to mitigate hydrodynamic slug but at considerable loss in production. This method has been used in oil and gas industry for many years to eliminate severe slugging by manipulating the valve opening at the exit of the riser which unfortunately could negatively affect production [1; 3]. The focus therefore is to satisfy the need for system stability and to maximize production simultaneously. Active feedback control is a promising way to achieve this [2]. However, due to the complexity of multiphase flow systems, it is a challenge to develop a robust slug control system to achieve the desired performance using existing design tools.

Significant efforts have been concentrated on modelling and understanding the slug attenuation mechanism for choking [3; 4] and active slug control [5-9]. These models can be used to gain insight into the mechanism and control design. Nevertheless, these models might not adequately represent real systems due to the complexity of multiphase flow. This leaves the robustness of slug control systems designed based on these models questionable. There is therefore the need for a simple but yet robust methodology that can be used for system analysis and controller design. In this chapter, a new method that can be used for slug control stability analysis and designing a controller for stabilizing the unstable slug flow was proposed. A theoretical analysis was attempted for the first time to show the slugging mitigation potential of active feedback control and an autonomous intermittent absorber at larger valve opening compared with traditional manual choking. This chapter is organized as follows: in section 5.2 the new approach to slug flow stability analysis is presented for manual choking; in section 5.3 stabilising slug flow using active feedback control is discussed while 5.4 presents the numerical case studies, section 5.5 introduces the intermittent absorber concept while the chapter is concluded in section 5.6.

5.2 Stabilising slug flow with choking

Slugging usually manifests in significant fluctuation of flow and pressure. This instability is as a result of the pipeline-riser configuration: The upward multiphase flow in the riser and compressibility of gas in the horizontal pipeline upstream the risers. Due to these two factors, any increment of gas flow can cause two opposite effects on the riserbase pressure, positive and negative. The negative effect can make the system unstable if it is dominant.

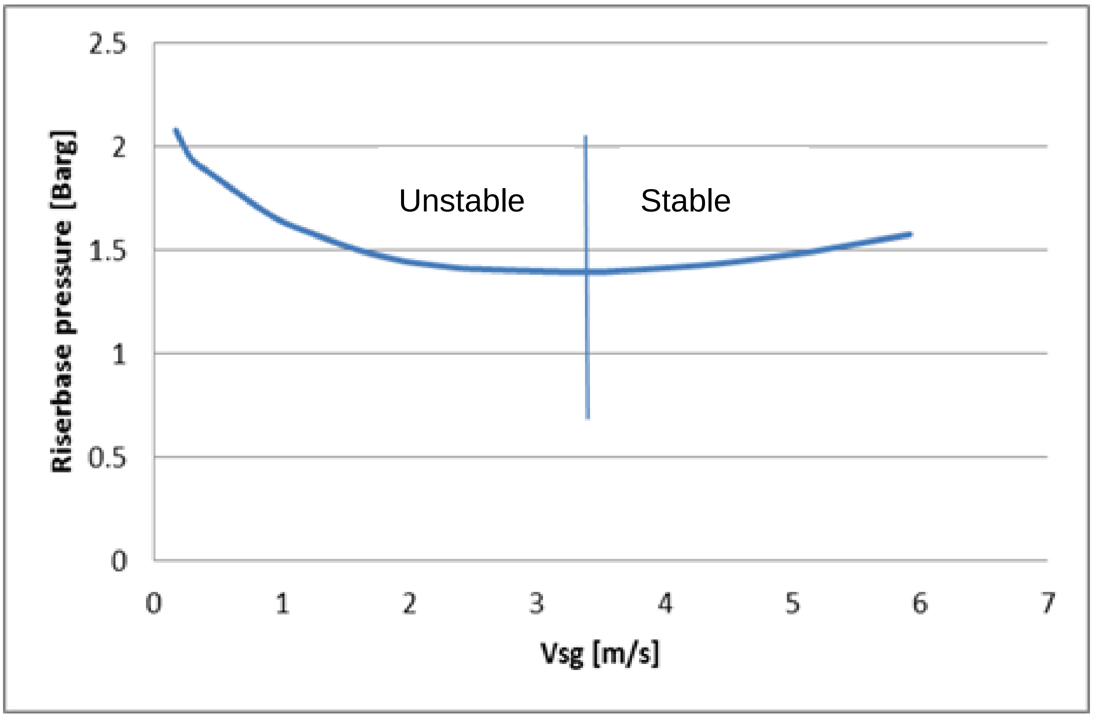


Figure 5-1 Stability map for riserbase pressure as a function of gas flow rate

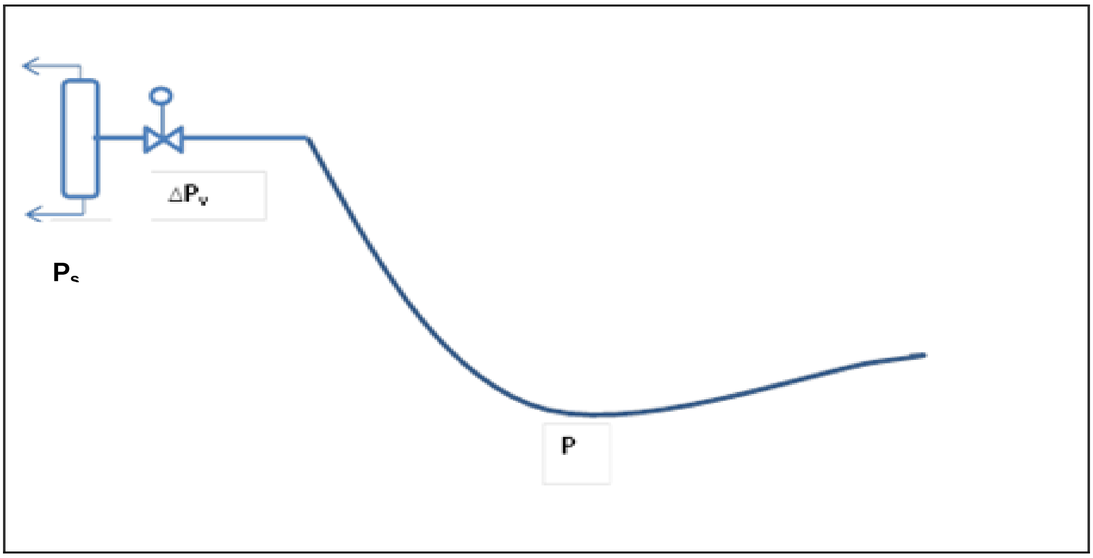


Figure 5-2 Schematic of a pipeline-riser system

Figure 5-1 shows the general relationship between the riserbase pressure and the gas flow rate for a given constant liquid flow rate of 0.25 m/s. When the gas flow rate is low, which corresponds to a low friction loss, any increment in the gas flow rate will cause an increase in the gas-liquid ratio within the riser, hence results in a decrease in the riserbase pressure. Conversely, when the gas flow rate is large enough (on the right side of the vertical line in Figure 5-1) the friction loss becomes dominant; hence any increase in the gas flow rate will increase the friction loss and results in the riserbase pressure increase**.** The region to the left and right of the minimum value represent the unstable flow and stable flow regimes as shown in Figure 5-1. Figure 5-1 shows clearly that the system will be stable only at considerably high gas flow rates. This is the bane of gas injection as a method for slug attenuation [15; 121]. Alternative method is therefore required for stabilizing the unstable system.

Considering a pipeline-riser system shown in Figure 5-2, the riserbase pressure depends on the liquid head, frictional head, acceleration head, and pressure drop across the valve and the separator pressure. This can be shown mathematically as (5.1).

$$P = \Delta P_h + \Delta P_f + \Delta P_a + \Delta P_v + P_s \quad \textbf{(5.1)}$$

Where P is the riserbase pressure, ΔP_h, ΔP_f, ΔP_a, Ps and ΔP_v are the hydrostatic head, frictional head, acceleration head, separator pressure and pressure drop across the valve respectively.

Assuming a constant liquid flow rate with small perturbation in gas flow rate, the riserbase response can be given as (5.2)

$$\frac{dP}{dQ} = \frac{d\Delta P_h}{dQ} + \frac{d\Delta P_f}{dQ} + \frac{d\Delta P_a}{dQ} + \frac{d\Delta P_v}{dQ} + \frac{dP_s}{dQ} \quad \textbf{(5.2)}$$

For the system to be stable the riserbase pressure response to the change in gas flow rate must have a positive slope as shown in (5.3).

$$\frac{dP}{dQ} > 0 \quad \textbf{(5.3)}$$

$$\frac{dP}{dQ} < 0 \quad \textbf{(5.4)}$$

The system will be unstable when the riserbase pressure slope is negative. The condition is given as (5.4).

Considering the pipeline-riser system shown in Figure 5-2, under unstable behaviour, the system can be stabilized by choking the topside valve. This can be achieved by increasing the pressure drop across the valve.

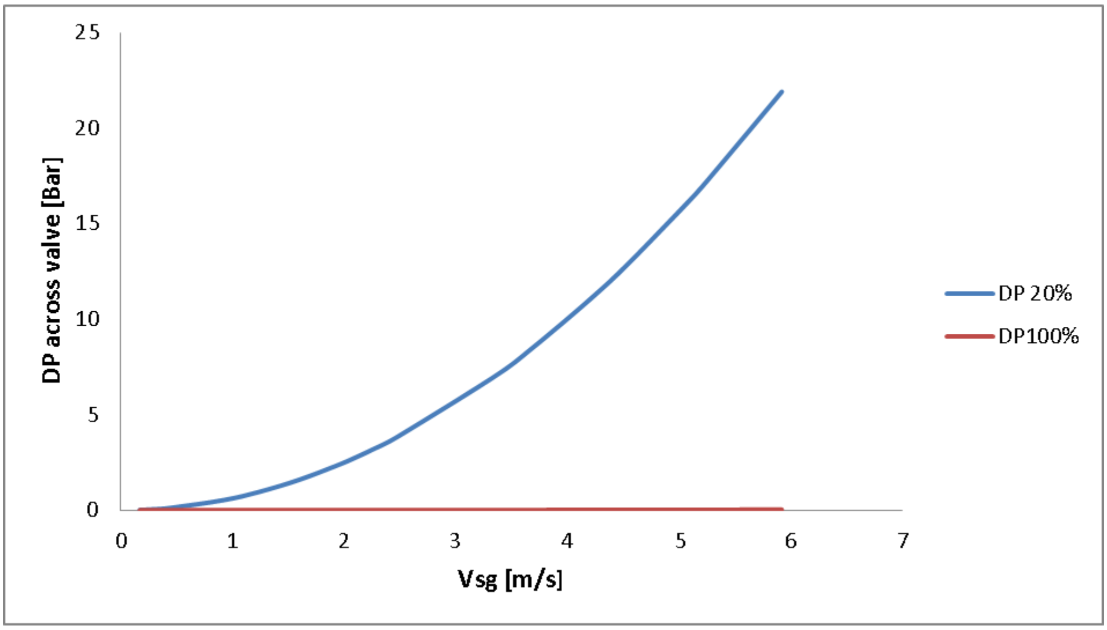


Figure 5-3 Pressure drop across valve as a function of gas flow

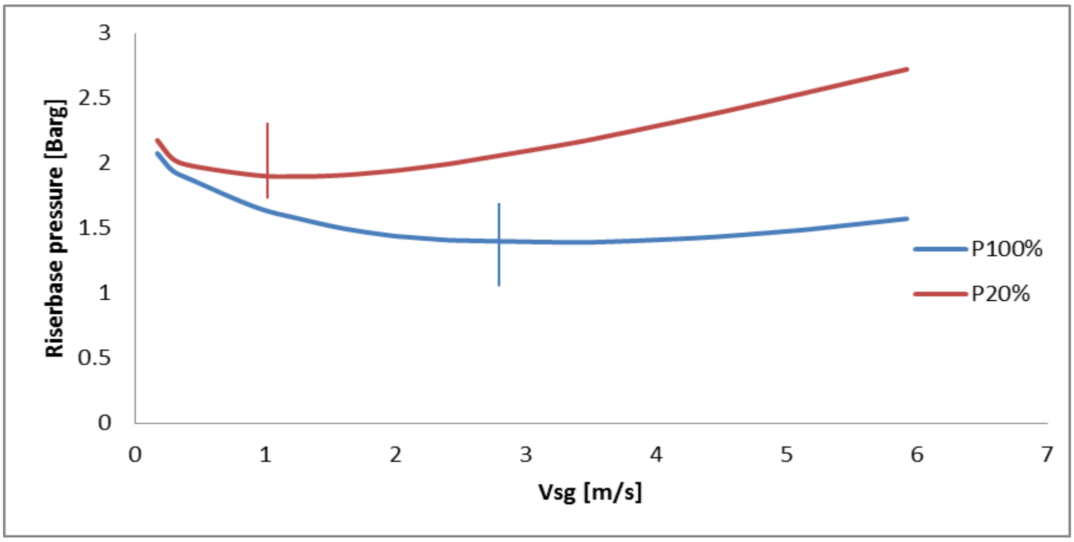


Figure 5-4 Use of choking to obtain stable flow

Figure 5-3 shows a plot of pressure drop across the valve against the gas flow rate at constant liquid flow rate. The pressure drop across the valve was shown to increase as the gas flow increases for a constant valve opening. This relationship is shown in (5.5).When the pressure drop across the valve is sufficiently large, the region of negative slope can be sufficiently made positive as shown in Figure 5-4

The pressure drop across the valve in (5.2) can be estimated using valve equation. Assuming linear valve characteristics, for a given liquid flow rate, the pressure drop across the valve can be given as (5.5)

$$\Delta P_v = \frac{Q^2}{C_v^2 u^2 \rho} \tag{5.5}$$

ρ is the density of fluid flowing through the valve (mixture density), C_v is the valve coefficient , *u* is the valve opening with values ranging between 0 and 1 and *Q* is the flow across the valve. The pressure drop across the valve is a function of the flow and the valve opening as shown in (5.5). At constant flow rate, the only variable that can be manipulated is the valve opening. This has been previously explored for slug attenuation by many authors [1; 98][41], others developed bifurcation maps based on this concept and further designed controllers for slug attenuation[2; 42; 99; 132].

If (5.5) is differentiated with respect to *Q* keeping valve opening *u* constant (typical of manual choking), we have (5.6)

$$\frac{d\Delta P_v}{dQ} = \frac{2Q}{C_v^2 u^2 \rho} \tag{5.6}$$

Substituting (5.6) into (5.2) and on rearrangement, we have (5.7).

$$\frac{2Q}{C_v^2 u^2 \rho} > -\left[\frac{d\Delta P_h}{dQ} + \frac{d\Delta P_f}{dQ} + \frac{d\Delta P_a}{dQ} + \frac{dP_s}{dQ}\right] \tag{5.7}$$

This shows the condition under which manual choke valve would stabilize the unstable slug flow when the gas flow is perturbed. For this condition to hold, the pressure drop across the valve must be sufficiently large that is, the valve opening must be considerably small which means low flow through the valve.

The riserbase pressure increases as the pressure drop across the valve increases. Choking causes restriction to flow and this can considerably reduce production rate. This is the bane of choking as a method for slug control and has been reported by many authors including [1]. Thus reducing the pressure drop across the valve would be desirable as this would lead to increase in production. One of the ways to achieve this is to use a controller. Ogazi [2] has reported the ability of controller to help stabilise an open loop unstable system however no robust stability analysis was given for this benefit. This was attempted in this work.

5.3 Stabilizing the unstable slug flow regime with feedback controller

The production of system is directly associated with the riserbase pressure (5.1), while the stability is related to the pressure gradient, *dP/dQ* in (5.2). Therefore, the aim of a slug control system can be translated as to achieve positive *dP/dQ* for certain flow rate with relatively low riserbase pressure *P*. Under feedback control, in (5.5) the valve opening *u* is not constant but varying as gas flow rate *Q* changes although the specific relationship between *u* and *Q* depends on the feedback law designed. Differentiating (5.5) therefore yields:

$$\frac{d\Delta P_v}{dQ} = \frac{2Q}{C_v^2 u^2 \rho} + \left(\frac{Q^2}{C_v^2 \rho}\right) \frac{d}{dQ}\left(\frac{1}{u^2}\right) \quad \textbf{(5.8)}$$

Comparing (5.6) and (5.8), the second term of (5.8) provides extra gradient to satisfy stable condition (5.3). In other words, active slug control can achieve oil production higher than manual choking when severe slugging is eliminated. Equation (5.8) also suggests that to maximise oil production of a slug control system, the second term of (5.8) should be maximised. This confirms that slug attenuation using choking can be more effective with the aid of controller compared with manual choking [2].

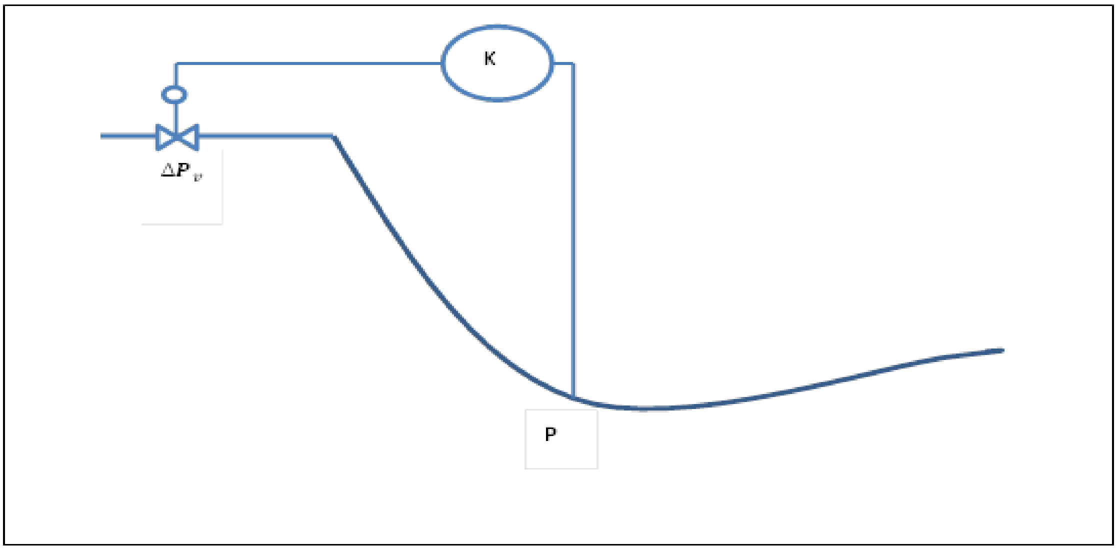


Figure 5-5 Pipeline-riser configuration with controlled choking

5.3.1 Bifurcation map

The first step in the design procedure is to establish the critical point after which a controller will be designed to stabilise the system in the open loop unstable region. The bifurcation map can be generated by keeping Q constant and varying u. The pressure gradient contributed by the valve to stabilize the system can be estimated at the critical valve opening using (5.5). An example of a bifurcation map generated at constant gas flow of 0.84kg/s flow rate is shown in Figure 5-6. Without choking, the pressure was observed to be fluctuating between 30 and 34 bar. The choke was able to stabilise the system at 20% valve opening and 46 bar pressure. This shows that about 13 bar pressure was added to stabilise the system. It is thus desired to stabilise the system at a larger valve opening to reduce the pressure.

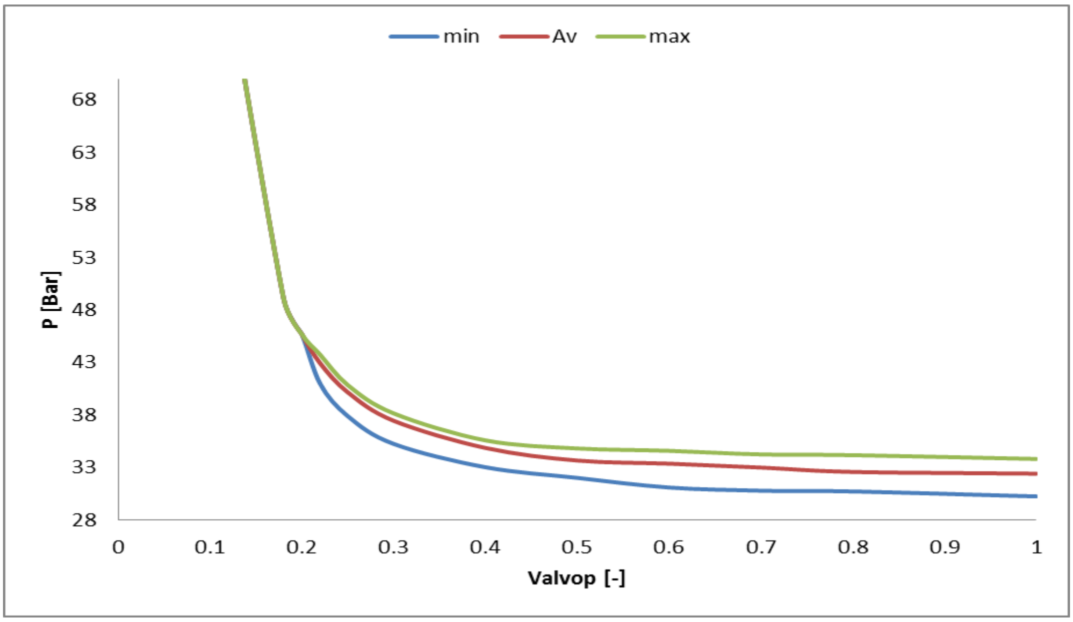


Figure 5-6 A typical riserbase pressure bifurcation map

5.3.2 Design of Active feedback controller

Considering a simple pipeline-riser system with feedback controller in Figure 5-5, the goal is to control system response at larger valve opening. To achieve this, an extra pressure gradient must be introduced through feedback control to compensate for the gradient loss due to increased valve opening. Assuming the parameter of interest is the gas flow rate Q, for a slight perturbation in the gas flow rate, Q will deviate from set point Q_0. It was proposed that Q can be driven to Q_0 with a feedback controller of the form:

$$u = K(Q_0 - Q) + u_0 \quad \textbf{(5.9)}$$

$$\frac{d}{dQ}\left(\frac{1}{u^2}\right) = \frac{2K}{u^3} \quad \textbf{(5.10)}$$

Therefore (5.8) becomes:

$$\frac{d\Delta P_v}{dQ} = \frac{2Q}{C_v^2 u^2 \rho} + \left[\left(\frac{Q^2}{C_v^2 \rho}\right)\frac{2K}{u^3}\right] \quad \textbf{(5.11)}$$

Therefore the stability condition for feedback control is given as (5.12).

$$\frac{2Q}{C_v^2 u^2 \rho} + \left[\left(\frac{Q^2}{C_v^2 \rho}\right)\frac{2K}{u^3}\right] > -\frac{d\Delta P_0}{dQ} \quad \textbf{(5.12)}$$

Where $\frac{d\Delta P_o}{dQ} = \left[\frac{d\Delta P_h}{dQ} + \frac{d\Delta P_f}{dQ} + \frac{d\Delta P_a}{dQ} + \frac{dP_s}{dQ}\right]$

For a desired $\frac{d\Delta P_v}{dQ}$, there exists a value of K, which stabilises the system. It is shown in (5.9) that large value of K will lead to increased oil production.

5.4 Numerical case studies for stabilising hydrodynamic slug flow using the proposed method

In order to meet the objective of this chapter, numerical study on the stabilization of an unstable slug flow in pipeline-riser system was attempted for a representative slug flow condition in the I-region identified in Chapter four using LedaFlow (an industrial multiphase code). Section 3.3 provides the detailed description of the pipeline-riser system. Having established the bifurcation point with manual choking in section 4.4, the next goal is to control system response at larger valve opening and an active feedback controller was employed.

5.4.1 Stability curve

Figure 5.7 shows the average riserbase pressure against the gas flow rate. The system was simulated for various gas flow rates at constant liquid flow rate of 119.16 kg/s. It is shown that at this constant liquid flow a gas flow rate (of 0.84kg/s, corresponding to a gas mass fraction at 0.007) is in unstable region. It is shown from the map that about 20kg/s gas flow rate will be needed to stabilize the system without choking. This is the bane of using gas injection as a slug mitigation technique [4]. Following (5.3), (5.6) and (5.7), it is proposed that when sufficient *dP/dQ* is added to the system such that total gradient is greater than zero, the system will become stable.

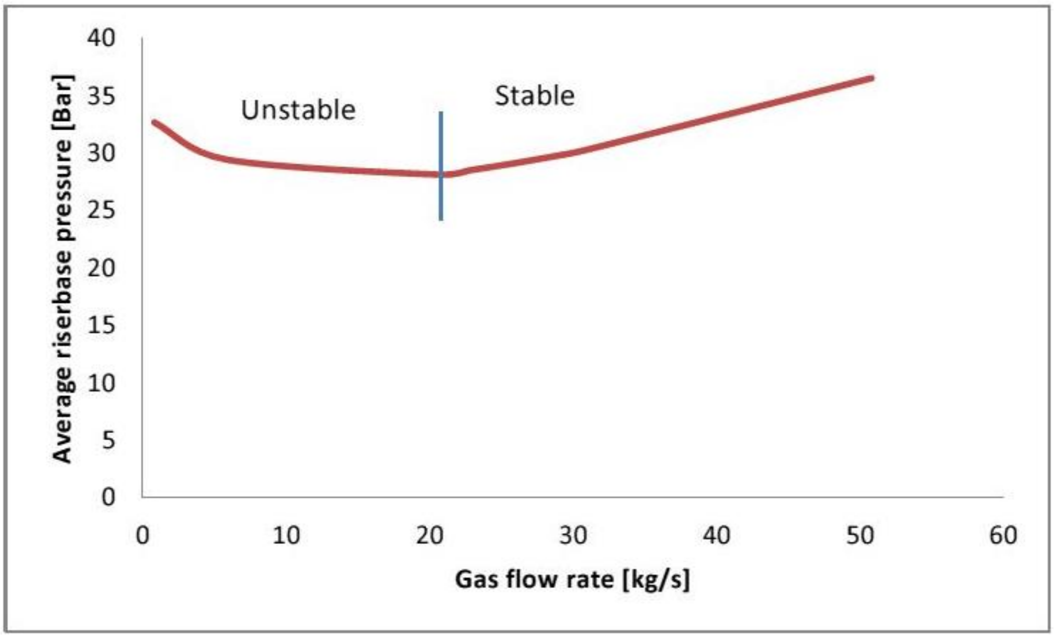


Figure 5-7 Riserbase pressure stability map using gas flow rate

For a close look, Figure 5-8 shows that without any choking, i.e. at 100% valve opening, around the operating point defined in Table 4.2, the local gradient (*dP/dQ*) was estimated as -14.29 bar/kgs^{-1} .This is in consonance with (5.4), thus the system is unstable. In this study, it is desired to stabilize the system around this operating condition. From (5.6), it was estimated that at least 14.29

bar/kgs^{-1} gradient must be supplied by the choke in order to stabilize the system at this operating condition such that (5.7) is satisfied. This was achieved by choking and the corresponding bifurcation map is shown in Figure 5-9.

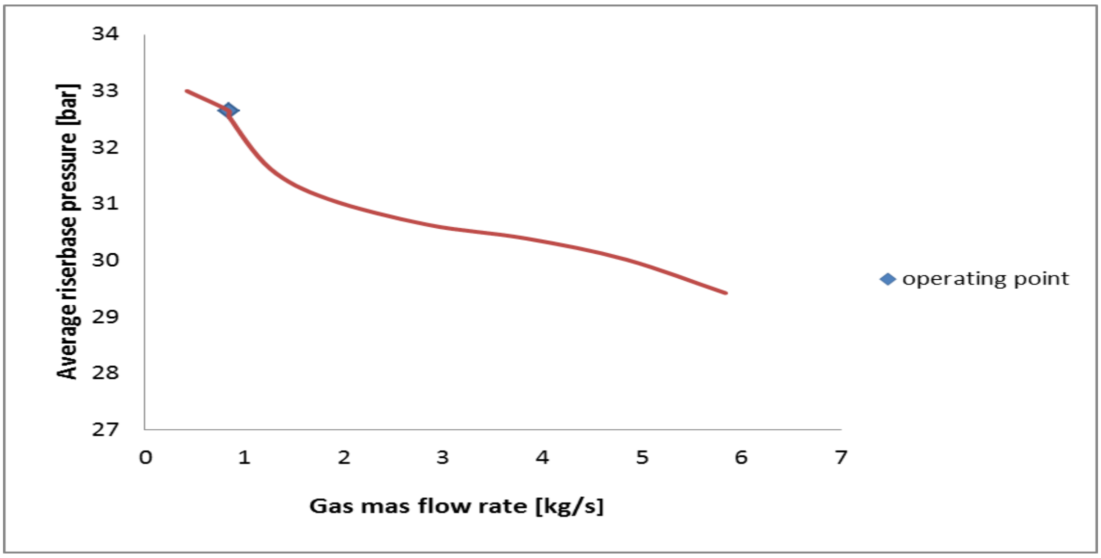


Figure 5-8 Stability curve showing the operating condition

5.4.2 Bifurcation map

The system was simulated for various valve openings and bifurcation map was generated for a typical slug flow for the boundary conditions shown in Table 4.2. The valve was significantly choked to 20% opening to achieve stability by providing the required gradient. This gradient was supplied by the pressure drop across the valve which added about 14 bar pressure to the system. It is desired to reduce the magnitude of this pressure so that the system pressure can be lowered for higher production.

Having established the bifurcation point with manual choking and the pressure gradient contributed by the valve, the next goal is to control the system response at larger valve opening.

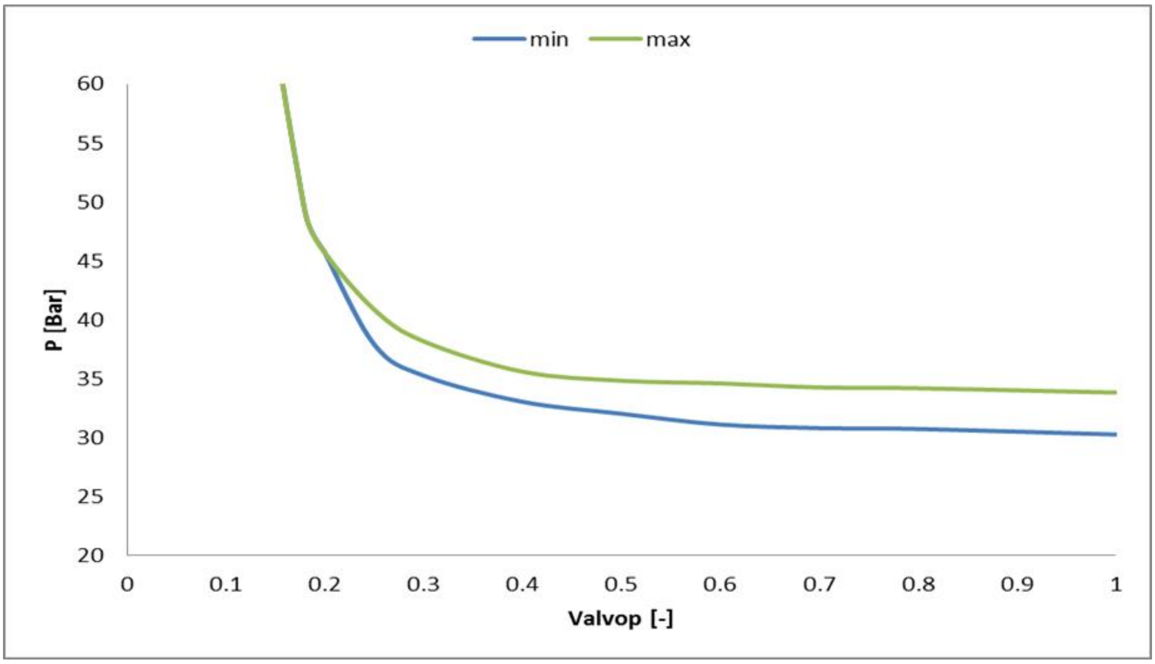


Figure 5-9 I-region riserbase pressure bifurcation map

It has been shown in (5.8) that with the help of active control, a system can be stabilized at larger valve opening. In this study, we attempt to control the gas flow rate using a simple proportional controller. At 22% valve opening for example, the gradient supplied at this valve opening was 10.71 bar/kgs^{-1} which was less than the required 14.29 bar/kgs^{-1} . From (5.8) , it was shown that a controller can provide this shortfall. The gain required to meet this shortfall gradient was estimated from (5.11). The minimum required gain required to stabilize our system at 22% valve opening was obtained as 0.0794.

5.4.3 Implementation of the active controller

The gain (0.0794) was implemented using the inbuilt proportional controller structure in LedaFlow. Figure 5-10 shows the system response to the application of control designed using the new method. The simulation was run for about 5000 seconds before the controller was introduced.

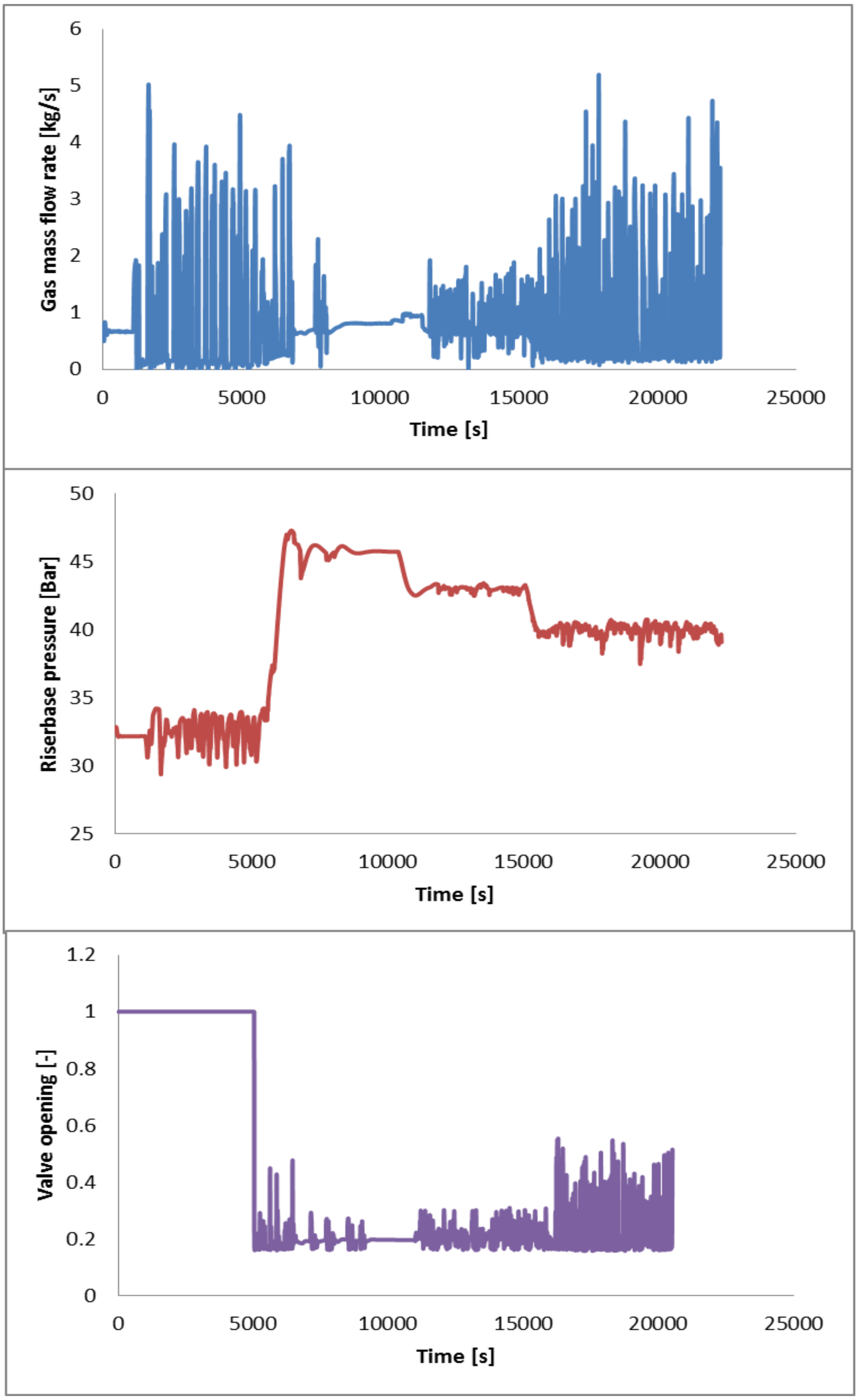


Figure 5-10 system response to active feedback control using the new proposed method

The reference valve opening u_0 was initially set at 20% valve opening, the controller was able to stabilise the system, and after 11000s, the reference valve opening was changed to 22% and the controller was still able to stabilise the system, but when u_0 was opened beyond this value at 23% from 16000s, the system became closed loop unstable. A benefit of 5% reduction in the riser base pressure from 45.73 bar to 43.4 bar was recorded. This practically implies increase in oil production [2; 42; 99].

5.5 Stabilising slug flow using intermittent absorber

In sections 5.3 and 5.4, it was shown that with the help of active feedback controller, the unstable slug flow can be stabilised at a larger valve opening compared with manual choking. The ability of the intermittent absorber to perform similar function is investigated. The intermittent absorber method proposed in this study is a non-feedback method for slug attenuation. This concept is similar to the shock absorber in vehicles and surge arrestors in single phase water pipeline system. Shock absorbers are mechanical devices installed in cars to suppress or dampen vibrations due to movement in a rough road. Slugging characteristically exhibit pressure fluctuations and it is believed that it can be attenuated using the intermittent absorber concept. This concept can also be compared with the chaotic oscillation absorber investigated for electronic circuits [174] and the vibration absorber used to alter the resonance condition by increasing the degree of freedom of the system [175].

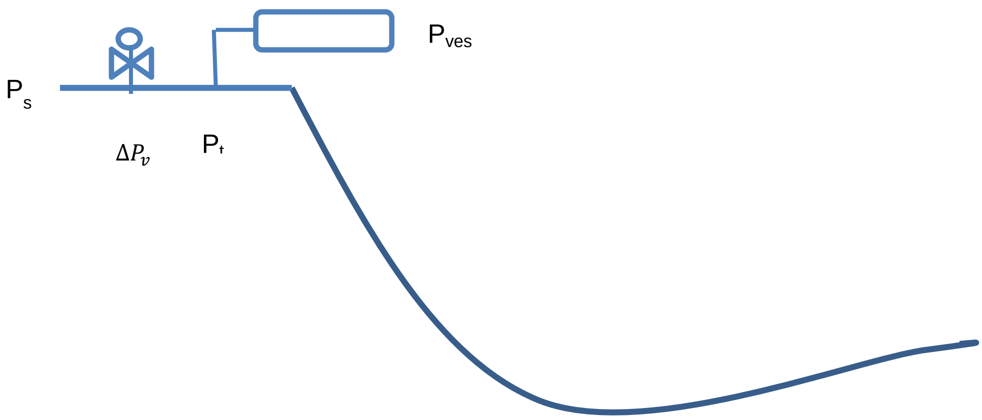


Figure 5-11 simplified pipeline-riser system with intermittent absorber coupled

The intermittent absorber concept is therefore investigated in this study for the role of quenching the fluctuation due to unstable slug flow. An attempt to show this theoretically is attempted next.

Considering an intermittent absorber coupled to a pipeline-riser system is at the top of the riser as shown in Figure 5-11. If the unstable pipeline-riser system can be represented by a dynamic equation described by (5.13)

$$\dot{P} = f(P, x) \tag{5.13}$$

Where P is a vector representing the system variables such as riserbase pressure, pressure drop across the valve etc. and *x* is a vector denoting system parameters. Assuming the variable of interest is the pressure drop across the valve (since this is cardinal to system stability), the element of the *x* vector are *Q* and *u* as shown in (5.5). It has been established in section 5.3 that a change in *x* will alter P significantly. This property has been explored for stabilising the unstable system by varying any of the elements in *x* in section 5.3.

The intermittent absorber concept is based on the fact that it is also possible to stabilise the unstable system by coupling another autonomous asymptotically stable system to the original unstable system. The role of the asymptotically stable R-subsystem is to alter the response of the unstable system. This additional system will increase the degree of freedom and provide stabilising effect [174; 175].

Considering an asymptotically stable autonomous system (the intermittent absorber) which can be described dynamically by (5.14)

$$\dot{R} = g(R, c) \tag{5.14}$$

Where *R* is a vector describing the system variables such as pressure and the *c* is a vector denoting the system parameters which can be varied. In this study *c* is the volume of the gas in the vessel.

The equation of the augmented system is given by (5.15) and (5.16).

$$\dot{P} = f(P, x) + \eta_r R \tag{5.15}$$

$$\dot{R} = g(R, c) + \eta_p P \tag{5.16}$$

Where η_r and η_p are the coupling matrices. The coupling matrices describe the connection behaviour of the two subsystems *P* and *R*. When $\eta_r = 0$ and $\eta_p = 0$, the P and R subsystems in (5.15) and (5.16) are uncoupled and for $\|\eta_p\|$ and $\|\eta_r\|$ > 0, stabilising impact is felt in the main system due to the R-subsystem. For a very small $\|\eta_p\|$ and $\|\eta_r\|$, P(t) of the coupled system (5.15) and (5.16) will evolve in the neighbourhood of the original attractor of (5.13). This implies that the dynamics of the unstable system and the coupled system will remain qualitatively same for a significantly small values of $\|\eta_p\|$ and$\|\eta_r\|$. Therefore autonomous system must be strongly coupled to the unstable system in order provide significant attenuation. This will happen at $\|\eta_p\|_\infty = 1$ and $\|\eta_r\|_\infty = 1$.

The augmented system shown in (5.15) and (5.16) describes a pipeline-riser system coupled with an intermittent absorber.

From Figure 5-11, the pressure at the junction P_t will be at equilibrium with vessel pressure P_{ves}. P_t can be estimated as (5.17).

$$P_t = P_s + \Delta P_v + \Delta P_1 = P_{ves} \tag{5.17}$$

Where ΔP_1 is the pressure drop along the pipe and P_s is the separator pressure.

Assuming a constant liquid flow rate with small perturbation in gas flow rate, (5.17) becomes:

$$\frac{dP_t}{dQ} = \frac{dP_s}{dQ} + \frac{d\Delta P_v}{dQ} + \frac{d\Delta P_1}{dQ} = \frac{dP_{ves}}{dQ} \tag{5.18}$$

Following the earlier analysis in section 5.2, the gradient provided by the vessel will effectively affect the total gradient. This vessel helps to increase the degree of freedom and provide stabilising effect [174; 175]. It can also provide destabilising effect when extremely large. The slug attenuation of this concept was further explored in chapters six and seven.

5.6 **Summary**

Slugging is an undesirable flow phenomenon which continues to attract the attention of researchers and operators alike. The most common method for slug mitigation is by choking the valve at the exit of the riser which unfortunately could negatively affect production.

In this chapter, a new general method for multiphase slug flow stability analysis was proposed. A stability criterion was defined based on this new method.

The theoretical understanding of slug attenuation potential of active feedback control at large valve opening has been investigated and active feedback control helps to maximise slug attenuation by optimising the pressure drop across the valve compared with manual choking. For the specific case study, additional 2% valve opening translating into 5% reduction in riserbase pressure was achieved for the proposed method. This practically implies increase in oil production for the system when active feedback control was used compared with the manual choking. A more robust controller designed based on this method might provide greater benefits. It has been clearly demonstrated that the new method can indeed help provide system stability and at larger valve opening.

Theoretical understanding of the slug attenuation potential of a non-feedback method, the intermittent absorber has also been provided. This concept explores the capability of an asymptotically stable autonomous system to alter the behaviour of an unstable system. It was shown that this concept can help provide stability effect when strongly coupled with the unstable system. This method was further explored for both hydrodynamic and severe slugging attenuation and discussed in the subsequent chapters.

6 EXPERIMENTAL STUDY ON HYDRODYNAMIC SLUG MITIGATION POTENTIAL OF INTERMITTENT ABSORBER

6.1 Introduction

The need to handle hydrodynamic slugs in a more efficient way becomes important as oil and gas activities shift deep offshore. Hydrodynamic slugging when compared with severe slugging has higher frequency and short slug length. Its fluctuation behaviours have previously been considered manageable by the system or with the aid of slug catcher. Hence, very little effort have been put on the issue of stabilising hydrodynamic slugging compared with the amount of studies on control of severe/terrain induced slugs. However, the findings from chapters two and four suggest that hydrodynamic slug can indeed be severe. It becomes evidently clear that hydrodynamic slug flow and control in pipeline-riser systems needs more attention and this chapter is therefore aimed at investigating the use of an intermittent absorber as a method for hydrodynamic slug attenuation. In chapter five, a theoretical background has been provided for this method. This chapter attempts an experimental investigation of hydrodynamic slug attenuation potential of the intermittent absorber concept introduced in chapter five.

In chapter four, the pipeline geometry interaction was studied and three slug flow regions of distinct behaviours in pipeline-riser system (H, I, V) were reported. The behaviour of hydrodynamic slug regions (H and I) is further investigated for possible attenuation using parameter variation technique. This chapter also attempt a proof of concept to demonstrate the slug attenuation potential of an intermittent absorber.

This chapter is organised as follows: in section 6.2 the proof of concept for the intermittent absorber was attempted. The absorber was also investigated for additional benefit of optimising the parameter variation technique. Section 6.3 presents the methods for quantifying the slug attenuation potential of the absorber. Slug attenuation index (SAI) and statistical slug attenuation index

(SSAI) were presented while section 6.4 describes the proposed mechanism for the slug attenuation capability of the method and the chapter is concluded in section 6.5.

6.2 Proof of concept for slug attenuation potential of the intermittent absorber

A proof of concept study was carried out to demonstrate that the intermittent absorber concept could have optimising impact on the parameter variation technique and also provide slug attenuation potential. The absorber was designed such that apart from the isolation mode, three modes of operation are possible. In order to proof that the intermittent absorber concept has the potential for slug attenuation and investigate its optimising capability of parameter variation technique, these modes of operation were employed for various flow conditions. The first operation mode was obtained when both isolation valves 1 and 2 are opened, the second when isolation valve 1 was opened and isolation valve 2 was closed and the third is achieved when valve 1 is closed and valve 2 is opened. These various modes are hereafter referred to as operation mode 1, 2 and 3 respectively.

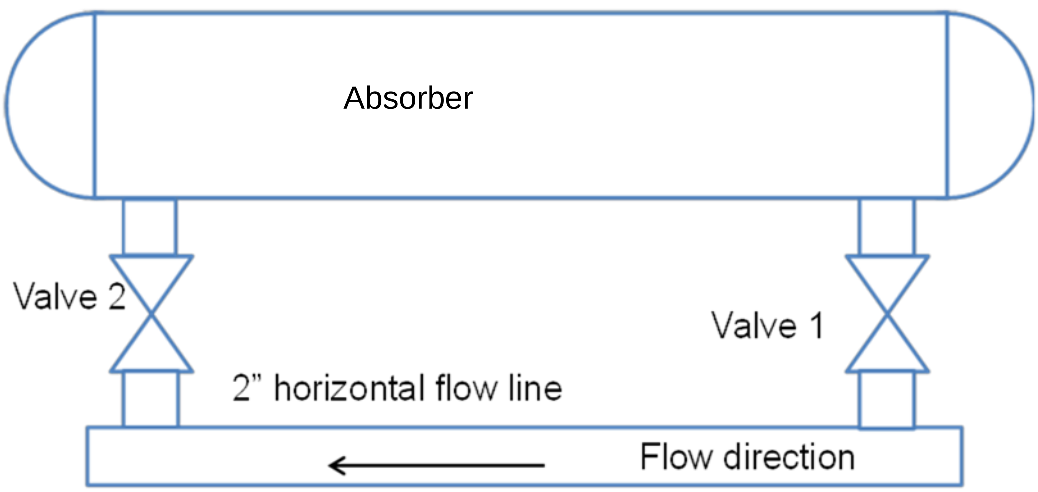


Figure 6-1 Intermittent absorber schematic

The absorber, the valves, and the connection to the 2" flow line are schematically shown in Figure 6-1. A detailed description of the vessel and experimental loop has been documented in Chapter 3.

An experimental matrix covering predominantly slugging conditions was defined for this study. Various flow behaviour observed has been presented in section 4.5 and the combined hydrodynamic slug regime showing the HIV behaviour is shown in Figure 6-2.

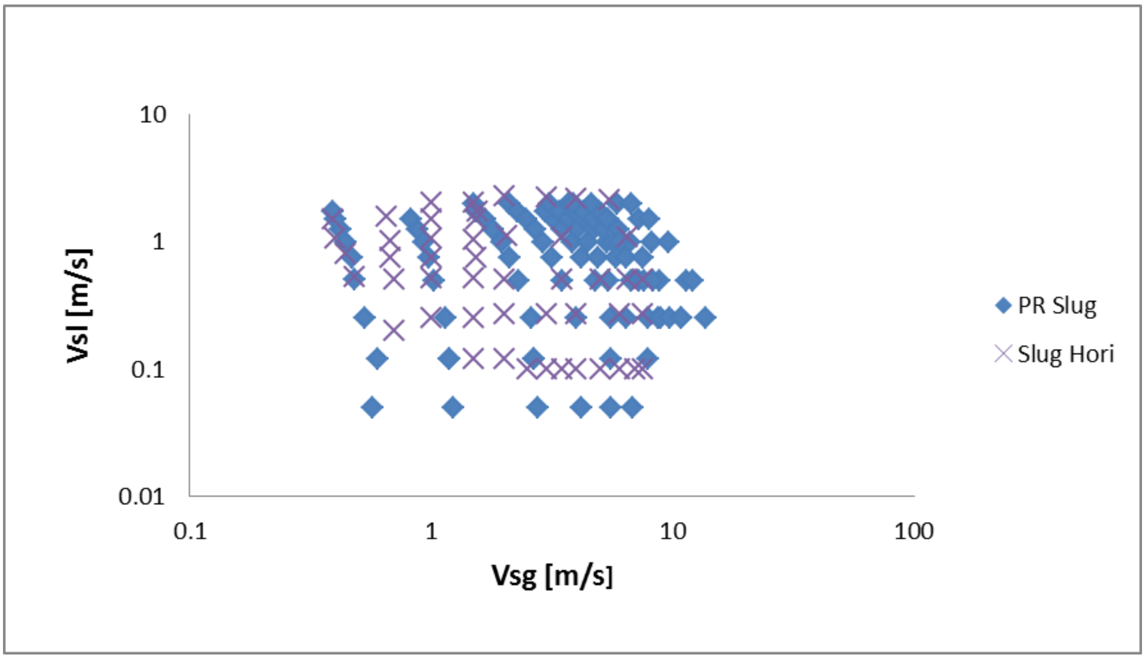


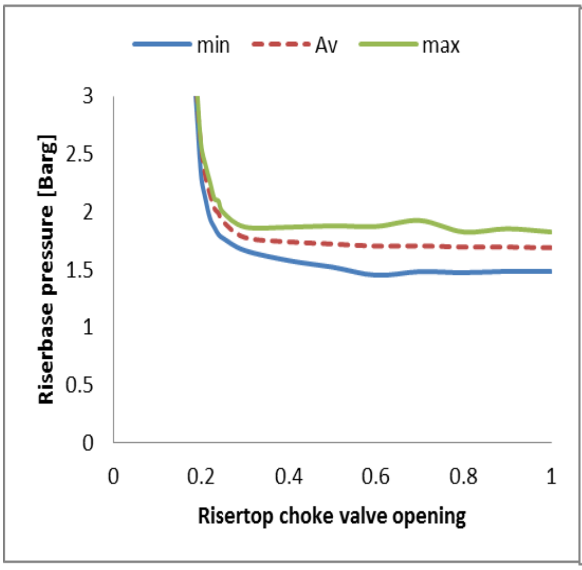
Figure 6-2 Hydrodynamic slug flow behaviour in pipeline-riser system

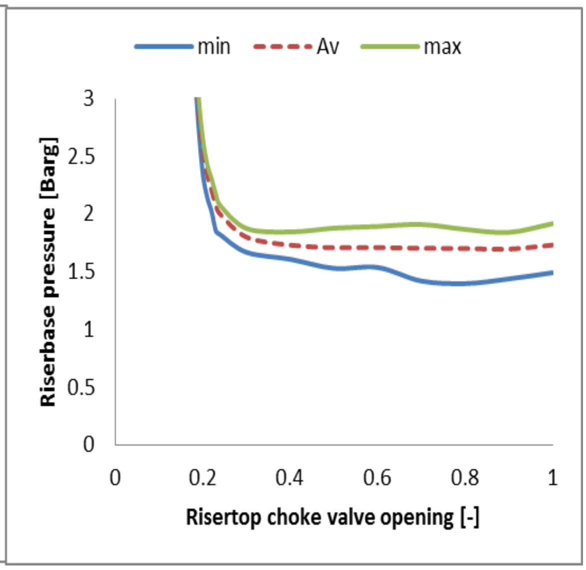
Representative slug flow condition from H and I- regions was investigated for various modes with and without choking and results presented next.

6.2.1 I-region hydrodynamic slug response to intermittent absorber

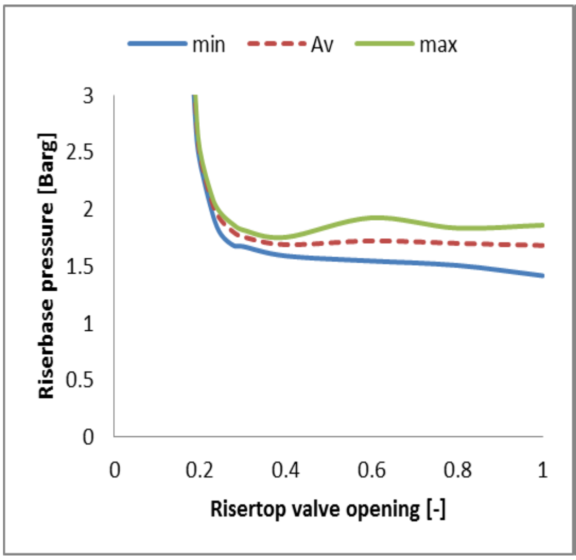
The first slug flow condition of 7 Sm^3/hr and 0.5 kg/s (0.71 m/s and 0.25 m/s superficial velocities) of air and water respectively was studied and the bifurcation maps are shown in Figure 6-3 for various operation modes.

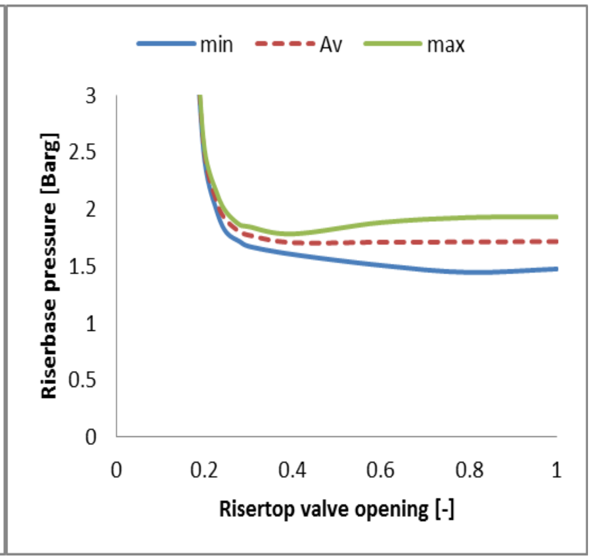
Figure 6-3 (a) shows the riserbase pressure bifurcation map for the isolation mode. The bifurcation occurs at 20% valve opening and average pressure value of 2.6 barg. Figure 6-3 (b) shows the riserbase pressure bifurcation map for mode 1 and the bifurcation was observed to occur at 20% and average pressure of 2.6 barg. The riserbase pressure bifurcation map for mode 2 is shown in Figure 6-3 (c). Here the bifurcation point was observed to occur at 23% valve opening and pressure value of 2.04 barg. Figure 6-3 (d) also shows the riserbase pressure bifurcation map for mode 3 with bifurcation point occurring at 23% valve opening and average pressure value of 2.04 barg. From the results it appears that the isolation mode and mode 1 behave alike while modes 2 and 3 are qualitatively same. The bifurcation points occurred at 20% valve opening and average pressure of 2.6 barg for isolation mode and mode 1 while the bifurcation occurred at larger valve opening 23% and lower pressure value of 2.04 barg for modes 2 and 3. The larger valve opening and lower pressure is evidently beneficial for larger production. This shows the contribution from the intermittent absorber. The attenuation benefit of the absorber was shown in modes 2 and 3 where the bifurcation occurred with additional 3% valve opening and 0.56 bar lesser pressure. This is in consonance with the theoretical analysis shown in section 5.5.





(a) (b)





(c) (d)

Figure 6-3 Riserbase pressure bifurcation map for 0.71m/s and 0.25m/s superficial velocities for air and water respectively (a) isolation mode (b) both valves opened (c) mode 2 (d) mode 3

6.2.2 H-region hydrodynamic slug response to intermittent absorber

Another slug flow condition of 30 Sm^3/hr and 2 kg/s (1.95m/s and 1.0m/s superficial velocities) of air and water respectively was studied and the bifurcation maps are shown in Figure 6-4 for various operation modes. Figure 6-4 (a) shows the riserbase pressure bifurcation map for the absorber in the isolation mode. The bifurcation occurs at 31% valve opening and average pressure value of 3.2 barg. Figure 6-4 (b) shows the riserbase pressure bifurcation map for the mode1 of the absorber. The bifurcation was observed to occur at 31% and average pressure of 3.2 barg. The riserbase pressure bifurcation map for mode 2 is shown in Figure 6-4 (c) . Here the bifurcation point was observed to occur at 33% valve opening and pressure value of 2.8 barg. Figure 6-4 (d) shows the riserbase pressure bifurcation map for mode 3 with bifurcation point occurring at 33% valve opening and average pressure value of 2.8barg.

From the results it was observed again that the isolation mode and mode 1 are qualitatively same while modes 2 and 3 behave alike. The bifurcation points occurred at 31% valve opening and average pressure of 3.2 barg for isolation mode and mode 1 while the bifurcation occurred at larger valve opening 33% and lower average pressure value of 2.8 barg for modes 2 and 3. The benefit of additional 2% valve opening with a lower average pressure is due to the introduction of the vessel. This was theoretically shown in equations (5.16) and (5.17)

The attenuation benefit of the intermittent absorber was shown in modes 2 and 3 where the bifurcation occurred with additional 2% valve opening and average pressure values less by 0.4 bar compared with the pressure reported in the isolation mode and mode 1.

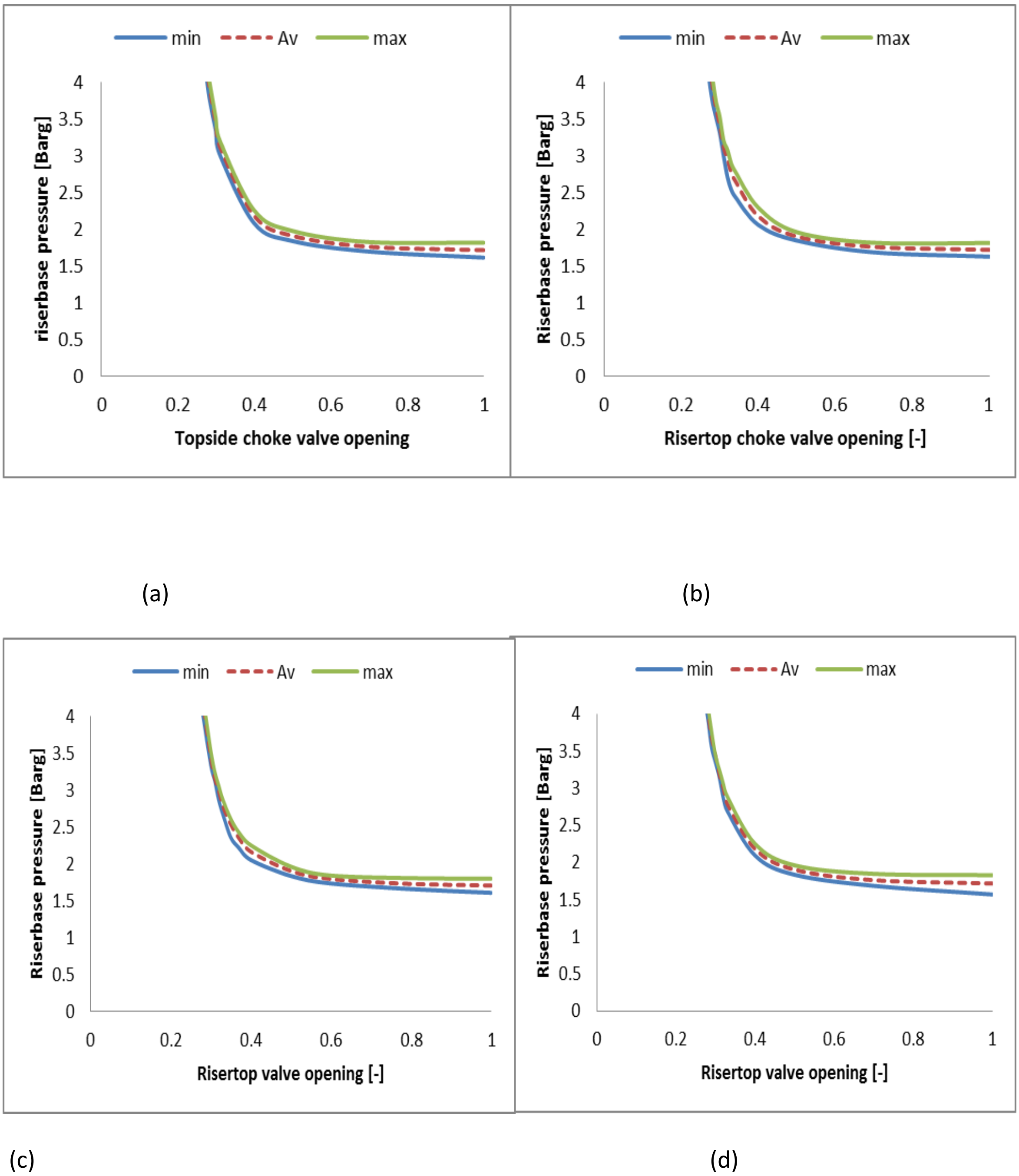
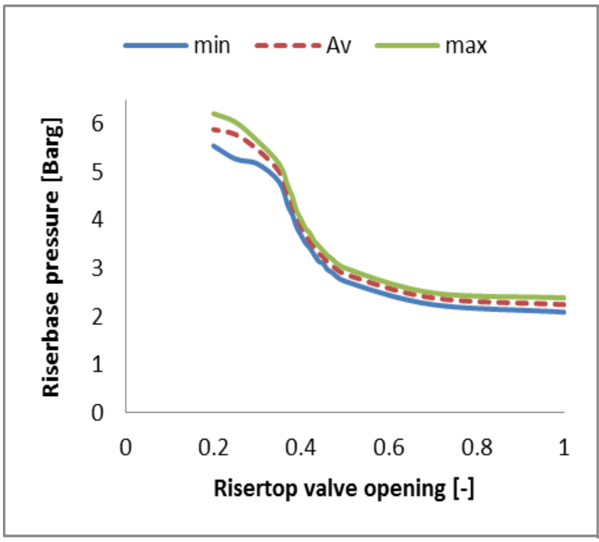


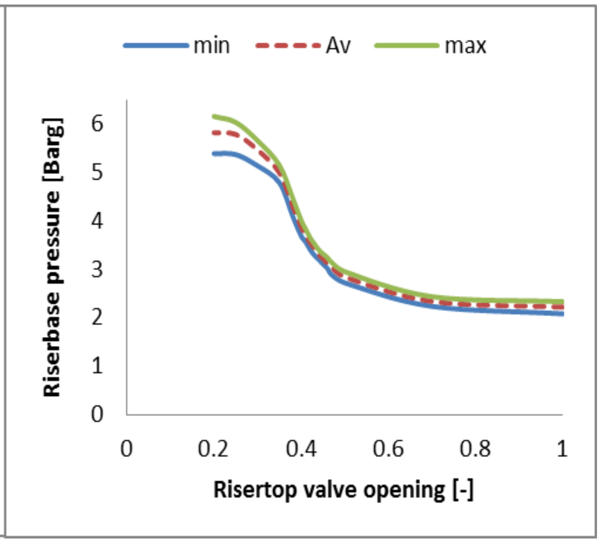
Figure 6-4 Riserbase pressure bifurcation map for 1.95m/s and 1.0m/s superficial velocities for air and water respectively (a) isolation mode (b) both valves opened (c) mode 2 (d) mode 3

6.2.3 Special H-region hydrodynamic slug response to intermittent absorber

At a flow condition of 75 Sm^3/hr and 3.5 kg/s (3.38 m/s and 1.72 m/s superficial velocities) for air and water respectively, a special behaviour of hydrodynamic slug flow was observed. For this flow condition, the risertop choking appears not to sufficiently attenuate the slugging and beyond a valve opening which could be taken as the bifurcation point, the overchoking induced phenomenon earlier reported in Yeung et al. [167] was observed. It is expected that as the valve opening reduces, the pressure fluctuation should also reduce and bring the system to stability. However it was observed that beyond a particular 'bifurcation point' the pressure fluctuation increases. The results are shown in Figure 6-5. Figure 6-5 (a) shows the riserbase pressure bifurcation map for the isolation mode. The 'bifurcation' occurs at 35% valve opening and average pressure value of 5.0 barg. This is similar to what is shown in Figure 6-5 (b) which is the mode 1 bifurcation map. Figures 6-5 (c) and 6-5 (d) show the bifurcation maps for modes 2 and 3. 'The bifurcation' point was observed to occur at 38 % valve opening and with about 4.4 barg average pressures. It was observed that choking the system beyond the bifurcation points aggravated the slugging instead of attenuating it. This observation was well captured in all the modes. The isolation mode and mode 1 are qualitatively same with no slug attenuation benefit accruable from the absorber while modes 2 and 3 behave and provide positive slug attenuation benefit. The additional 3% valve opening and lower average pressure benefit is due to the introduction of the vessel.



(a)



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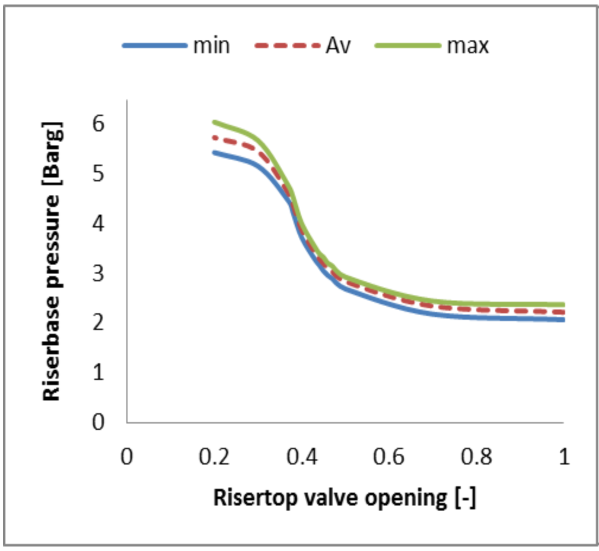

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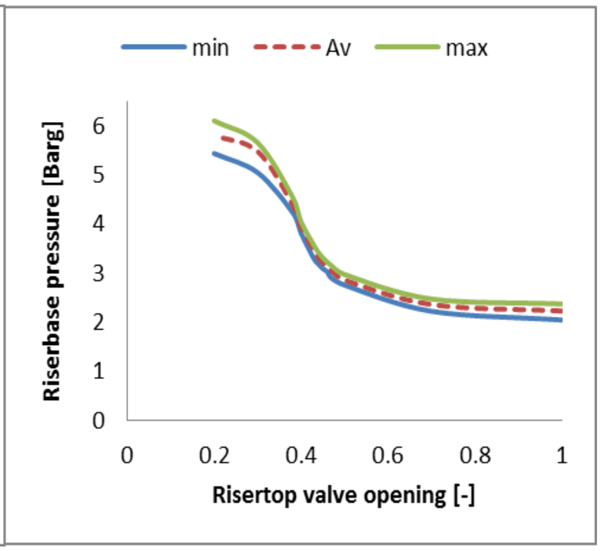


(d)

Figure 6-5 Riserbase pressure bifurcation map for 3.38 m/s and 1.72 m/s superficial velocities for air and water respectively (a) isolation mode (b) both valves opened (c) mode 2 (d) mode 3

6.3 Hydrodynamic slug attenuation potential of an intermittent absorber

In section 6.2, it has been shown that the intermittent absorber can provide additional benefit of stabilising slug flow at larger valve opening when combined with parameter variation technique compared with traditional parameter variation technique. This benefit was believed to be due to the interaction between the absorber and choking. This section was dedicated to investigating the slug attenuation potential of the absorber without choking qualitatively and quantitatively.

6.3.1 Qualitative investigation of slug mitigation potential of intermittent absorber

The flow regime map has been used as a qualitative method for investigating the slug attenuation potential of the intermittent absorber. Flow regime maps were developed for the pipeline-riser system with and without the absorber using the riserbase pressure and visual observation.

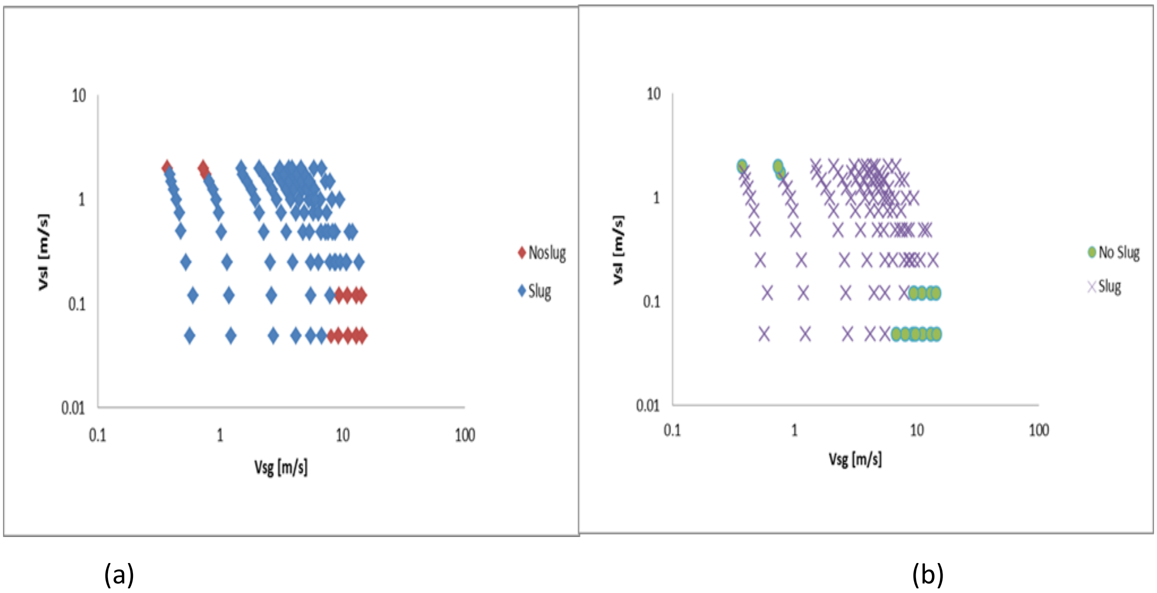


Figure 6-6 Flow regime map of pipeline-riser system (a) isolated (b) coupled

Figure 6-6(a) shows the flow regime map for the pipeline-riser system without the absorber .The blue diamond represent the region of slug flow while the red ones are the region of no slugging. Figure 6-6 (b) shows the flow regime map of when the absorber was coupled. The coupling of the absorber appears not to qualitatively affect the flow regime map. Using the riserbase pressure plots and visual observation, region of slugging with or without the absorber appears to be same. It is therefore important to develop a quantitative method for estimating the attenuation potential of the intermittent absorber concept.

6.3.2 Quantitative investigation of intermittent absorber benefit

Having observed that for the various flow conditions investigated, the flow regime maps of pipeline-riser system with or without the absorber are qualitatively same, a further investigation was conducted to ascertain any quantitative attenuation potential of the absorber. A slug attenuation index was defined for this purpose.

6.3.2.1 Hydrodynamic slug attenuation index (SAI)

The hydrodynamic slug attenuation potential of intermittent absorber was also investigated using a quantitative index known as slug attenuation index (SAI). Other authors including Sarica et al. [145] has developed similar index for severe slug elimination. However no such method exists for hydrodynamic slug attenuation. In this study, a new index for hydrodynamic slug attenuation has been defined for the first time.

The slug attenuation index (SAI) is proposed to quantify the attenuation capability of the absorber and it is defined as:

$$SAI = \left[\frac{(P_{max} - P_{min})_{isolated} - (P_{max} - P_{min})_{coupled}}{(P_{max} - P_{min})_{isolated}}\right] \times 100 \qquad \textbf{(6.1)}$$

P_{max}, P_{min} are the maximum and minimum values of riserbase pressure fluctuation. P_{max}-P_{min} is a measure of the magnitude of pressure fluctuation. This parameter was measured at 100% valve opening for the isolation mode which captures the maximum natural behaviour of the slugging in the system. Three classes of degree of attenuation were proposed: The total attenuation (TA), partial attenuation (PA) and no attenuation (NA). For SAI =100% total attenuation is expected, and 0<SAI<100 describes condition of partial attenuation while SAI ≤0 defines the no attenuation case. This attenuation classification was based on the visual observation during the experiment and the behaviour of the riserbase pressure fluctuation under the various conditions.

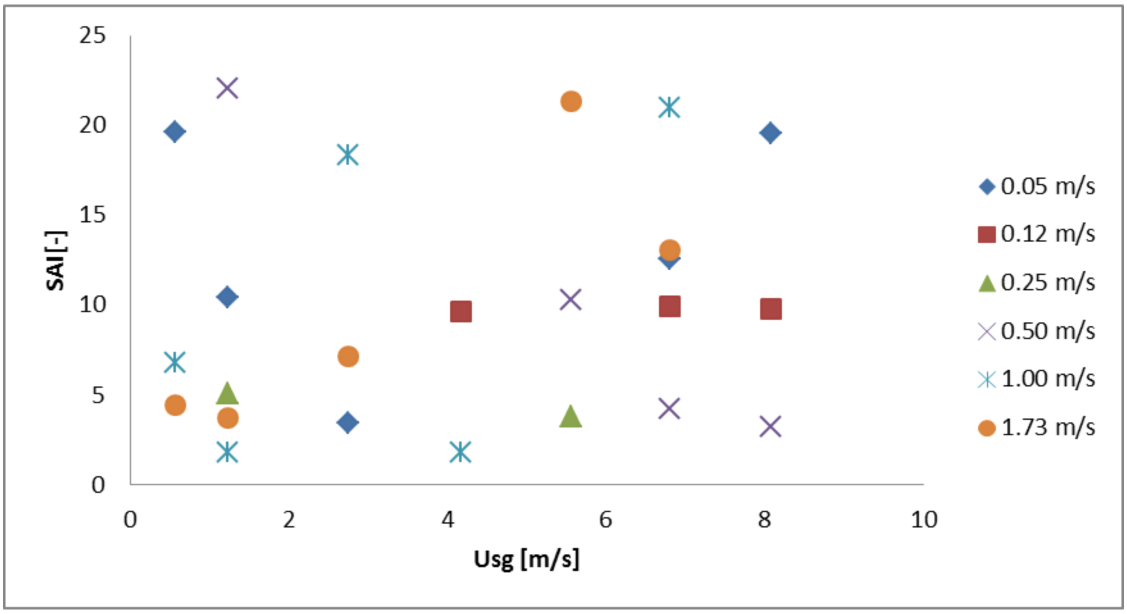


Figure 6-7 Slug attenuation index for intermittent absorber

Figure 6-7 shows the slug attenuation index plot against the gas flow rates for constant liquid flow rates. Interestingly, the vessel was shown to partially attenuate the slugging at various flow conditions across the flow regime map. At low gas and liquid flow rates of 0.57m/s and 0.049 m/s ((7Sm^3/hr and 0.1kg/s) for air and liquid respectively, the SAI estimated was about 20. This means that the absorber helped to reduce the pressure fluctuation by 20% of the original magnitude. The highest SAI of about 22 was recorded at moderate flow rates 0.5m/s and 1.23m/s (15Sm3/hr and 1kg/s) air and liquid flow rates respectively. This implies that the absorber was able to reduce the pressure fluctuation by about 22% of the original value. At high liquid and gas flow rates, absorber attenuation was still recorded with a SAI value of about 21 for 5.56 m/s and 1.73 m/s (60Sm^3/hr and 3.5 kg/s) air and water respectively. Similar value was also observed at 6.8m/s and 1m/s (75Sm3/hr and 2kg/s) for air and water respectively. The SAI analysis has provided a very useful insight into the slug attenuation capability of the absorber. Although no total attenuation was observed, the intermittent absorber can considerably reduce the pressure fluctuation due to slugging up to about 22%. This shows that the absorber can provide partial slug attenuation across the flow regime map but not total attenuation.

6.3.2.2 Statistical slug attenuation index (SSAI)

The accurate estimation of the pressure fluctuation magnitude is very important to quantifying the slug attenuation potential of the absorber. The SAI was defined based on pressure fluctuation magnitude estimated using arithmetic methods. However slug flow can exhibit some variance and random behaviour therefore a statistical method was explored to estimate the pressure fluctuation magnitude. The standard deviation was used as a measure of pressure fluctuation magnitude for cases with or without the intermittent and a new index, the statistical slug attenuation index (SSAI) was defined to quantitatively describe the ability of the absorber to attenuate slug flow.

It follows from SAI definition that SSAI is given as:

$$SSSAI = \left[\frac{(SD_{riserbase\ pressure})_{isolated} - (SD_{riserbase\ pressure})_{coupled}}{(SD_{riserbase\ pressure})_{isolated}} \right] \times 100 \quad \textbf{(6.2)}$$

Where SD is the standard deviation

Figure 6-8 shows the statistical slug attenuation index plot against the gas flow rates for constant liquid flow rates. Interestingly, like the SAI, the SSAI analysis shows that the vessel was able to partially attenuate the slugging at various flow conditions across the flow regime map although some points where the SAI shows attenuation, SSAI shows no attenuation.

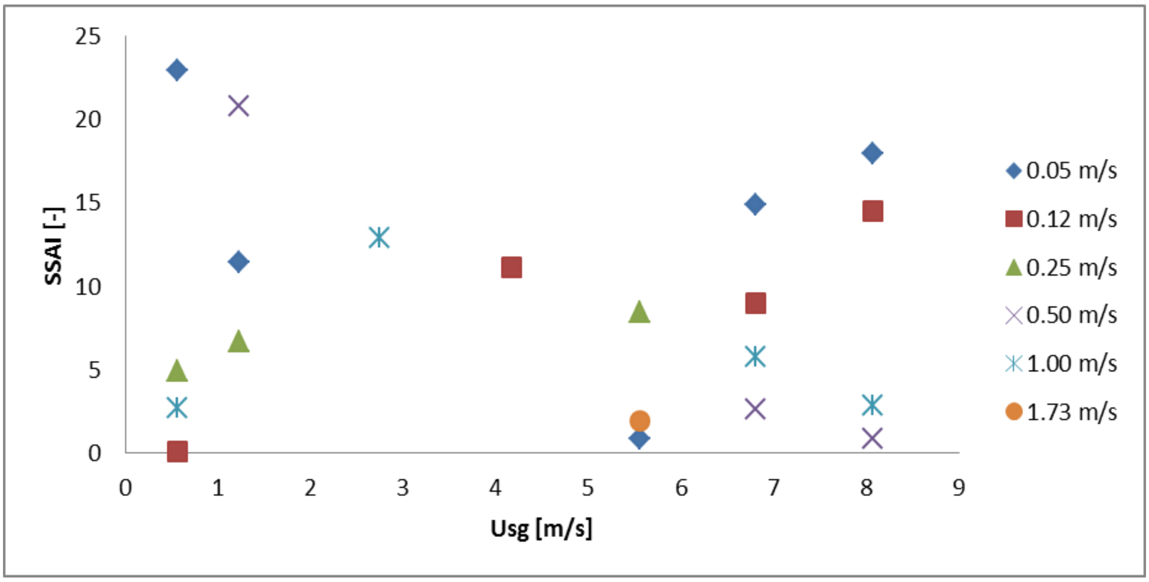


Figure 6-8 Statistical slug attenuation index for intermittent absorber

At low gas and liquid flow rates of 0.57m/s and 0.049 m/s (7Sm^3/hr and 0.1kg/s) for air and liquid respectively, the SSAI estimated was about 23 compared with value of 20 for SAI. This means that the absorber helped to reduce the pressure fluctuation by 23% of the original magnitude.

A SSAI of about 21 was recorded compared with SAI value of 22 at moderate flow rates 1.23m/s and 0.5m/s (15Sm^3/hr and 1kg/s) air and liquid flow rates respectively. This implies that the absorber was able to reduce the pressure fluctuation by about 21% of the original value. At high liquid and gas flow rates, absorber attenuation was still recorded with a SSAI value of about 2 for 5.56 m/s and 1.73 m/s (60Sm^3/hr and 3.5 kg/s) air and water respectively whereas SAI value estimated at same condition was about 21. For moderate gas flow rate and high liquid flow rates 1.23m/s and 1.73m/s (15Sm^3/hr and 3.5kg/s) SSAI value of about 15 was recorded compared with SAI value of 4 estimated at the same condition. The SSAI shows that the vessel can provide partial slug attenuation across the flow regime map like the SAI. However, the SSAI appears to be more conservative compared with SAI.

Although, both the SAI and SSAI appears to quantify the slug attenuation potential of the absorber, the results showed that at low flow rates the estimation by SAI and SSAI are considerably in the same range. However at higher flow rates it appears some conditions where attenuation was recorded for SAI was estimated not to enjoy attenuation using the SSAI. Therefore, conservatively, the SSAI appears to be a better approach to quantifying the slug attenuation potential of the intermittent absorber concept.

6.4 Discussion of slug attenuation mechanism for the intermittent absorber

The intermittent absorber helps to attenuate the slug pressure fluctuation using the compression and expansion property of gases. The compression/ expansion properties of gases have been previously explored for transient surge vessels in water pipeline systems [149; 150]. These vessels are designed with external or internal influencers to help provide pressure gradient between the vessel and the pipeline. In this study however, a ‘self-acting’ vessel was investigated for hydrodynamic slugging attenuation.

The results from all the flow conditions showed that for the absorber to provide slug attenuation benefits, one of the isolation valves must be opened while the other is closed. This shows that the absorber must be coupled to the unstable system as described in equations (5.15) and (5.16). The proposed mechanism of slug attenuation of the intermittent absorber is discussed next.

The vessel helps to stabilise the slug flow. Although no instrumentation on the vessel to provide pressure reading, it is reasonable to assume that the least pressure in the vessel will be in the magnitude of 1 barg which is the pressure value of the two phase separator when the system is pressurised. During slug flow, the pressure difference between the vessel and the flowline with the help of the T-junction helps separate some flow into the vessel and the multiphase flow through the run reaches downstream devices in a less problematic manner. The flow into the vessel increases the vessel pressure and when this exceeds the system pressure, compression takes place in the vessel.

Previous studies including Azzopardi and Whalley [176] have reported the effect of flow regime on the splitting behaviour at T-junction, there is no existing work on the behaviour of slug flow splitted into intermittent absorber through a T-junction. Prickaerts et al. [116] however, suggested three transient severe slug flow behaviour at T-junction leading to dual riser systems depending on the flow rate and the back pressure imposed by the topside choking. In this study, two transient behaviours have been proposed for the behaviour of hydrodynamic flow at the T-junction leading to the intermittent absorber and the pipeline upstream the two phase separator without choking.

At low flow rate, the absorber might receive only gas. It is expected that the gas tail following the slug liquid body is easily separated and flow into the absorber while the liquid slug flow through the choke valve in a less problematic manner. More choking would have been required to stabilise the multiphase slugging without the absorber helping to take off the gas from the slug flow. The gas taken off helps to provide a stabilising gradient as shown in section 5.5. Hence the partial slug attenuation recorded with SAI and SSAI.

At higher flow rate, the split ratios of flow into the absorber and run pipeline are expected to be different from that of the low flow rate. Here relatively small fraction of gas phase is expected in the run pipeline and small liquid fraction in the absorber. Since liquid is not compressible and no outlet for such flow into the vessel the liquid would fall back into the pipeline.

The ability of the absorber to optimise parameter variation technique (choking) has also been observed. In the isolation mode, the back pressure required to stabilise the flow is provided solely by the choke valve. However, during the operation modes 2 and 3 when the absorber is coupled to the pipeline-riser system, it was possible to stabilise the system at larger valve opening and lower pressure. This was because part of the transient flow has been splitted into the absorber. The remaining slug flow therefore passes through the valve and reaches the separator with less problematic fluctuations, hence the large valve opening and lesser pressure.

6.5 Summary

The possibility of stabilising hydrodynamic slug flow in a pipeline-riser system using choking and intermittent absorber was investigated. The concept has been shown to possess some slug attenuation capability and benefit. The experimental results showed that the intermittent absorber concept can indeed provide additional benefits of stabilising the flow at higher valve opening and lower pressure compared to traditional choking when one of the isolation valves is opened and the other closed. For the configuration where the two valves are closed or opened, no attenuation benefit was observed for the absorber. For all the conditions investigated, a minimum additional 2% valve opening and up to 3% valve opening translating to 0.4 bar and 0.6 bar reduction in average riserbase pressure could be accruable as a benefit of the intermittent absorber. This in practical sense means higher production.

The intermittent absorber was also observed to help attenuate special case of hydrodynamic slugs flow which exhibit overchoking induced slugging (OIS)

The intermittent absorber benefit has been investigated both quantitatively and qualitatively. The qualitative study was done using the flow regime map while the slug attenuation index and statistical slug attenuation index were used to quantify the potential benefits of the vessel. The flow regime map and physical observation could not be used to judge the slug attenuation capacity of the absorber. The SAI and SSAI provide a veritable tool for quantifying the slug attenuation potential of the absorber with SSAI given more conservative estimations. About 22% reduction in pressure fluctuation magnitude was recorded.

Further work was conducted on the severe slugging attenuation potential of the intermittent absorber. The next chapter is dedicated to this.

7 TAMING SEVERE SLUGGING AT LARGE VALVE OPENING WITH INTERMITTENT ABSORBER

7.1 Introduction

In the co-current flow of gas-liquid mixtures through pipeline-riser system, severe slugging is frequently encountered for wide range of pipe inclinations and flow rates. Severe slugging is a flow regime which can be described as a four stage transient cyclic phenomenon. At low flow rate, the liquid accumulates at the riserbase blocking the gas flow while the riser column get filled with liquid (slug formation stage), the gas is compressed in the upstream pipeline causing a pressure build-up which later becomes sufficient to overcome the hydrostatic head in the riser thereby forcing the liquid slug out of the riser (slug production stage). This is followed by a gas surge (gas blow out) and the remaining liquid in the riser fall back to the riserbase (liquid fall back stage) which again starts the cycle [3]. Severe slugging usually manifests in significant fluctuation of flow and pressure. This instability is as a result of the upward multiphase flow in the riser and compressibility of gas.

The threat of severe slugging to production facilities has been known since the 70's. This undesirable flow phenomenon continues to attract the attention of researchers and operators alike. The problem of controlling slugging has attracted much interest in the past decades[1; 4; 13; 15; 41; 48; 101; 109; 112; 121; 123; 125-127; 138; 143].

The most common method of mitigating severe slugging is by choking the valve at the exit of the riser which unfortunately could negatively affect production.

This chapter investigates a new passive attenuation method –the intermittent absorber for severe slugging in pipeline-riser systems. This is a non-feedback method which can be very useful most especially where a robust model which adequately describes the pipeline-riser is not available.

A series of experiments were conducted on the 4” pipeline-riser system with or without the intermittent absorber and the stabilising performance of this concept on severe slugging attenuation is shown using bifurcation maps and pressure benefit index. Numerical studies were also conducted using a commercial multiphase code OLGA and the slugging attenuation of this method was observed. The effect of the absorber size and the working principle disclosed.

This chapter is organised as follows: in section 7.2 the experimental investigation of severe slug attenuation potential of the intermittent absorber was attempted and its ability to optimise parameter variation technique was explored. Section 7.3 presents numerical studies on the severe slug attenuation potential of the method while the pressure benefit index was presented in section 7.4 and section 7.5 describes the proposed mechanism for the severe slug attenuation of intermittent absorber concept. The chapter is concluded in section 7.6.

7.2 Experimental investigation of severe slug attenuation in pipeline-riser system using intermittent absorber

Severe slugging in pipeline-riser systems can cause upset in topside process facilities. This undesirable flow phenomenon can manifest as a cyclic process with period of liquid production into the separator followed by period of no liquid production. This is undesirable due to the characteristic fluctuation in pressure and flow rates. The continuous intermittent large pressure fluctuation can lead to structural integrity issues and reduction in the life of the field while the large liquid production can lead to separator inefficiency and ultimate plant shut down.

7.2.1 Characterisation of slug flow in catenary riser systems

Severe slug flow in a pipeline-riser systems have been previously characterised by many authors as discussed in section 2.3 [29; 48; 50; 160]. In this study, the flow regimes observed in the 4” catenary riser have been classified into four categories based on physical observation, bifurcation maps and the riser pressure drop plots. These regimes are: Classical severe slugging (CSS), transitional severe slugging (TSS), oscillating continuous flow (OSC) and stable flow (ST).

Figure 7-1 shows the severe slugging flow regime map and the observed regimes are discussed next.

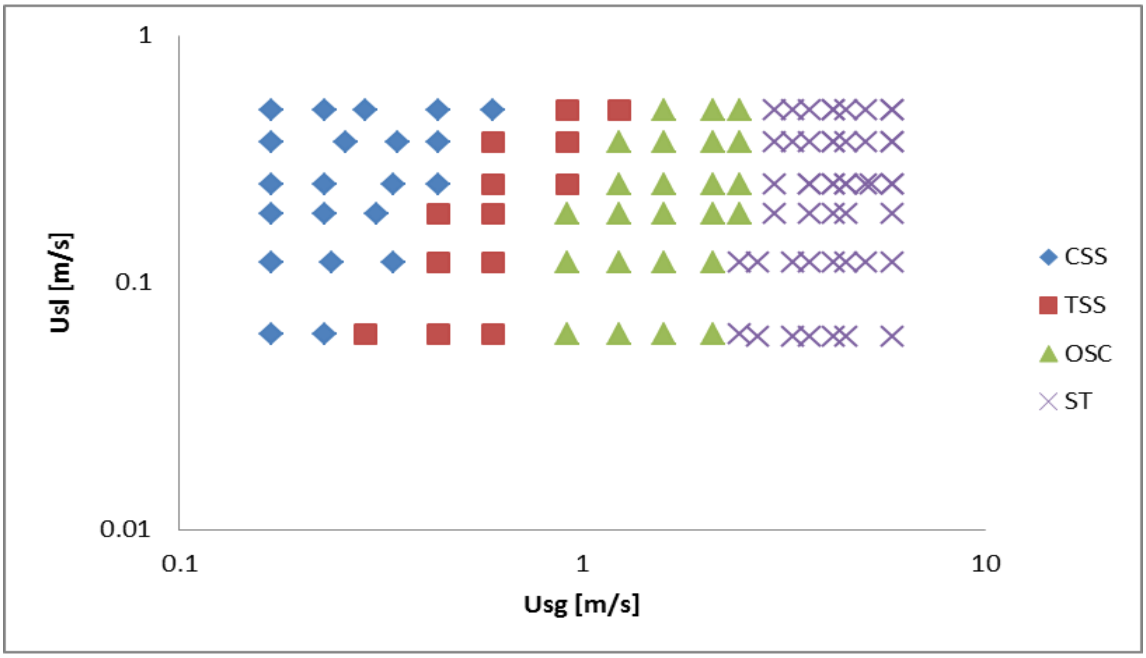


Figure 7-1 Severe slugging flow regime map for a catenary riser system

Classical severe slugging (CSS): This type of severe slugging is the traditional severe slugging that have been previously identified by many authors as either severe slugging or severe slugging type 1 [44; 47; 48; 50; 160]. Classical severe slugging was observed to exhibit cyclic behaviour that can be described in four stages; the slug formation stage, slug production stage, gas blow down and liquid fallback. Figure 7-2 shows the riser pressure drop response of a typical classical severe slugging. It could be seen that during the slug production stage, the riserbase was blocked and the liquid/gas interface moved far into the pipeline. The liquid level in the riser and the pipeline increases until the riser is filled with liquid. At this point the DP reaches maximum and the slug production begins characterised by a constant DP. This plateau is shown in Figure 7-2. The penetration of the gas bubble causes gas blow down and sharp drop in the pressure ensued as can be seen in the DP response. This sharp pressure drop is accompanied by liquid fall back in the riser since the pressure at the riserbase is no longer sufficient to transport the liquid up. This marks the beginning of another cycle. It was observed that the liquid/gas interphase moved into the pipeline during the slug formation stage, it could therefore be concluded that the severe slugging under this condition is of length greater than the riser height. This is in consonance with the observation of other authors including [48].

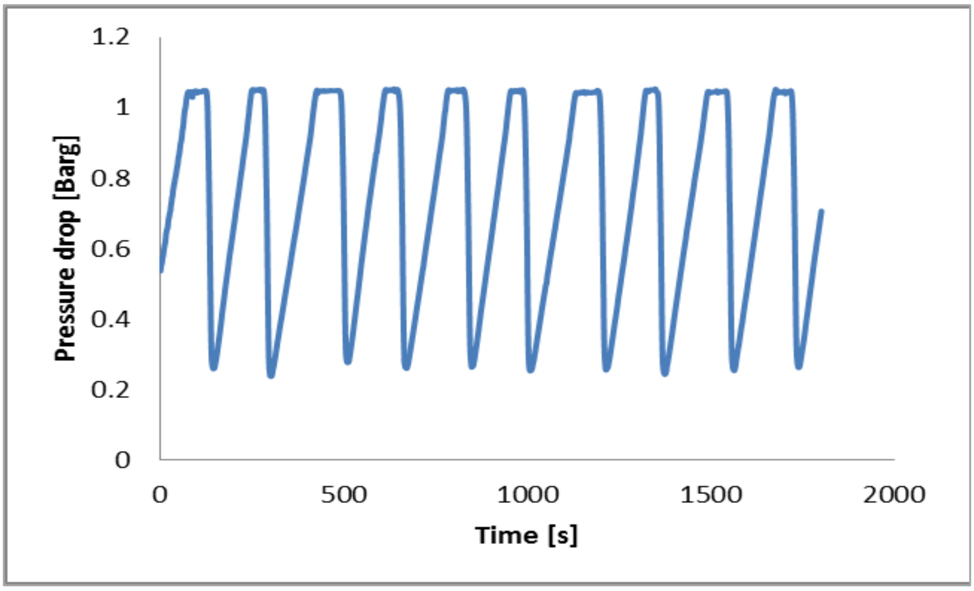


Figure 7-2 Riser pressure drop of Classical Severe Slugging condition

Transitional severe slugging (TSS): The transitional severe slugging is similar to the classical severe slugging (CSS), but the length is less or equal to the riser height. The gas/liquid interphase was observed close to the riser base and the liquid fall back was also observed. However the plateau constant behaviour of the DP typical of CSS was not observed. This implies that the gas blowdown occurs on or before the liquid filled the riser pipe and the slug production could be said to be very fast and of short period. Xing [48] has opined that the slug production stage is absent but in this study, it was observed that the slug production was present but occurred in a short time and more frequently. This is evident in the sharp maximum peak of the riser DP as shown in Figure 7-3. This type of slug possesses higher frequency compared to the CSS.

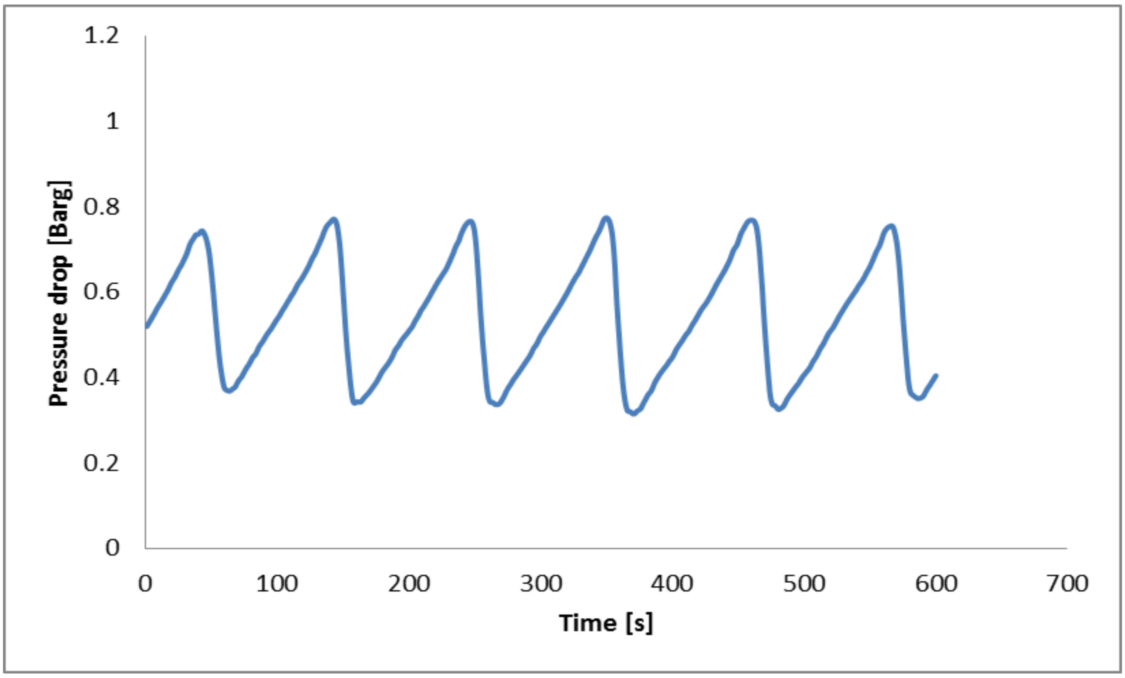


Figure 7-3 Riser pressure drop of Transitional Severe Slugging condition

Oscillating continuous flow (OSC): This type of riser slugging is characterised by flow of continuous oscillating slug precursors in the pipeline and riser. At the riserbase no liquid fall back or blockage was observed therefore this type of slug is of very short length and high frequency hydrodynamic slug or churn flow. The flow regime exhibit cyclic behaviour as shown by the riser DP in Figure 7-4, but the amplitude of the pressure drop fluctuations remained very small compared to the CSS and TSS.

Stable flow (ST): At considerably high flow rates, high frequency, short slugs and slug precursors are generated in the horizontal section upstream the riser pipe. Figure 7-5 shows the trend of pressure drop across the riser. These slugs and slug precursors were transported through the riser unchanged.

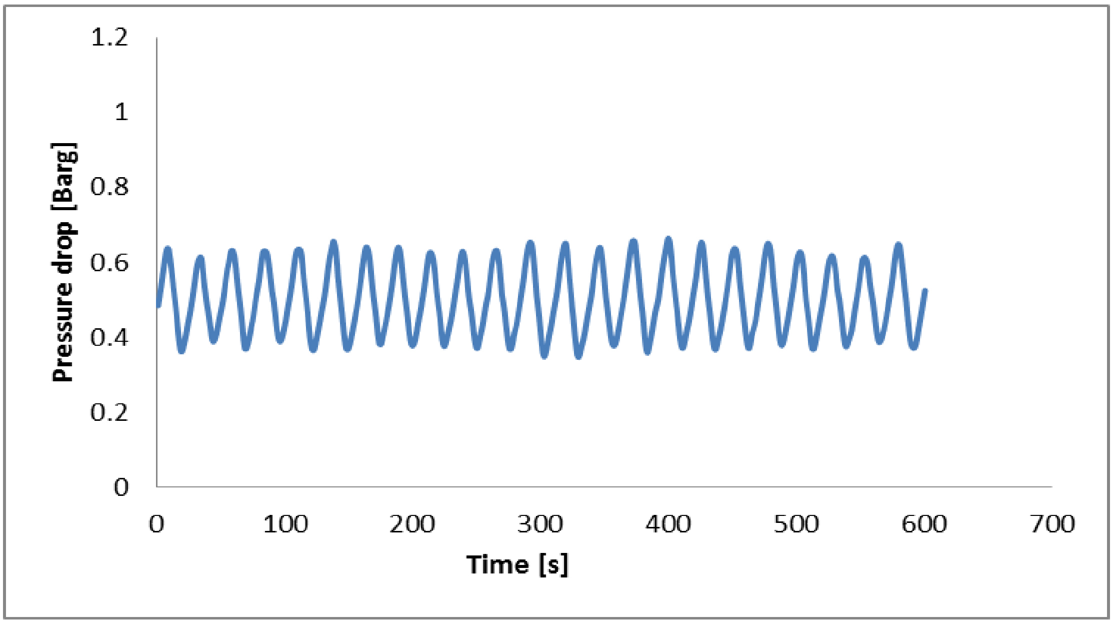


Figure 7-4 Riser pressure drop of Oscillating Continuous flow condition

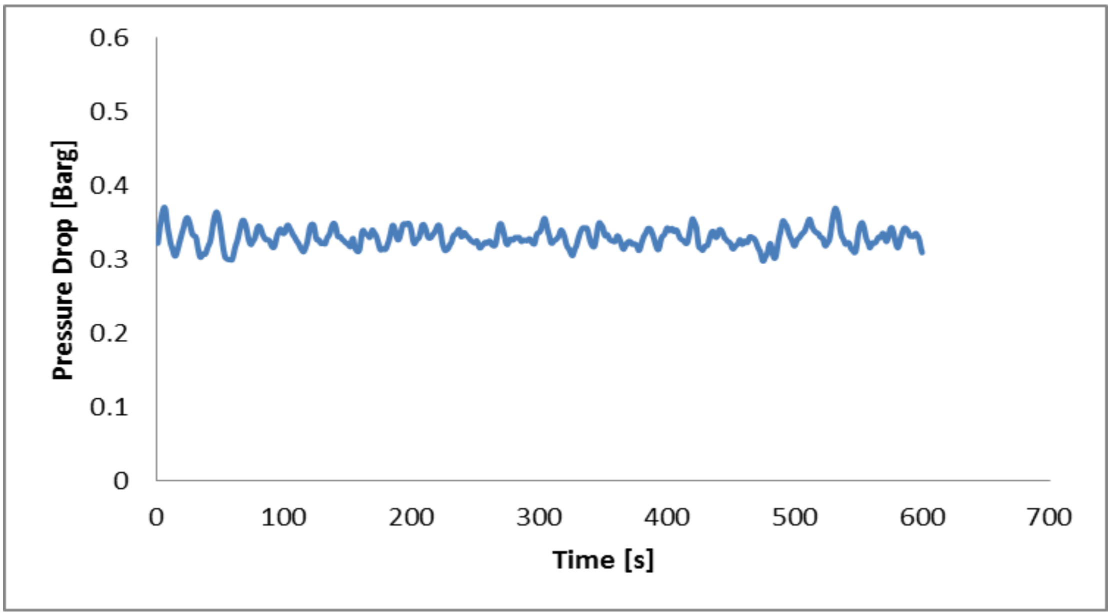


Figure 7-5 Riser pressure drop of stable flow condition

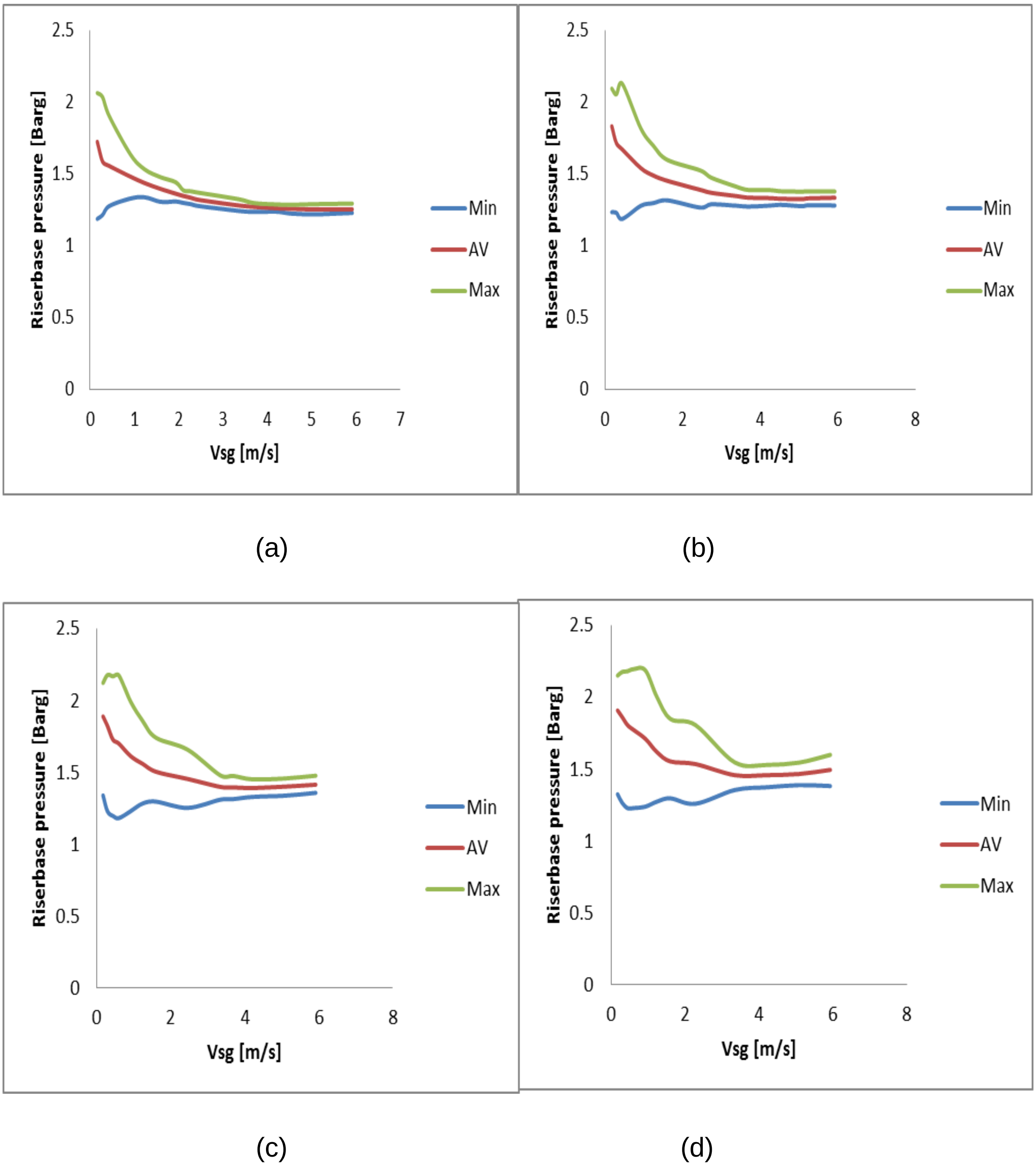


Figure 7-6 Riserbase bifurcation map for stability study at varying gas flow rates at constant liquid flow rates (a) Vsl =0.12m/s (b) Vsl= 0.25m/s (c) Vsl= 0.37m/s and Vsl =0.5m/s

Figure 7-6 shows that at low gas flow rate up to about 1m/s, the magnitude of the riserbase pressure fluctuations ranges between 0.8 and 1 Barg. This shows a typical CSS. As the gas flow increases, the slug behaviour changes TSS, OSC and stable flow regimes ensued.

A further analysis of the results for range of liquid and gas superficial velocities with the riserbase pressure was plotted against the superficial gas velocities at constant liquid velocities as shown in Figure 7-7. The system was broadly classified as stable and unstable flow using visual observation and the bifurcation maps shown in Figure 7-6. The result also shows that at considerably high liquid flow rate the riserbase pressure as a function of gas flow rate decreases to a minimum value and then increases as the gas flow rate increases. The negative slope is due to decrease in the liquid head (gravity dominated region) while the positive slope is as a result of increase in acceleration and frictional head. The regions to the left and right of the stability boundary are the unstable and stable flow regimes respectively.

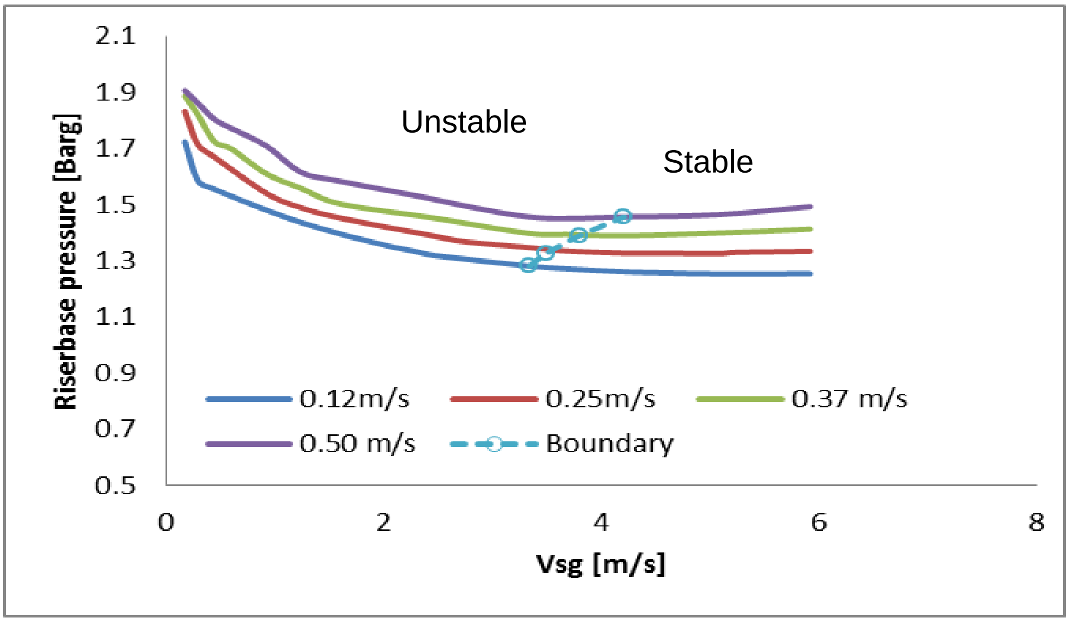


Figure 7-7 Stable and unstable flow regime at various gas flow rates and constant liquid flow rates

Having established the stability boundary for the various regimes in the pipeline-catenary riser system, the next objective is to investigate the slug attenuation potential of the intermittent absorber concept and its optimising capacity of the choking method. First, the impact of slugging on the separator was established, followed by the slug attenuation potential of the intermittent absorber.

7.2.2 Severe slug attenuation benefits of the intermittent absorber

The test separator serves as the gateway to the three-phase separator. In the industry such test separator is very strategic to the topside process equipment and its performance can be severely undermined by severe slug flow. It is therefore very important that such equipment be protected.

The impact of slugging on separator was first established. A non-slugging condition of 0.5kg/s and 150stm^3/hr for water and air respectively was investigated and the level controller was able to keep the level at 0.6m as shown in Figure 7-8. The parameter of a PI controller used for the level control is shown in Table 7.1

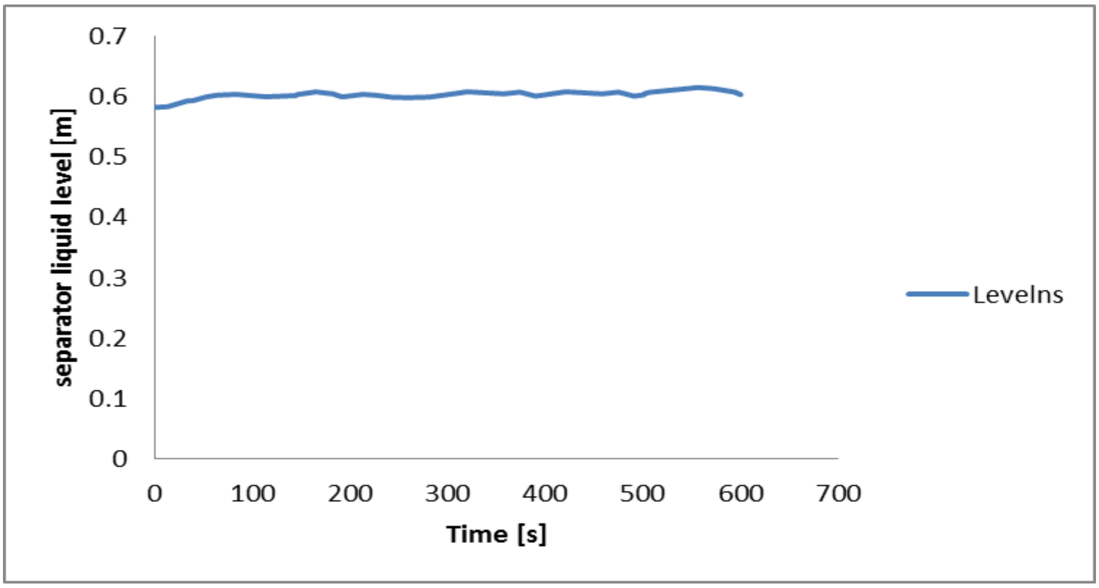


Figure 7-8 Separator liquid level control response for non-slugging condition

Table 7.1 PI controller parameter for separator liquid level control

Parameter	K_c	T_i(s)
Values	0.56	47.7

The effect of slugging on the separator level is shown in Figure 7-9. The level was observed to experience large fluctuation between 0.4 and 0.7m .This fluctuation is typical of severe slugging and is undesirable.

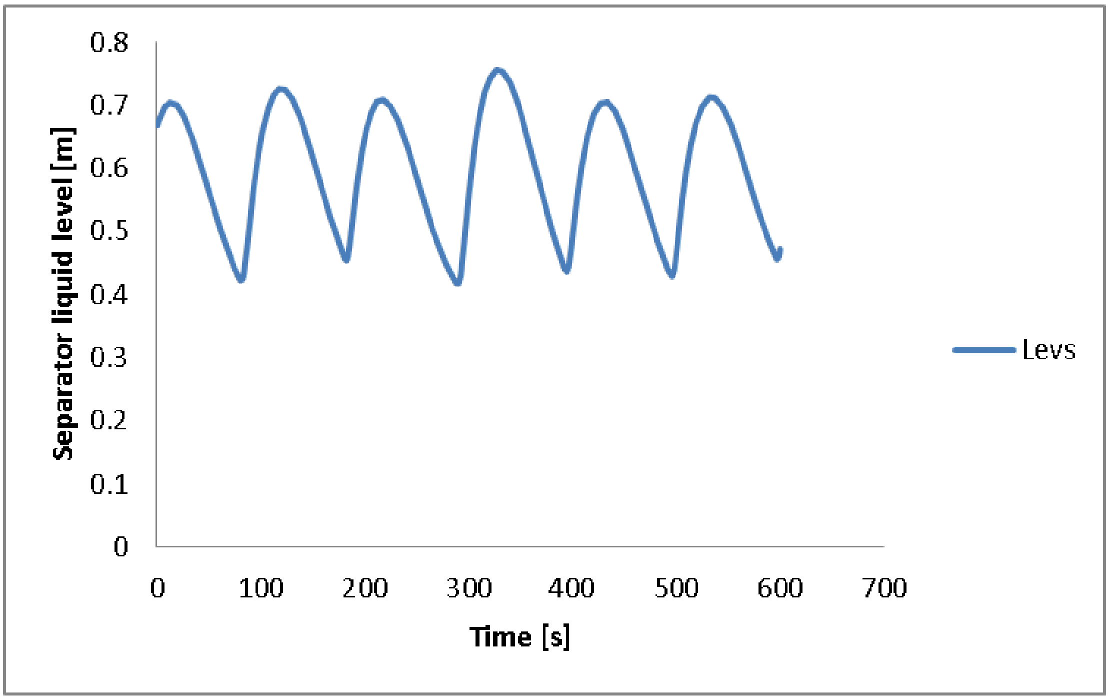


Figure 7-9 separator liquid level control response for slugging condition

Having established the impact of slugging on separator level control, the next objective is to carry out a stability study using the traditional parameter variation technique.

The stability study is needed to establish the bifurcation point in order to be able to ascertain the severe attenuation potential and optimising impact of the intermittent absorber on parameter variation technique. Ogazi [2] has discussed the need for any slug control strategy to meet the primary objective of stabilizing the flow and secondary objective of increasing production. In this study the secondary objective of increase in production would be based on the ability of the method to stabilise the system under the investigated flow condition in the open loop unstable region.

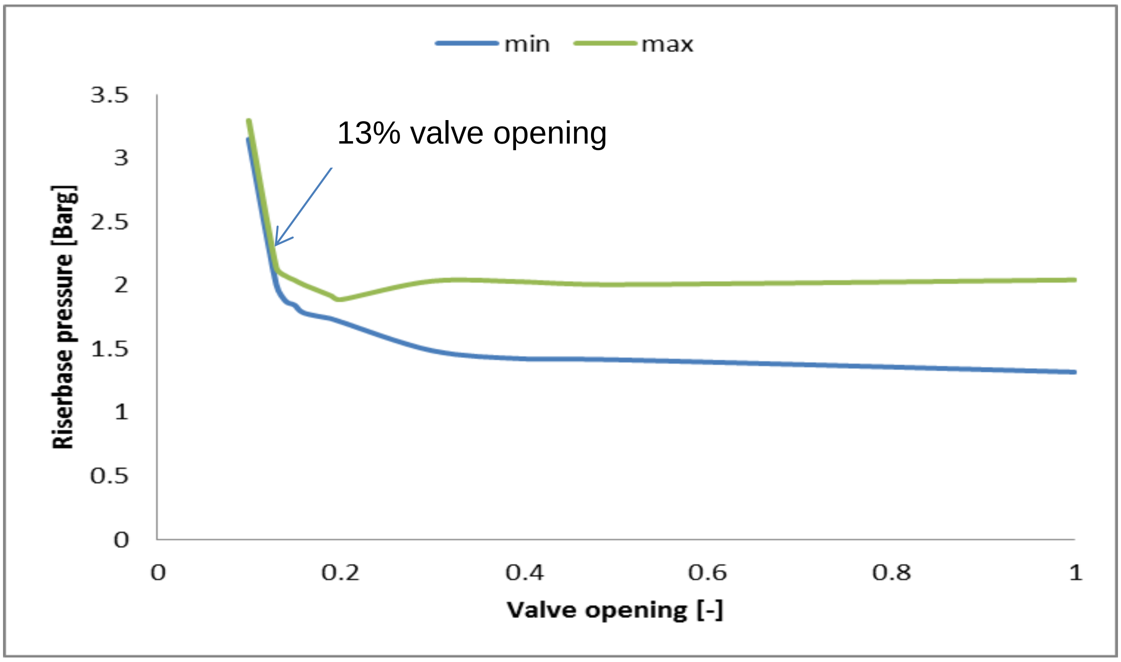


Figure 7-10 Riserbase pressure bifurcation map without absorber

The severe slugging attenuation impact of the intermittent absorber has been investigated for a typical classical severe slugging condition of 1kg/s and $20Sm^3/hr$ for water and air respectively and the results are presented next.

Figure 7-10 shows the riserbase pressure bifurcation maps for the severe slugging condition investigated without the absorber (isolation mode). The green line represents maximum pressure at various valve openings while the blue line represents the minimum pressure at various valve openings. It was observed that as the back pressure increases, the severity was reduced and most significantly at 30% valve opening, the slug nature in the pipeline-riser system changed from severe slugging to normal slug. Further choking later stabilised the system and the bifurcation occurred at 13% valve opening and average pressure value of 2.1 Barg.

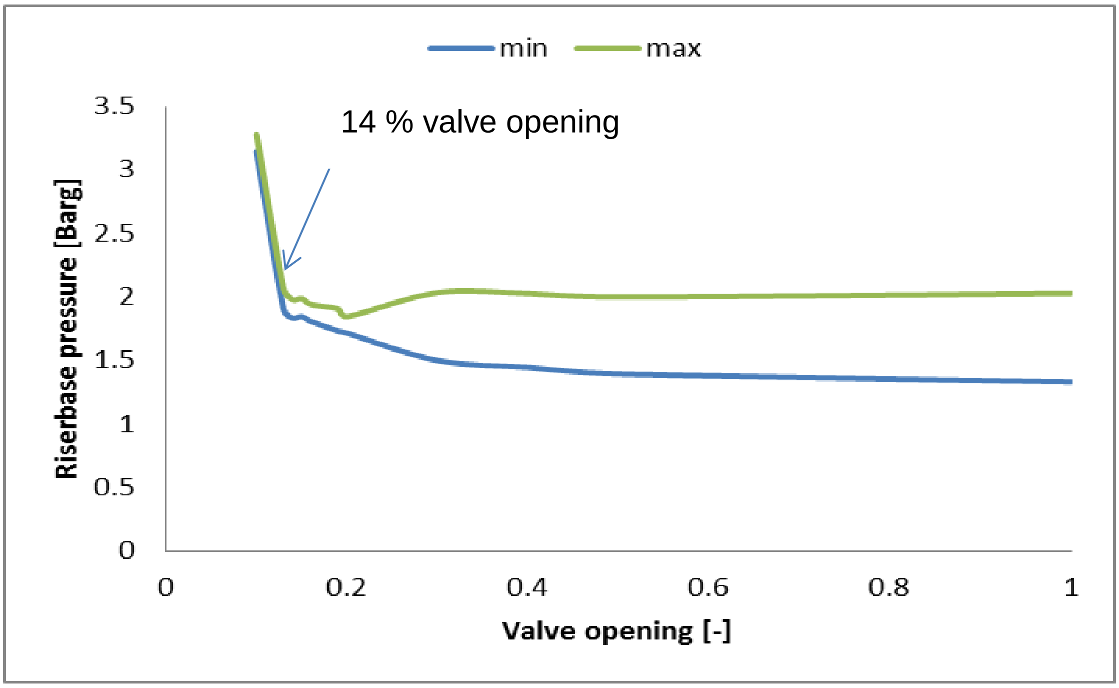
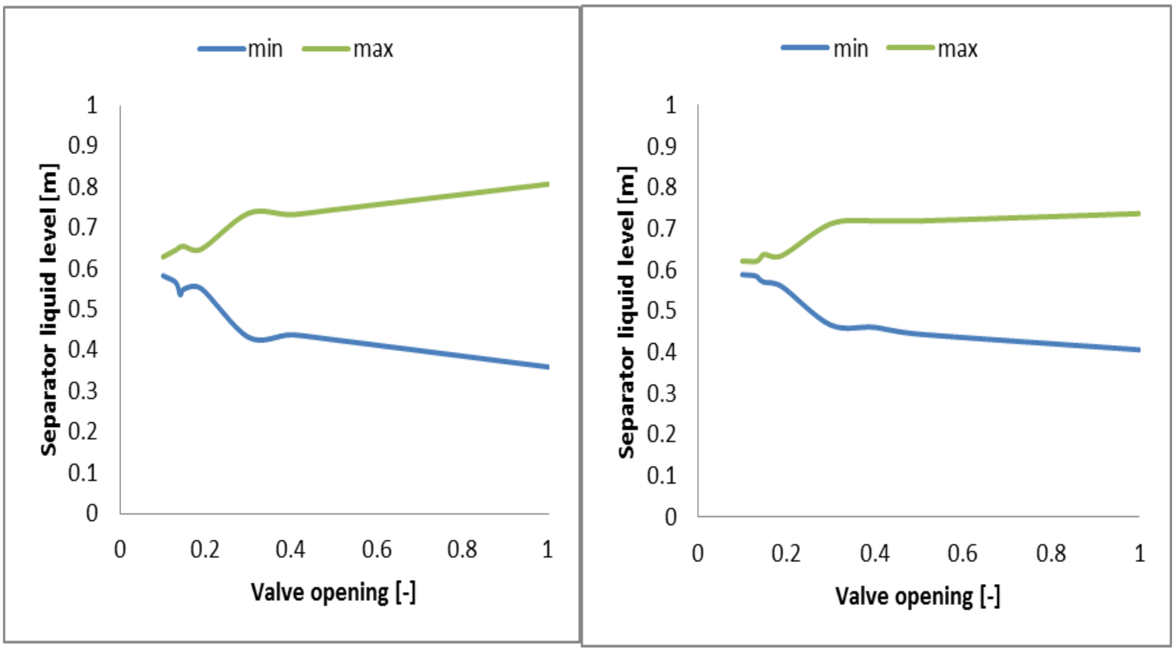


Figure 7-11 Riserbase pressure bifurcation map with absorber

Figure 7-11 shows the riserbase pressure bifurcation maps for the severe slugging condition investigated when the absorber was coupled to the system. Again it was observed that as the valve opening reduces from 100% towards 30% the back pressure increases and the slug severity was reduced and most significantly at 20% valve opening, the slug nature in the pipeline-riser system changed from severe slugging to normal slug. Further choking later stabilised the system and the bifurcation occurred at 14% valve opening and average pressure value of 1.91 barg. This benefit of 1 % additional valve opening and lower pressure was due to the intermittent absorber. This 1% gain can be explained using equation (5.15) and (5.16). Without the absorber, the valve needed to be choked down to 13% in order to generate sufficient back pressure to meet the criterion in (5.3) but the coupling of the absorber was able to help meet the stability requirement at larger valve opening of 14% and at lower riser base pressure of 1.91 barg. This translates to about 9% reduction in the riserbase pressure which would practically translate into increase in production since lower pressure means higher production [2].

Figures 7-12 shows the separator liquid level bifurcation maps for the cases with and without the absorber. It was observed that with or without choking, the intermittent absorber can help attenuate the separator liquid level fluctuation caused by the severe slugging.



(a) (b)

Figure 7-12 separator liquid level bifurcation map (a) without absorber (b) with absorber

At 100% for example, the separator liquid level fluctuation was reduced by 26%. This reduction can be traced to the intermittence absorption potential of the device. It has been proved in section 5. 5 and equation (5.18) that the device has stabilising potential. From 100% valve opening to about 20% valve opening, the mechanism of separator liquid level fluctuation attenuation appears to be different from that of below 20% valve opening. At larger valve opening, part of the flow was freely diverted into the intermittent absorber slowly thereby reducing the compressibility of the pipeline-riser system. This leads to the reduction in the intensity of the severe slugging reaching the separator at large valve opening. However at valve openings below 20%, the coupling effect due to both back pressure contribution from choking and absorber contribution helps to provide stability effect. The instability will therefore be dampened with the help of the absorber as a result of increase in the vessel pressure or pressure drop across the valve.

7.3 Numerical investigation of severe slugging attenuation using choking and absorber in pipeline-riser system

The experimental set up described in section 3.4 was modelled using multiphase simulator OLGA (Version 7.3.0 released in 2014). This study was performed to support the theoretical analysis and experimental observation that the intermittent absorber possesses severe slugging attenuation potential.

7.3.1 Modelling and simulation of 4" pipeline-riser system

The 4" pipeline-riser system was modelled in OLGA to reproduce the experimental observation. A simplified geometry was developed and discretised and grid convergence study was carried out. It was observed that a grid resolution of 2m and 1.35m are good enough for the pipeline and the riser respectively. A total of 30 grid cells were used for the pipeline-riser system with additional 4 grid cells for the 1m horizontal pipe linking the risertop to the two phase separator. The absorber was initially modelled as a 2" pipeline-riser system as configured for the experiment to proof the concept. The temperature transmitters in the experimental loop indicated that the temperature is in the neighbourhood of 15^{o}C. This value was used for the numerical study. A constant mass flow source inlet and pressure node outlets downstream the two phase separator were specified as boundary conditions. The internal node was used as a splitter to couple the absorber to the 4” pipeline-riser system.

7.3.2 Stabilising effect of the intermittent absorber

The severe slug attenuation capability of the intermittent absorber has been reported in section 7.2.2 for a typical classical severe slugging condition of 1kg/s and 20Stm3/hr for water and air respectively. A numerical study was conducted on the same slug flow condition and the results are presented next.

The bifurcation maps were generated for both isolation and coupled mode. The isolation mode describes the situation when the intermittent absorber was isolated from the pipeline-riser system while the coupled mode refers to the case when the intermittent absorber was coupled to the pipeline-riser system.

Figure 7-13 shows the separator liquid level bifurcation map for OLGA prediction and experimental results in isolation mode. The solid lines represent the experimental values while the dotted lines represent the OLGA predictions. The dotted blue line represents the maximum liquid levels at various valve openings while the purple represents the minimum values. For the experimental results, the green line represents the maximum while the solid blue line represents the minimum liquid levels at various valve openings. Although the software was able to reproduce the bifurcation point (13% valve opening), there was slight difference in magnitude of the liquid level fluctuations. OLGA appears to slightly over predict the fluctuation compared with experimental results.

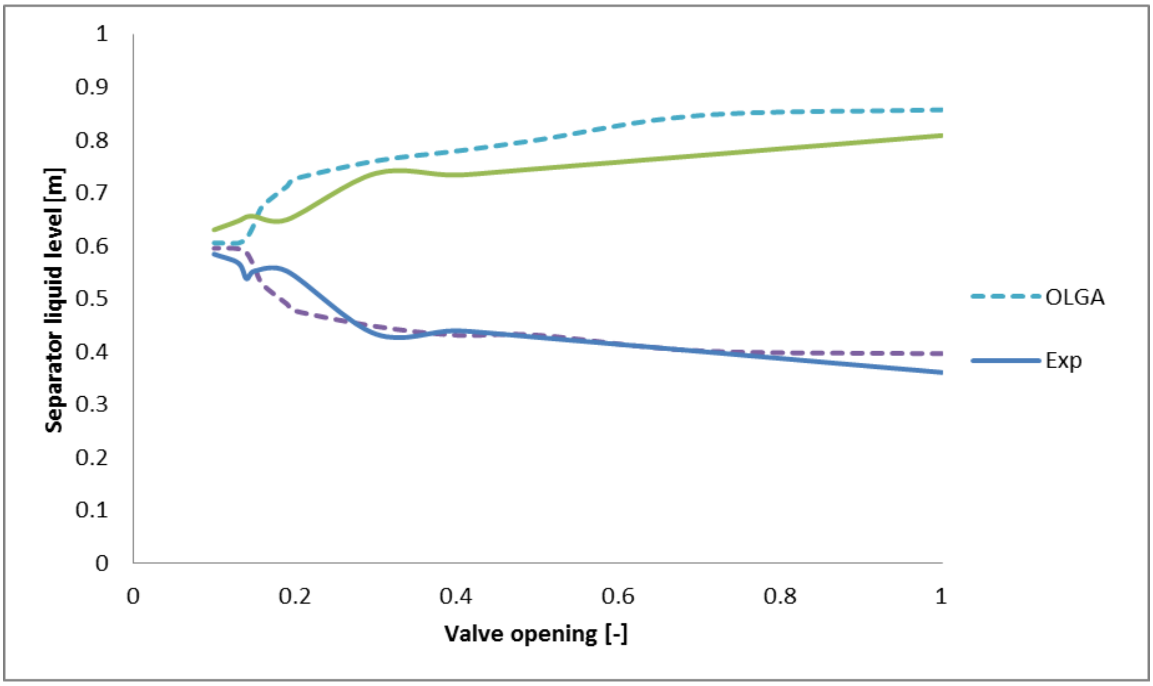


Figure 7-13 Separator liquid level OLGA prediction compared with Experiment in isolated mode

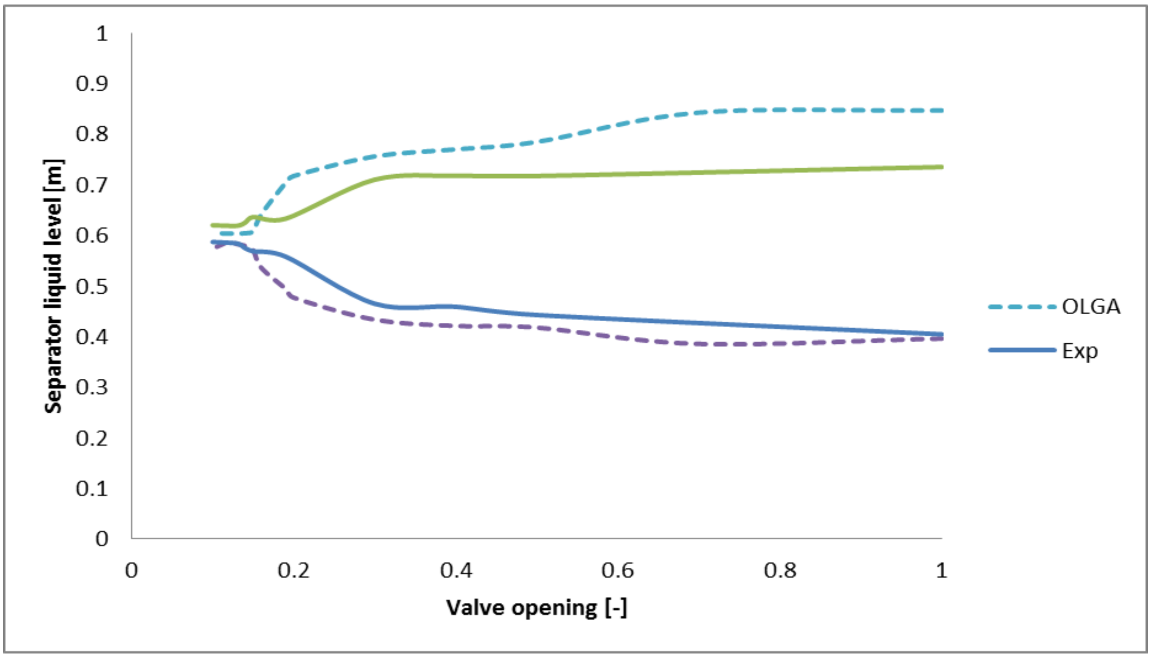


Figure 7-14 Separator liquid level OLGA prediction compared with Experiment in coupled mode

Figure 7-14 shows the separator liquid level bifurcation map for OLGA prediction and experimental results in coupled mode. Although the software was able to reproduce the bifurcation point (14% valve opening), there was slight difference in magnitude of the liquid level fluctuations. Again OLGA appears to slightly over predict the fluctuation compared with experimental results.

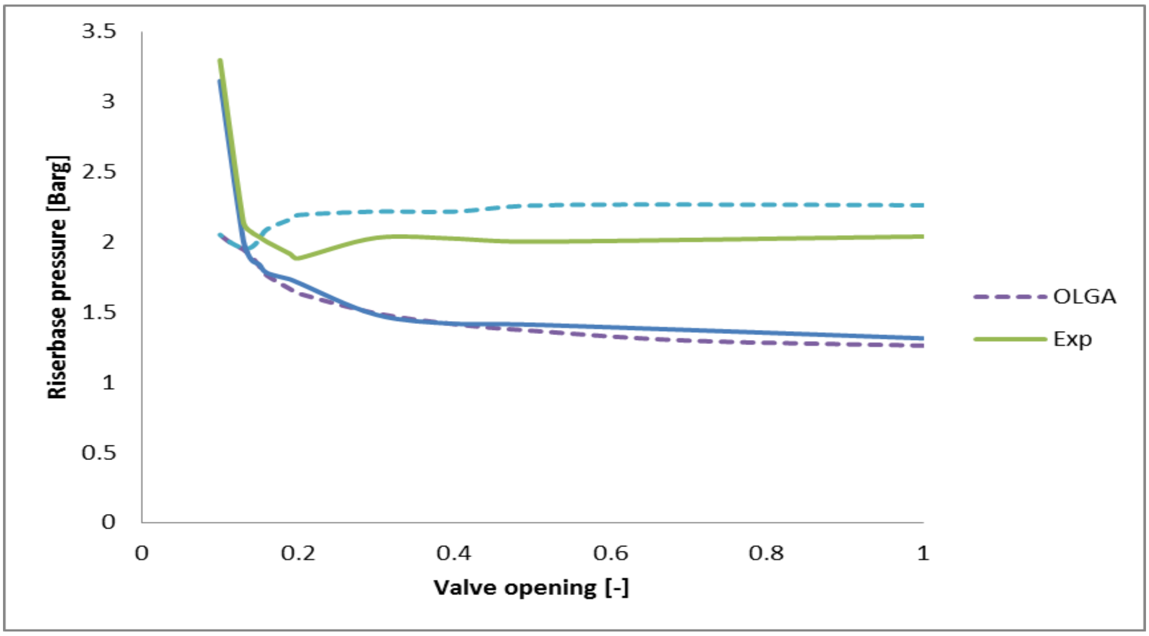


Figure 7-15 Riserbase pressure OLGA prediction compared with Experiment in isolation mode

Figure 7-15 shows the riserbase pressure bifurcation map for OLGA prediction and experimental result in isolation mode. The solid lines represent the experimental values while the dotted lines represent the OLGA predictions. The dotted blue line represents the maximum pressure values at various valve openings while the purple represents the minimum values. For the experimental results, the green line represents the maximum while the solid blue line represents the minimum pressure values at various valve openings. As was previously observed for the separator liquid level bifurcation maps, the software slightly over predicted the fluctuation magnitudes. However, the 13% bifurcation valve opening was well reproduced by OLGA. Similar trend was observed for figure 7-16 which showed the comparison between the riserbase pressure bifurcation maps of OLGA prediction and experimental results for coupled mode. However, the 14% valve opening for bifurcation point was well reproduced by OLGA.

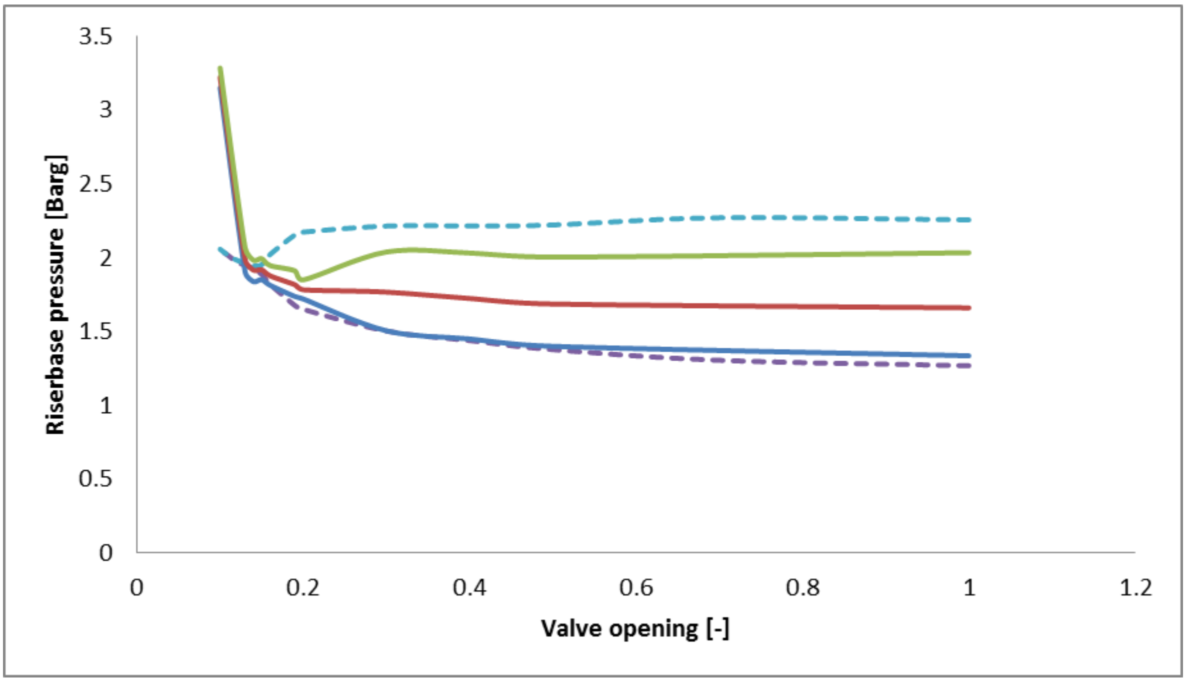


Figure 7-16 Riserbase pressure OLGA prediction compared with Experiment in coupled mode

It has been shown that the absorber has the potential to meet the primary objective of stabilizing flow and secondarily at larger valve opening. The absorber is a self-acting device without any influencer unlike the surge arrestors in water pipeline application where an internal or external influencer helps to pressurize the precharged gas in the vessel [149; 150] . The pressure needed to achieve compression for absorber is derived from the slug force which helped to compress the gas in the vessel. The experimental observation shows that back pressure propagated from topside choking interacts with the absorber. This is the practical implication of equation (5.15) and (5.16) which describes the augmented system. When the slug flows across the coupling section, part of the intermittence is absorbed by the absorber and the rest multiphase fluid flow through the choke valve into the separator in a less problematic manner.

The choking helps to change the severe slugging to short slugs which are still able to cause slight perturbation at the separator. However, the application of absorber helps to further attenuate this fluctuation by absorbing part of the intermittence. The absorber also receives back pressure propagated from the choking which helps to compress the gas in it and ultimately helps optimise the attenuation strategy. At large valve opening, the intermittent absorption potential of the absorber is the dominating mechanism while the back pressure optimisation is the dominating mechanism at smaller valve openings.

7.3.1 Effect of intermittent absorber on stability boundary

Figure 7-17 displays the riserbase pressure over a range of superficial gas and liquid velocities. The figure shows that for a constant liquid flow rate, the riserbase pressure decreases to a minimum value and then increases for increasing gas flow rates. The regions to the right and left of the minimum value represent the stable and unstable flow regimes for the pipeline-riser system respectively. This is similar to what was experienced for the experimental study shown in Figure 7-7. The code was able to predict the boundary at relatively same level for high flow rates. However the stability boundaries are not quantitatively same at low flow rates.

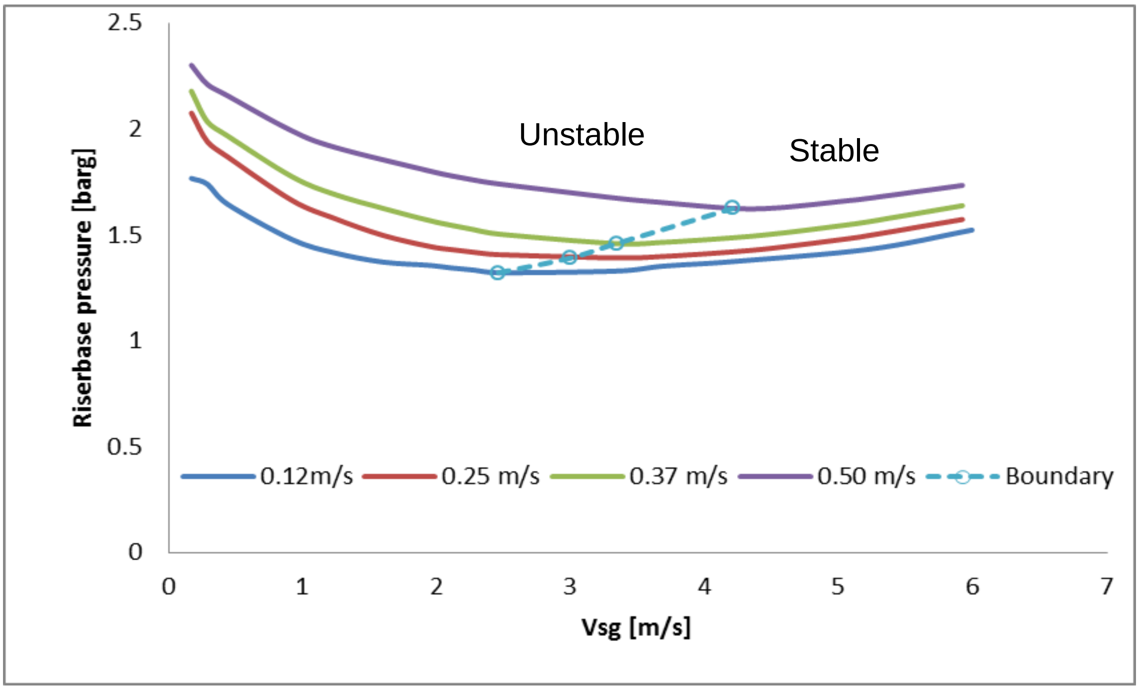


Figure 7-17 stability curve at various gas flow rates and constant liquid without slug control

A further study was conducted to see the impact of choking and intermittent absorber on the stability boundary. Figure 7-18 shows the effect of choking for a typical slug flow condition 2 kg/s (0.25 m/s) water flow rate and for various gas flow rates when the choke valve was closed down. The unstable and stable regions for case with and without choking are represented with red US and S, black US and S respectively. The stability boundary was shifted leftwards from 3.34 m/s to 1.24 m/s but unfortunately at a cost. The pressure at minimum point rose from 1.39 to 1.90 barg. However, it appears the cost is small compared with significant increase in the stable region. This shows that combination of choking and pipeline gas increase can be an effective method for slug control. This is in consonance with previous proposition that choking and gas injection methods are complimentary with choking helping to reduce the volume of gas required for stability, gas injection helps to reduce the degree of choking needed thereby reducing the back pressure imposed on the system [4; 123; 125].

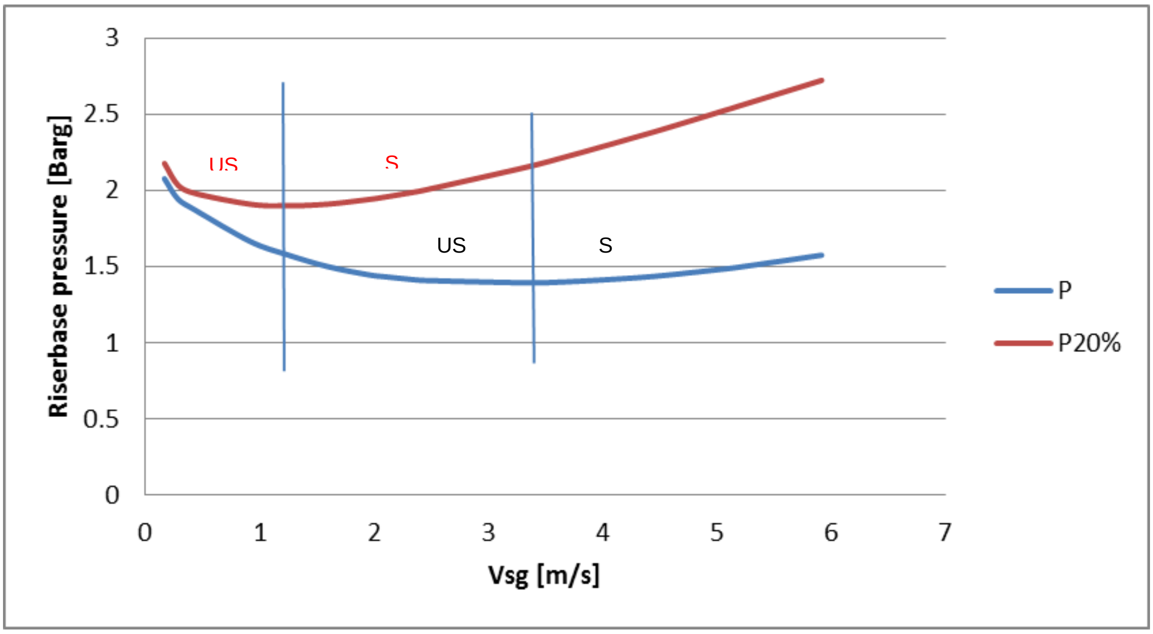


Figure 7-18 Use of choking to obtain stable flow

Figure 7-18 has shown that the use of choking for slug flow stability comes at a cost. To illustrate that this cost can be reduced with aid of the intermittent absorber, the gas flow was kept constant while the valve opening was varied and the absorber was coupled to the system. It was observed that with the help of the absorber, the system was stabilised at a lower pressure as shown in Figure 7-19. The absorber helped to reduce the riserbase pressure by 4% and reduced the pressure drop across the valve by 26%. This result supports the theoretical investigation performed in chapter five. With the help of the intermittent absorber, the degree of freedom of the system is increased and stability can therefore be achieved at larger valve opening.

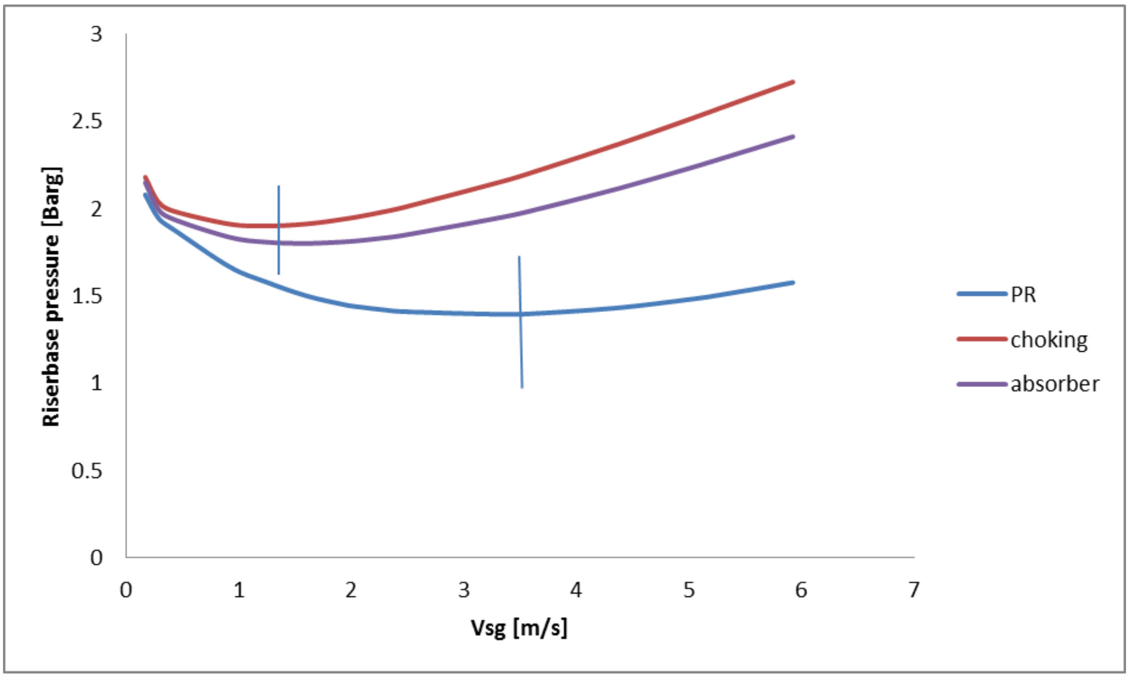


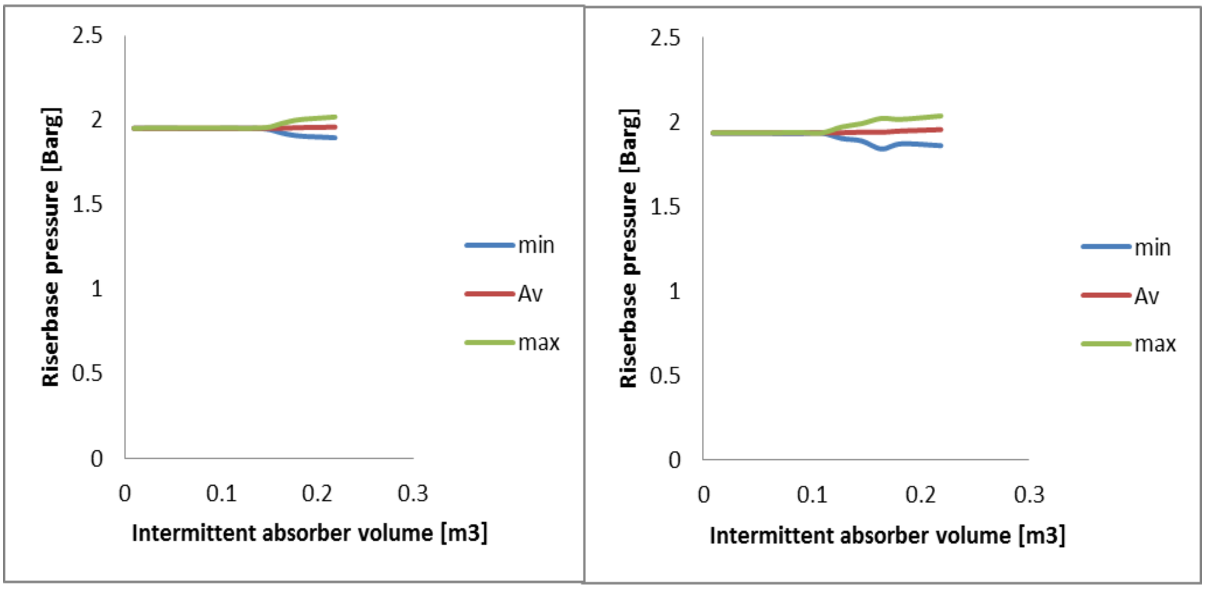
Figure 7-19 Impact of intermittent absorber on stability boundary

7.3.2 Sensitivity study of absorber volume on slug attenuation

A sensitivity study was conducted on absorber volume effect on severe slugging attenuation. The internal node was used as a splitter to split flow into another pipeline (absorber) and isolated with the help of isolation valve.

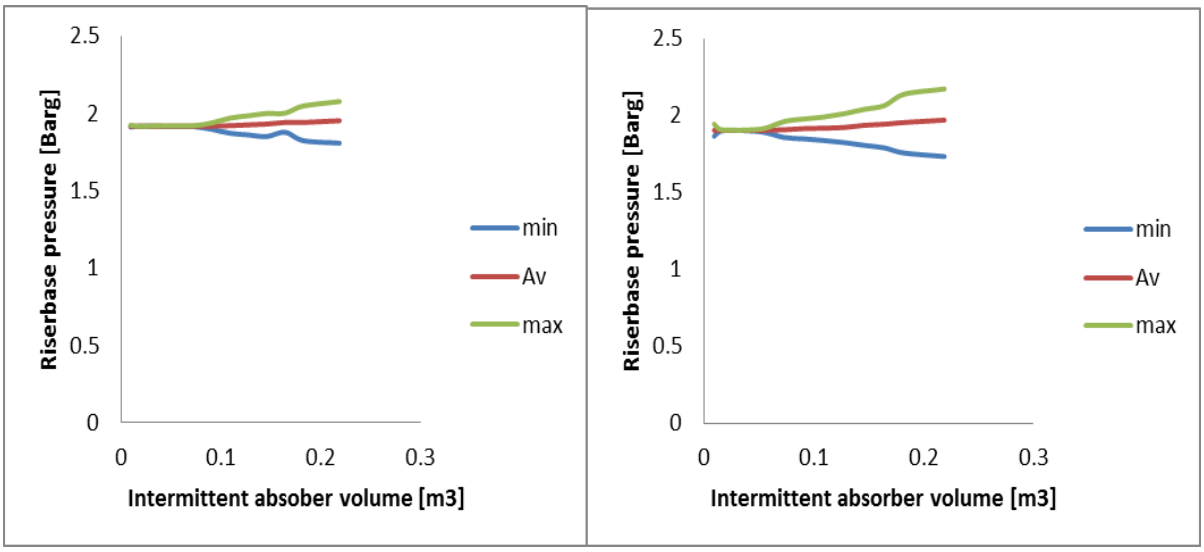
Figure 7-20(a) and (b) show the bifurcation map of the riserbase pressure keeping the valve opening constant at 13% and 14% respectively. The bifurcation point has been observed to occur at 13% valve opening for the isolated mode (without absorber). This valve opening becomes the reference point.

It is shown that at 13% valve opening, the system remained stable even with absorber of considerable large volume up to $0.15m^3$. Beyond this volume, the system lost its stability. At 14% valve opening, the system remained stable up to $0.11m^3$.



(a) (b)

Figure 7-20 Absorber riserbase pressure bifurcation map (a) 13 % valve opening (b) 14% valve opening



(a) (b)

Figure 7-21 Absorber riserbase pressure bifurcation map (a) 15% valve opening (b) 16% valve opening

Figure 7-21 (a) and (b) show the bifurcation map of the riserbase pressure keeping the valve opening constant at 15% and 16% respectively. It is shown that at 15% valve opening, the system remained stable even with absorber of considerable volume up to 0.07m^3. Beyond this volume, the system lost its stability. At 16% valve opening, the system remained stable up to 0.04m^3.

For the flow condition investigated, the trend shows that an inverse relationship exist between the valve openings at the size of absorber required for the system stability. In order to operate this system at larger valve opening a considerable small size of vessel will be needed. This is because the size of the intermittent absorber determines the attenuation potential during slug flow. At a constant valve opening, the larger the absorber volume, the lesser the compressibility effect within the vessel and the lesser the attenuation impact.

7.3.3 Effect of coupling configurations on the absorber performance

In section 5.5, the analysis showed that, the slug attenuation potential of the absorber is strongly dependent on its coupling with the main system.

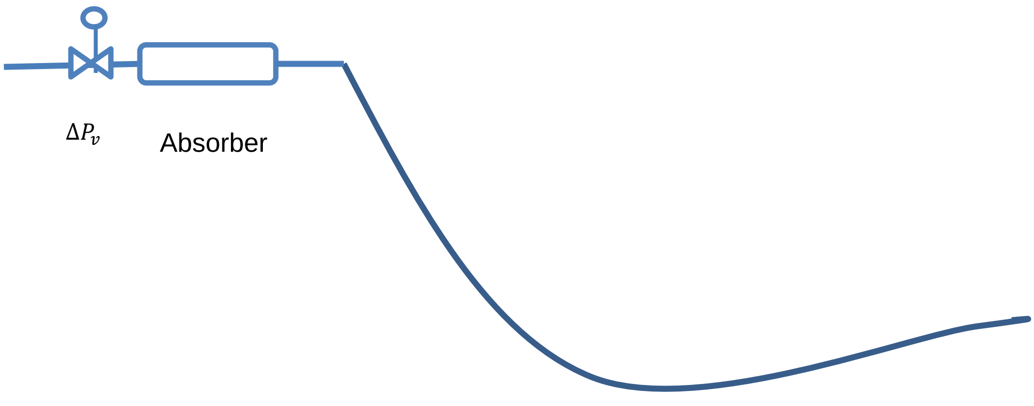
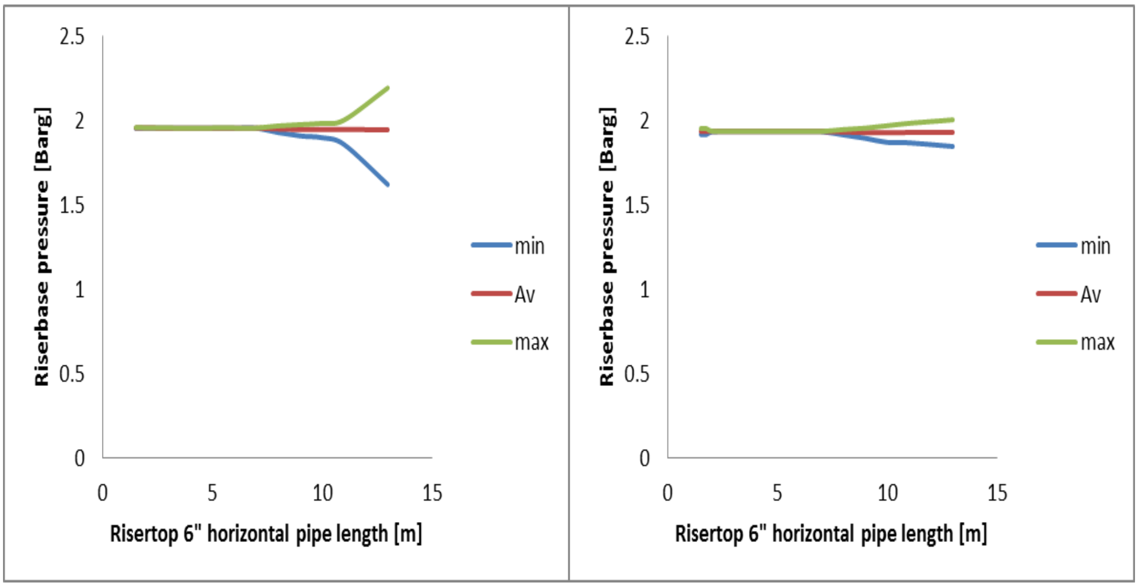


Figure 7-22 Inline coupled intermittent absorber

The original intermittent absorber coupling configuration was shown in Figure 5-11. In this section, an alternative coupling configuration shown in Figure 7-22 was investigated. The various absorber volumes were modelled as 6" horizontal pipelengths coupled as an inline vessel in the horizontal section upstream the choke valve.

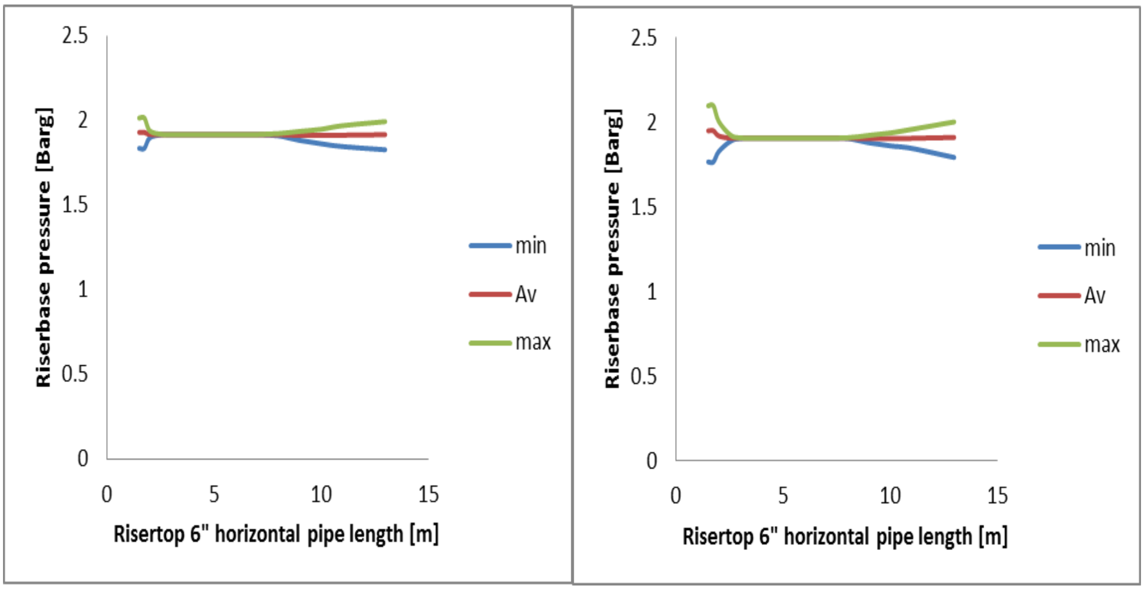


(a) (b)

Figure 7-23 Riserbase pressure bifurcation map for inline coupling (a) 13 % valve opening (b) 14% valve opening

Figure 7-23 (a) and (b) show the bifurcation maps of the riserbase pressure keeping the valve opening constant at 13% and 14% respectively. It is shown that at 13% valve opening, the system remained stable even with horizontal absorber of considerable length up to 7m. Beyond this length, the system lost its stability. At 14% valve opening, the system remained stable between length of 2 and 7 m outside this range stability is lost.

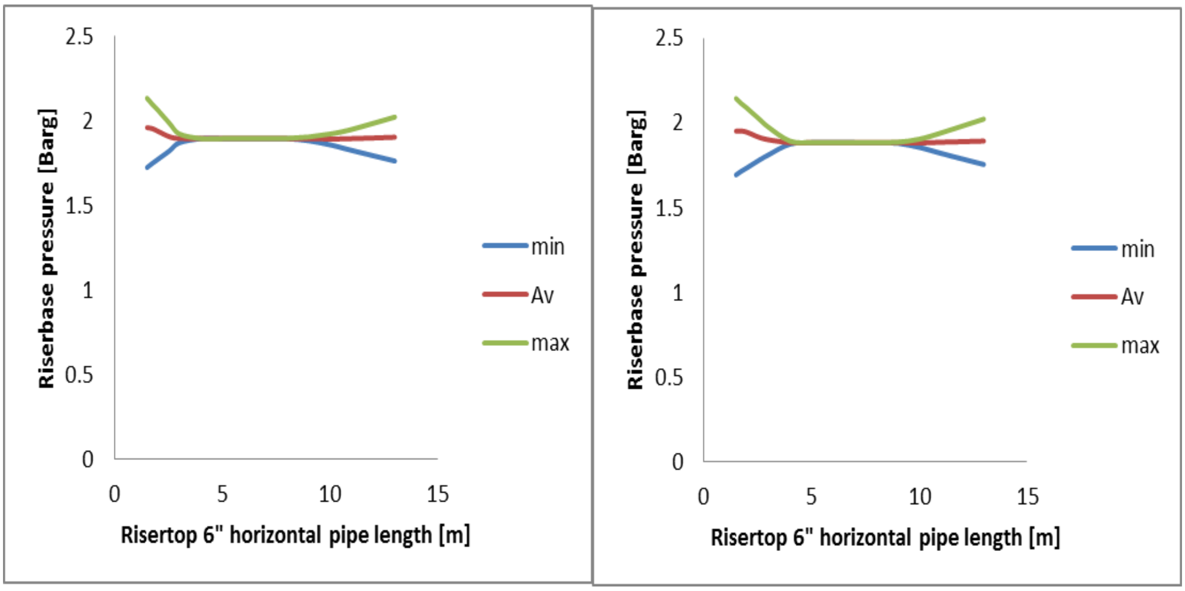
Figure 7-24 (a) and (b) show the bifurcation maps of the riserbase pressure keeping the valve opening constant at 15% and 16% respectively. It is shown that at 15% valve opening, the system remained stable between length of 2.5 and 8 m outside this range stability is lost. Also at 16% valve opening, the system remained stable between length of 3 and 8 m outside this range stability is lost.



(a) (b)

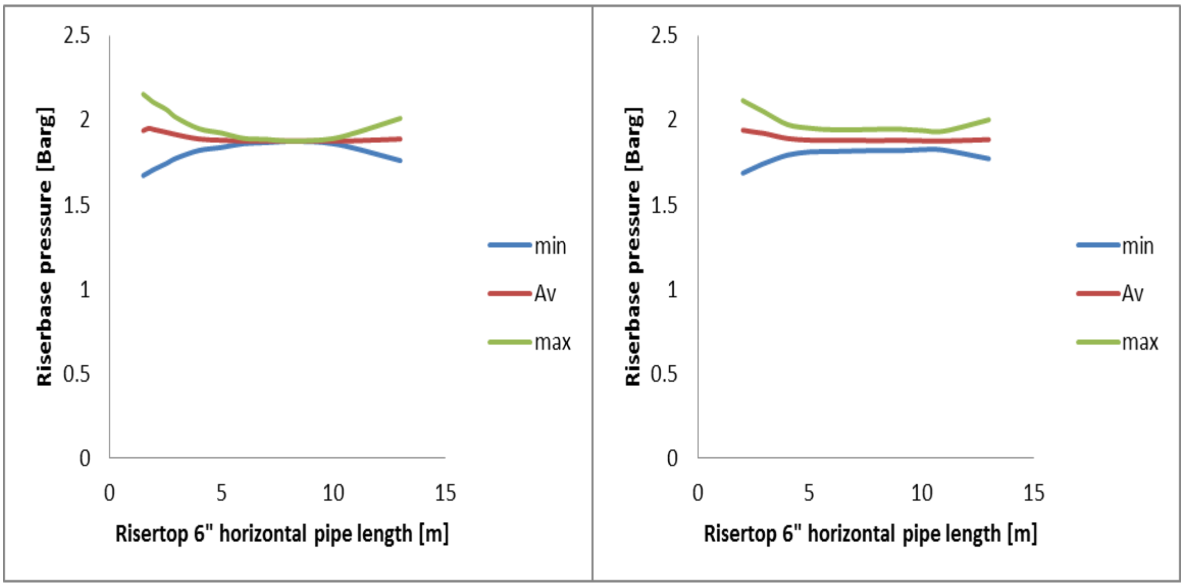
Figure 7-24 Riserbase pressure bifurcation map for inline coupling (a) 15 % valve opening (b)16 % valve opening

Figure 7-25 (a) and (b) show the bifurcation map of the riserbase pressure keeping the valve opening constant at 17% and 18% respectively. It is shown that at 17% valve opening, the system remained stable between length of 4 and 8 m outside this range stability is lost. Also at 18% valve opening, the system remained stable between length of 5 and 9 m outside this range stability is lost.



(a) (b)

Figure 7-25 Riserbase pressure bifurcation maps for inline coupling (a) 17 % valve opening (b) 18 % valve opening



(a) (b)

Figure 7-26 Riserbase pressure bifurcation map for inline coupling (a) 19 % valve opening (b) 20 % valve opening

Figure 7-26 (a) and (b) show the bifurcation maps of the riserbase pressure keeping the valve opening constant at 19% and 20% respectively. It is shown that at 19% valve opening, the system remained stable between length of 6 and 9 m outside this range stability is lost. But at 20% valve opening, the system appears to be unstable.

Figures 7-23 to 7-26 suggest that at larger valve opening, there is a range of pipe length (absorber volume) where stability was observed outside this range no attenuation was possible. This can be explained thus: The unstable left hand side shows that initially the system is unstable under the valve opening with/without additional vessel volume. The back pressure from the choke was not sufficient to cause stability. The second region which is the region of stability shows the pipe length (absorber volume) provides sufficient buffer zone that can help attenuate the slug produced from the riser before entering the separator in a stable manner. The right hand unstable region could be explained to be region where increase in the length contributes to the increase in gravitational pressure drop across the riser leading to slug growth and the slugging becomes more severe.

The results for the inline configuration also show that increasing the volumes can provide stabilizing or destabilizing effects. Similar observation has been reported in Pickering et al. [177] for a study on the increase in riser height. However no account was given for which of these effects was particularly dominant and to what extent.

The results from this section and section 7.3.2 suggest that the coupling configuration has serious effect on the slug attenuation potential and mechanisms of the vessel. For the external coupling configuration, the system stability was achieved at large valve openings with considerable smaller absorber size while the inline configuration shows that a larger volume (longer length) would be required for system stability at larger valve opening.

It thus appears that the inline coupling helped to reduce the slug intensity by changing the severe slugging to less severe hydrodynamic slugging. Here the vessel could be said to be acting like a stratifier. The external coupling however could be said to attenuate the severe slugging as an external dampener. From the results and the theoretical analysis, the absorber must be strongly coupled to the unstable system in order to provide significant attenuation. The inline coupling configuration therefore appears to be more attractive compared with the external coupling configuration.

7.4 Pressure/production benefit of the intermittent absorber

The intermittent absorber concept has shown potential for stabilising unstable pipeline-riser system at larger valve opening. There is a need to develop a systematic technique for quantifying the benefit accruable from the absorber. Ogazi [2] has developed a method based on bifurcation map for the assessment of the production potential of active control system. However no existing method for quantifying production benefit of a passive control system. In this work, a dimensionless index known as production/pressure benefit index (PBI) has been proposed to estimate the potential gain that could be achieved with the intermittent absorber. Although a constant mass source has been used in this study, the understanding of production dependence on pressure drop was used. By using a linear well model shown in (7.1), the oil production rate can be linked to system pressure drop using Darcy's law [2; 178].

$$q = B(\Delta P) \quad \textbf{(7.1)}$$

Where q is the well production rate, B describes the production index while ΔP is the pressure drop across the system (P_r- P_w) where P_r is the reservoir pressure and P_w is the well head pressure.

Equation (7.1) shows that production rate (q) is directly proportional to the pressure drop. It is clear that q will be maximum when the downstream pressure is kept low compared with upstream (inlet) pressure. In a pipeline-riser system, using the risertop choke to achieve stability contributes largely to the system pressure and this considerably reduces production rate. This is the bane of choking as a method for slug control and has been reported by many authors including [1]. Thus reducing the pressure drop across the topside valve would lead to increase in production. This study thus focuses on achieving this aim with the help of the intermittent absorber.

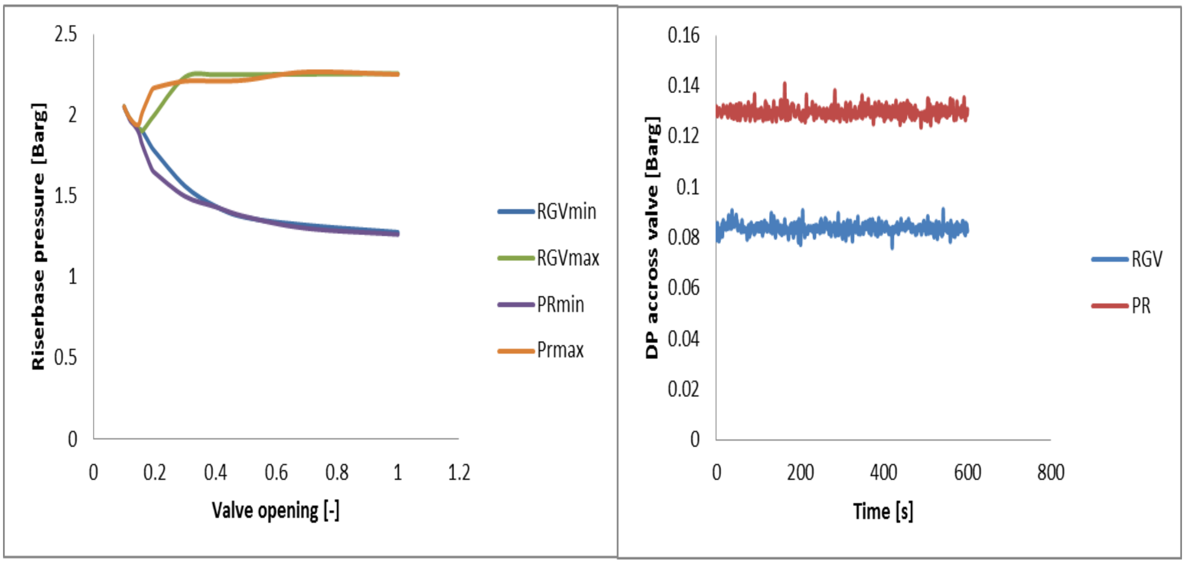
To quantify the production benefit that can be obtained from the absorber, a pressure benefit index (PBI) was proposed. Bifurcation maps were developed for the systems with and without absorber in order to develop the PBI. The riserbase pressure and the pressure drop across the choke valves were assessed for potential benefit. The bifurcation map of the optimum absorber was used.

The PBI is defined as the ratio of the difference between the pressure drop across the choke valve with and without the absorber to the pressure drop across the valve without the absorber. PBI is given by equation 7.2.

$$PBI = \left[\frac{(\Delta P\ accrossvalve)_{isolated} - (\Delta P\ accrossvalve)_{coupled}}{(\Delta P\ accrossvalve)_{isolated}}\right] \quad \textbf{(7.2)}$$

Where ΔP is the pressure drop across the valve

Figure 7-27 (a) and (b) show the riserbase pressure bifurcation maps and pressure drop across the topside valve for the isolation and coupled modes. It was observed that the absorber helped to slightly reduce the riserbase pressure while significant reduction was observed for the pressure drop across the valve. Generally, passive slug mitigation methods have been reported to be more efficient in the neighbourhood of its position [48] . The pressure drop across the valve was therefore chosen as a better candidate to quantify the benefit accruable from the absorber.



(a) (b)

Figure 7-27 (a) Coupled and isolated modes riserbase pressure bifurcation maps (b) Pressure drop across the valves for coupled and isolated modes

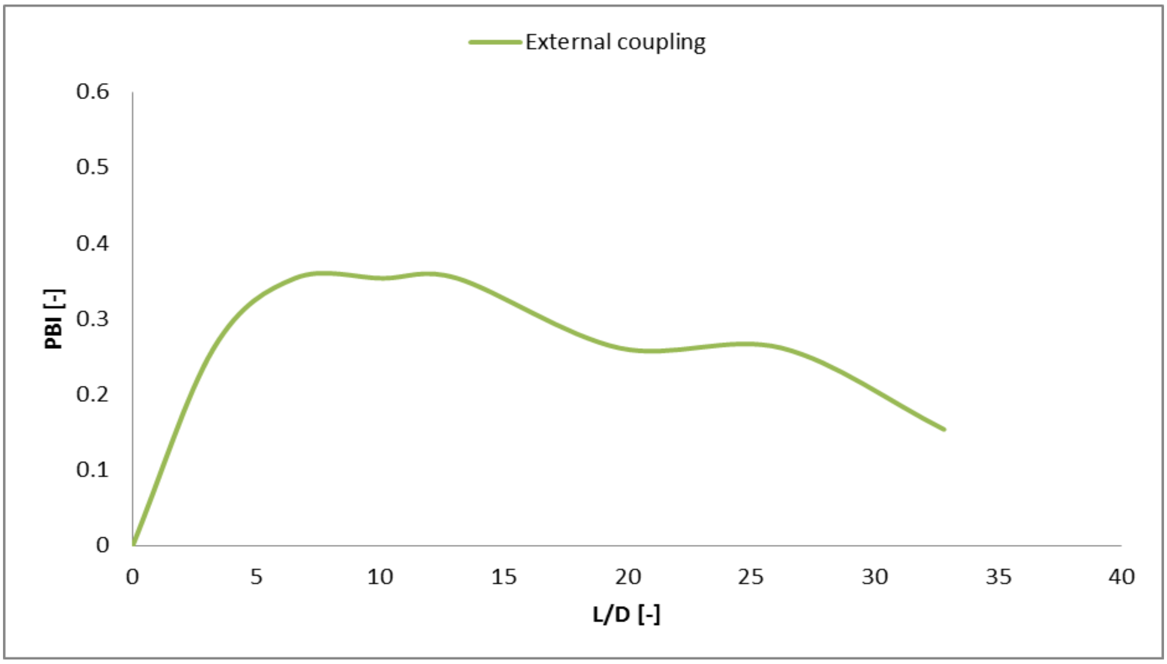
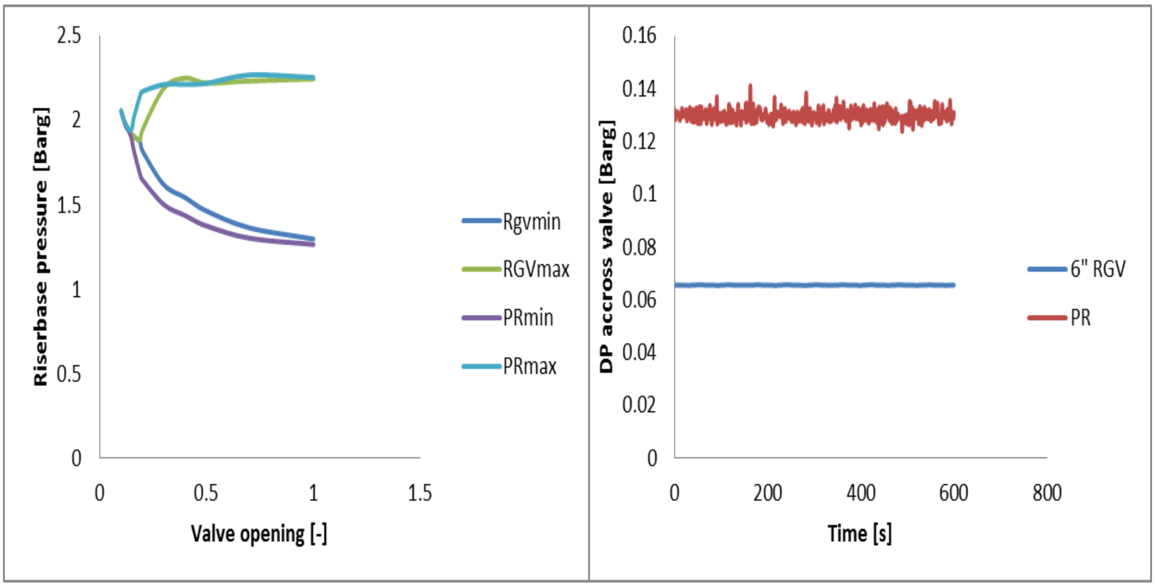


Figure 7-28 intermittent absorber benefit index

Figure 7-28 shows the plot of the PBI against a vessel the vessel length to diameter ratio.The plots shows that the attenuation benefit increases with increasing absorber size until an optimum point was reached beyond which further increase in the absorber yeilded a lesser benefit. A maximum value of 35% reduction was observed.

Figure 7-29 shows the riserbase pressure bifurcation maps and pressure drop across the topside valve for isolation and coupled modes using the inline coupled configuration. It was observed that the riserbase pressure was slightly reduced while significant reduction was observed for the pressure drop across the valve.



(a) (b)

Figure 7-29 (a) Inline coupled absorber and isolated riserbase pressure bifurcation maps (b) Pressure drop across the valves for inline coupled configuration and isolated mode

Figure 7-30 shows the PBI plots for the both coupling configurations. The plots shows that both absorber coupling configurations can provide benefit. At relatively small size, the externally coupled absorber provided greater benefit of 35% compared with 15% for inline coupled absorber. However the inline coupled configuration provided better benefits of about 49% compared to 15% at larger size. This supports the theoretical analysis that the attenaution of the intermittent absorber would be maximum when the system is strongly coupled.

The results also show that when the size of inline coupled absorber was doubled, additional marginal benefits was accruable. In a situation where there is a new field development the inline coupling configuration might be the preffered option while the other configuration might be better suited for existing field.

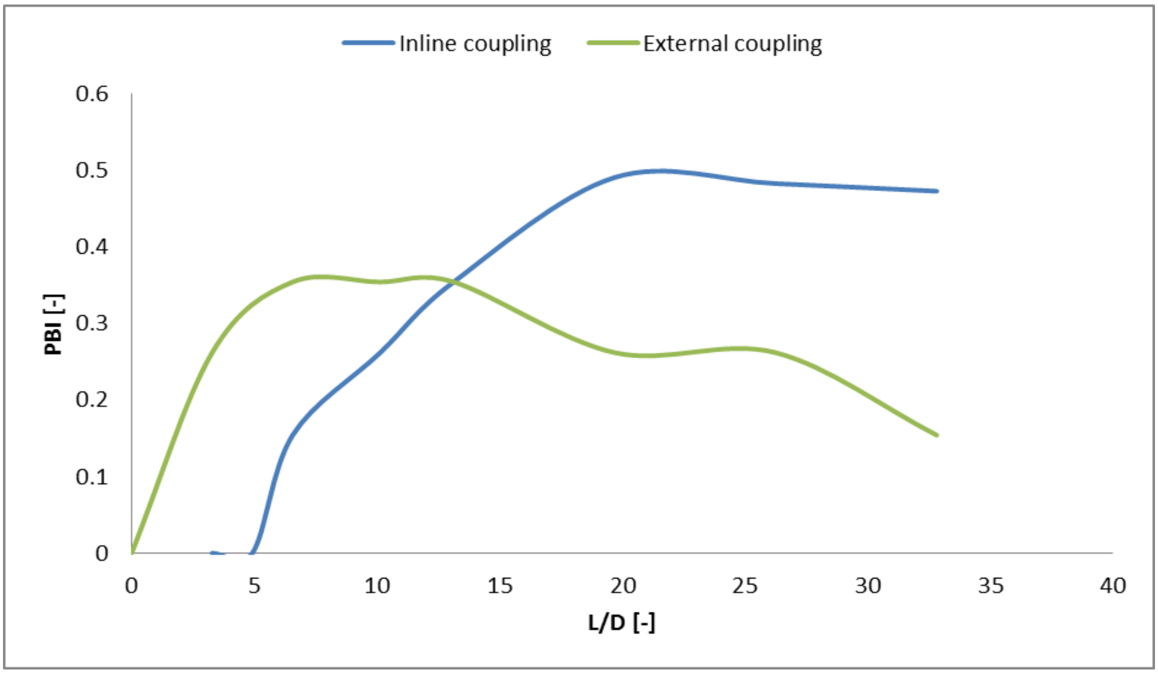


Figure 7-30 PBI plots for the two absorber configurations

7.5 Summary

The severe slugging attenuation potential of an intermittent absorber in a pipeline-riser system was investigated in this chapter using both experimental and numerical methods. The absorber was observed to be able to stabilise the flow at a larger valve opening compared with the parameter variation technique. A minimum of additional 1% valve opening was recorded which translated to about 9 % reduction in the average riserbase pressure.

A new method- Pressure Benefit Index (PBI) was proposed to quantify the attenuation benefit accruable from the intermittent absorber using the pressure drop across the choke valve. For the original coupling configuration of absorber, about 35% PBI was recorded while up to 49% PBI value was recorded for the inline coupling configuration. The PBI analysis provided a useful insight into the appropriate coupling configuration that could be deployed under various constraints. For a fresh field development, the inline coupling configuration would be more desired while the other coupling configuration would be more suited for existing facilities. The PBI also revealed that there exist an optimum volume where both size and production constraints are satisfied. The working mechanisms for the concept investigated have been revealed. The method helps to dampen the intermittence due to severe slugging.

8 CONCLUSIONS AND FURTHER WORK

8.1 Introduction

The conclusions from the studies presented in this thesis are presented in this chapter. This work has undertaken a comprehensive study on the stabilization of slug flow using active feedback control and passive method- intermittent absorber. The conclusions drawn from the studies are summarised next.

8.2 Conclusion

A review of hydrodynamic and severe slug flow and slug control techniques was undertaken in chapter 2. A number of control techniques such as the use of wavy pipes, pipe diameter modification, riser base gas injection, gas re-injection, the use of slug catcher, manual and active choking of the riser top valves, use of flow conditionals, and foaming agents have been discussed. The use of gas vessel in slug studies and other industries were also reviewed. Despite the advances made in severe slug prediction and control, it appears hydrodynamic slug control has not received much attention. The observable gaps from the review also include: The need for better understanding of the mechanism of hydrodynamic slug contribution to riser slugging and geometric interactions. It was also observed that there is need for work on the optimization of existing slug control techniques.

The understanding of the hydrodynamic slug flow in pipeline-riser system and the impact of geometry interaction on hydrodynamic slug flow behaviour was reported in chapter four. One of the major findings/contributions which are the interaction between vertical and horizontal pipeline and impact on slugging in pipeline-riser system has been reported. The contribution of hydrodynamic slugging to pipeline-riser system has been explained here and three distinct region of hydrodynamic slugging were reported. The knowledge of these behaviour and regions could be very valuable in the design of pipeline-riser system and the choice of appropriate control strategy.

In chapter five, a new approach to slug flow stabilisation was presented. Active feedback control and intermittent absorber concept were theoretically analysed and stability criteria proposed. These methods were observed to possess the potential for stabilising slug flow at larger valve opening compared with manual choking. The reason for such potential has been revealed. For the case study, additional 2% valve opening translating to 5% reduction in pressure was recorded. This implies an increase in oil production.

In chapter six, the passive device-intermittent absorber introduced in chapter five was implemented experimentally in form of a horizontal vessel for hydrodynamic slug attenuation. This method was proven to indeed possess slug attenuation potential and ability to optimise the parameter variation technique. The chapter also covered the development of methods for estimating the slug attenuation potential of the intermittent absorber. Both flow regime map (qualitative method) and new concept known as statistical slug attenuation index (SSAI) and slug attenuation index (SAI) (quantitative methods) were proposed. Ultimately the attenuation mechanism for hydrodynamic slug attenuation of the absorber was also revealed. The absorber was shown to have the potential of stabilizing the unstable slug flow at larger valve opening. This is of great importance since increased oil production can be achieved at larger valve opening.

The severe slugging attenuation potential of the intermittent absorber was investigated in Chapter seven. Both experimental and numerical methods were explored. The intermittent absorber concept was observed to be able to stabilise the flow at a larger valve opening compared with the parameter variation technique (manual choking). A minimum of additional 1% valve opening was observed translating to about 9% reduction in average riserbase pressure. A new method- Pressure benefit-index (PBI) has been proposed to quantify the attenuation benefit accruable from the intermittent absorber. The severe slug attenuation mechanism has been developed using bifurcation map and the theoretical stability analysis presented in chapter five. The parametric study conducted on the absorber volume revealed that there exist an optimum volume where both size and production constraints are satisfied. The effect of coupling configuration has also been reported.

8.3 Contribution of this PhD work

This work has contributed the following among others to the body of knowledge.

- The impact of geometry interaction on hydrodynamic slug flow in pipeline-riser system has been revealed
- A new method for slug flow stabilisation developed
- The hydrodynamic slug attenuation potential of intermittent absorber and method for quantifying such potential established
- Severe slugging attenuation capability of intermittent absorber and the mechanism for such attenuation disclosed

8.4 Further work

This work has developed a new method to slug flow stability analysis and established the slug attenuation potential of intermittent absorber using both experimental and numerical methods.

Further work can be undertaken to develop a mechanistic model for the pipeline-riser system and coupled with the intermittent absorber to further develop the stability analysis method for robust slug controller analysis and design.

It has been shown theoretically that the autonomous intermittent absorber must be strongly coupled to the unstable system to provide stabilization role, further work is needed to quantify the slug flow behaviour at the junction leading to the vessel. Other coupling devices or methods can also be investigated.

The intermittent absorber can also be redesigned to have Instrumentation and control. This will add to the degree of freedom of the system and may provide greater attenuation. Other intermittent absorber geometry and different inlet configuration can also be investigated.

The optimising potential of the intermittent absorber concept on other slug control techniques can be also be studied.

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APPENDICES

Appendix A

Modelling Slug flow using CFD tool

A.1 Problem definition

The capability of ANSYS FLUENT has been explored to model slug flow. The aim of the study was to ascertain the suitability of CFD method for our study. It was however observed that for an industrial scale pipeline-riser system, it would be impractical to use CFD method for the study of entire length.

CFD employs some basic steps to solve any problem. They include: Pre-processing, processing and post-processing. During the pre-processing, appropriate geometry and mesh which represent the flow problem are generated, and prepared for the solver (processing stage) for example Figure A-1. During the processing stage, an appropriate solver is selected to solve the problem already discretised in form of mesh. In this work, FUENT 12.1 and 14.1 were used as a solver while ICEM CFD was the mesh generating software employed. The result/data generated by the solver is now processed during the post processing stage. FLUENT has the capacity for post processing. Microsoft Excel has been used for post processing. Other softwares such as MATLAB, and TECPLOT can be used.

A.2 Modelling and simulation

A.2.1 **Geometry and mesh generation**

Meshing is an important part of simulation process. The geometry of the problem needs to be prepared in form in which the solver would be able to solve the problem. This form is usually referred to as grid/mesh. They are connected discrete points which represent the flow domain. They could be structured or unstructured, otherwise called structured or unstructured mesh respectively. The 2D geometry used in this work was built and set up using ICEM CFD preprocessor software. The mesh used in this work is shown in Figure A1. This is a 0.078m diameter pipe and 30m length. The mesh properties for the three cases are detailed in Table A1.

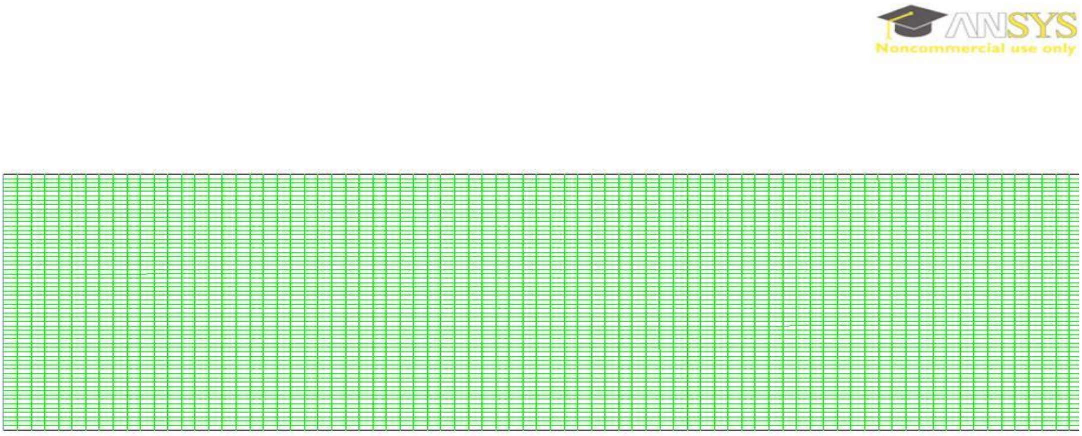


Figure A 1 Schematic of 2D mesh generated using ICEM

Table A 1 Mesh Properties

Cases	Nodes
Coarse	60,000
Medium	240,000
Fine	540,000

A.2.2 **Numerical methods**

The mesh set up in ICEM CFD was exported to FLUENT for solving. The pressure based transient solver was employed using the SIMPLE scheme for pressure-velocity coupling. The VOF multiphase model has been used and the effect of gravity and surface tension were modelled. The k-ε turbulence model was used. The solution methods is as shown in Table A 2

Table A 2 Solution methods

Spatial Discretization	Scheme
Gradient	Least squares cell based
Pressure	PRESTO
Momentum	First order Upwind
Volume fraction	Geo-reconstruct
Turbulent kinetic energy	First order upwind
Turbulent dissipation rate	First order upwind

A.2.3 **Boundary conditions**

The simulation of a 30m long horizontal pipeline of 0.078 internal diameter has been carried out at atmospheric conditions of temperature and pressure. The wave model was used to study the perturbation at the interface between the gas and liquid. The amplitude of the wave was chosen small enough compared to the wavelength and initial liquid height. A considerably long wave of 4m wavelength and 0.02 amplitude was studied for various h_L/D of 0.4, 0.5, and 0.7 for the medium case. The superficial gas and liquid velocities (V_{SG} and V_{SL}) were 4.016 and 0.519 respectively as in Kalogerakos et al. [74]. The initial stratified flow is as shown in Figure A 2.

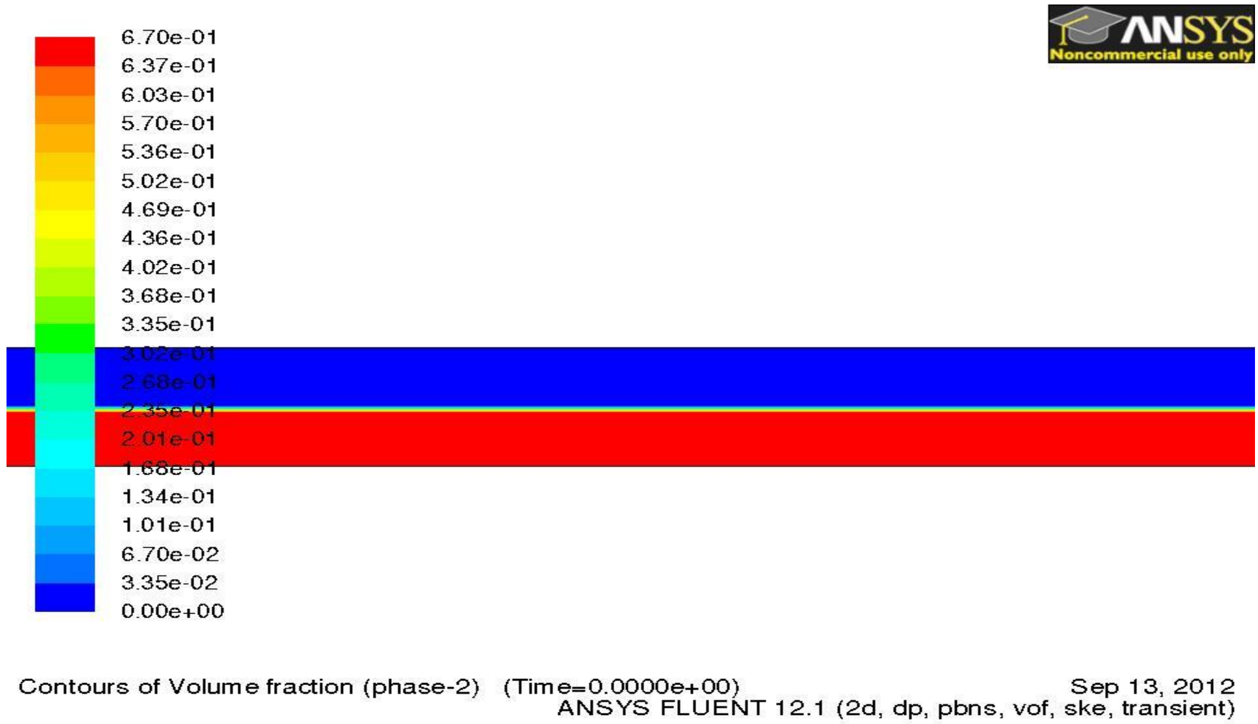


Figure A 2 Initial Stratified Flow set up in FLUENT

A.3 Results and discussion

This section presents the results of the simulation set up in section A 2. The aim of the simulation is to ascertain that FLUENT can be used to predict the point of initiation and further behaviour of slug flow from a stratified initial condition. In this present work a wave has been introduced into the computational domain. Various grid cases have been tested and results compared with analytical equations.

A.3.1 **Slug flow development**

The stratified flow pattern at the initial state of the simulation is as shown in Figure A 2. The stratification is known to occur as a result of density difference. Here the gas and liquid phase are distinctly separated from each other. After the introduction of the wave and at later time t greater 0, the stratification began to give rise to a wavy interface as seen in Figure A 3. This interface grows and eventually bridges the pipe cross section as in Figure A 4. The transient and intermittent nature shown in the results are typical of slug flow.

A.3.2 **Liquid volume fraction**

The liquid contained in a cross section of a pipe is captured by the liquid volume fraction also known as liquid hold up. The values of which vary between 0 and 1 according to the VOF model. At the inlet of the pipe the liquid hold up was 0.5 at t=0, as shown in Figure A 2.The area weighted liquid hold up fluctuates between 0 and 1 across the pipe length. When the volume fraction is zero, it implies that the pipe cross section is filled with gas whereas at value of 1, the pipe cross section is filled with liquid, thus slug is said to be formed as shown in Figure A 4. For liquid hold up between 0 and 1, it implies that the two phases are present. This type of scenario is observed in aerated slug flow as shown in Figure A 5. This is also the case in Figure A 3 where the wave is approaching the pipe wall but has not fully bridge the pipe wall. Certainly it is expected that at this point the liquid hold up is closer to 1 than 0.The area liquid volume fraction was monitored at 1m interval downstream the pipe inlet.

A.3.3 **Slug frequency**

Slug frequency is defined as the number of slugs that pass through a particular point in a given period. Usually the frequency is estimated based on a defined threshold liquid hold up. To consider the need for slug stability, a value of 1.0 which is a very clear indication of slug formation has been used. The frequency estimated based on this liquid hold up is approximately 1/s which is close to the frequency of the wave introduced at the inlet. Though in real life situation, slug frequency has been reported to exhibit statistical randomness Issa and Kempf [58]. This is observed in this work as the frequency ranges from 1.13/s to 1.2/s.

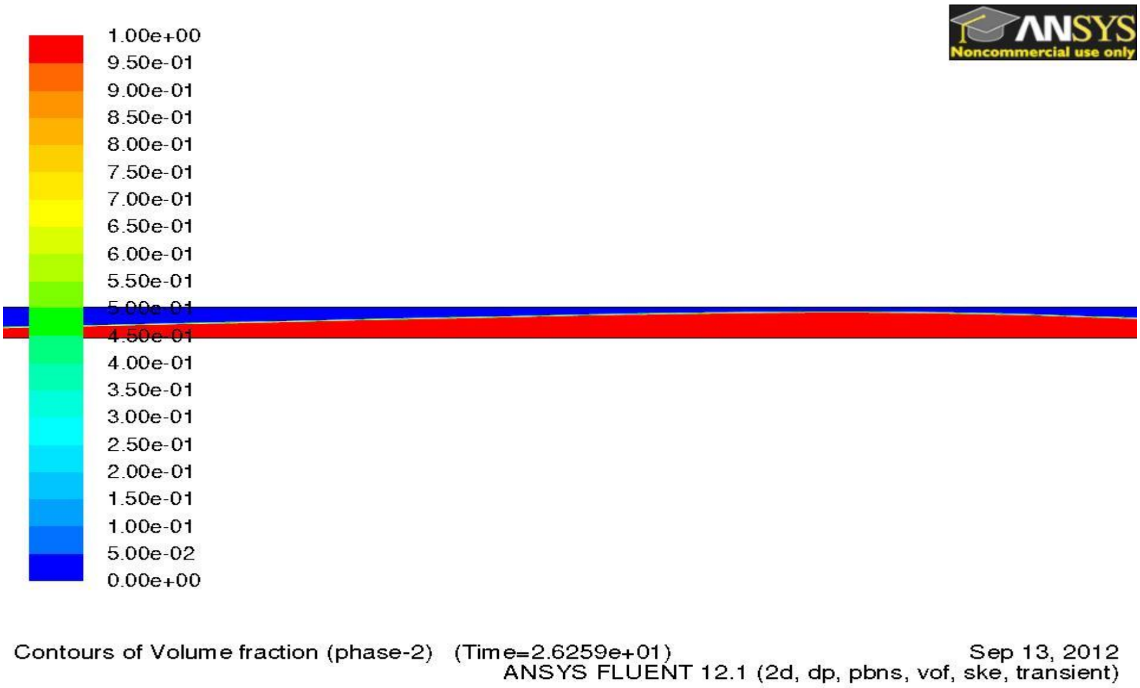


Figure A 3 Wave approaching the pipe walls

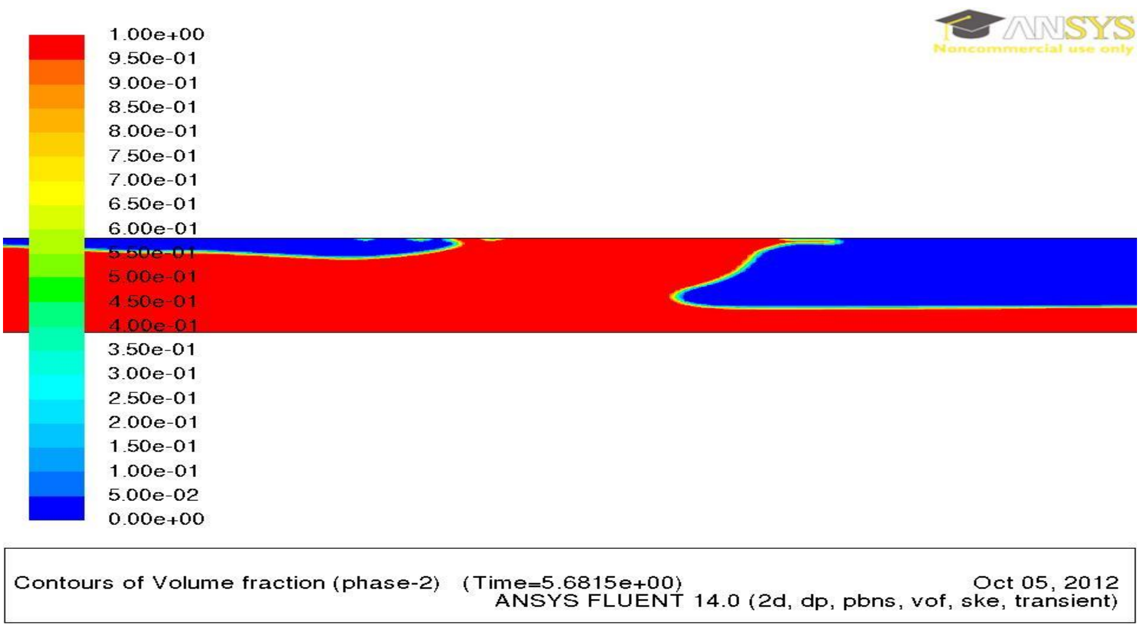


Figure A 4 Slug formation as liquid bridges pipe cross section

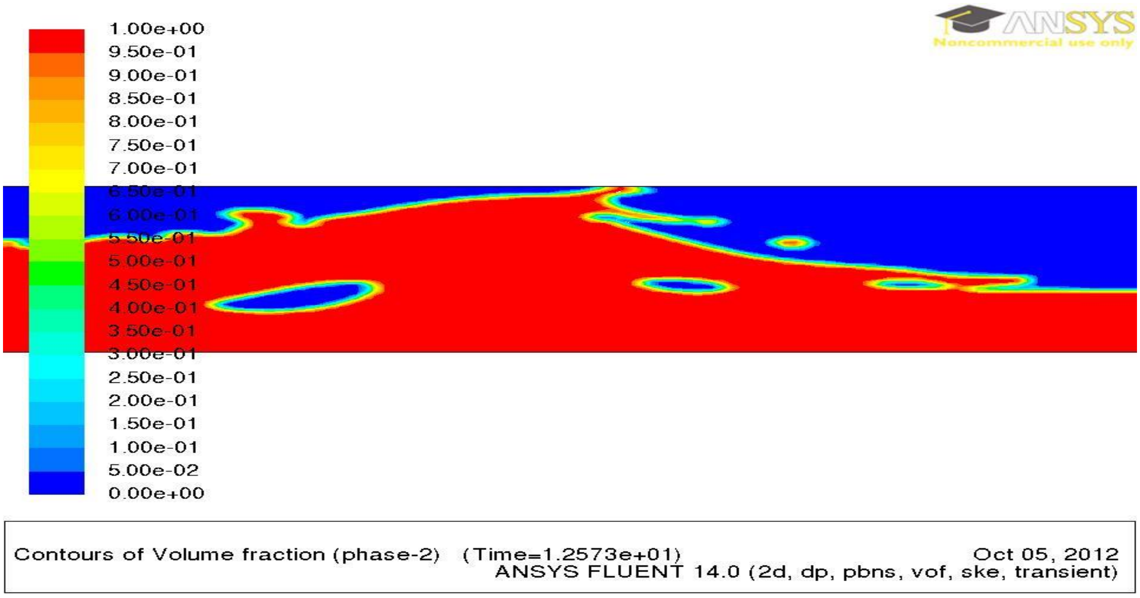


Figure A 5 Developing Aerated slug flow

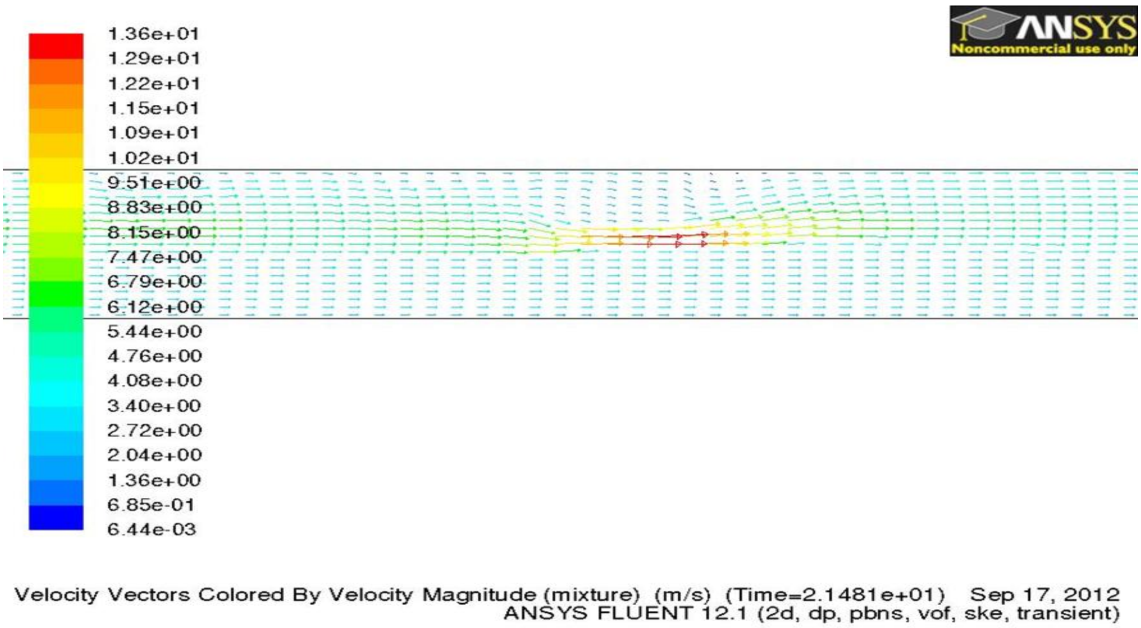


Figure A 6 Velocity profile plot

A.3.4 **Velocity Profile**

Apart from the liquid hold up and slug frequency, slug velocity is another slug parameter very useful in slug flow characterization. It is known that slug moves at higher velocity compared with the mixture velocity. Figure A 6 is a typical plot velocity vector profile. According to Gregory and Scott [179], the slug velocity is equivalent to 1.35Vm. The velocity profile shows that at the walls the velocity is minimum while at the centre it is maximum. The plot also shows that the slug translational velocity is 5.44m/s which is same as 1.2Vm as reported in the literatures.

A.3.5 **Slug pressure profile**

The pressure drop for slug flow is greater than that of single phase flow for the same flow condition. This has been confirmed in a study not reported here and other literatures. Figure A 7 is a contour of slug dynamic pressure. The pressure before the slug body is about 7kpa.

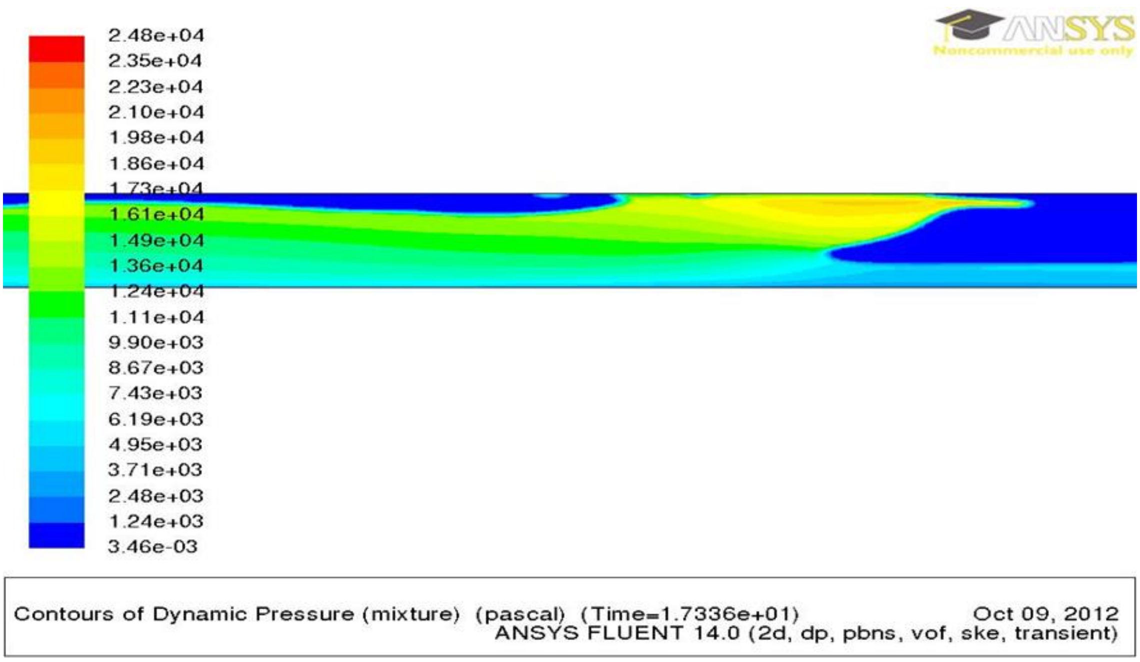
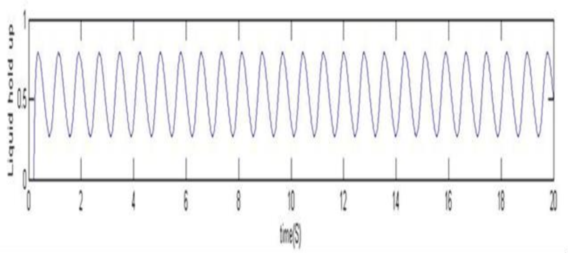


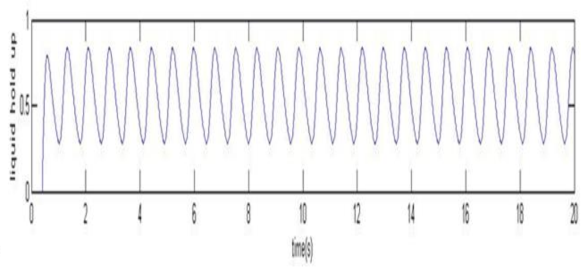
Figure A 7 Slug pressure profile

There is a sudden increase to about 12kpa and eventually above 18kpa in the slug body and drops to about 4kpa after the slug body. This pressure oscillation is a well-known behaviour of slug flow. This shows clearly the dynamics of hydrodynamic slug formation where there is sudden increase in pressure due to Bernoulli effect causing instability and eventual bridging of pipe cross section and later drop after the slug formation.

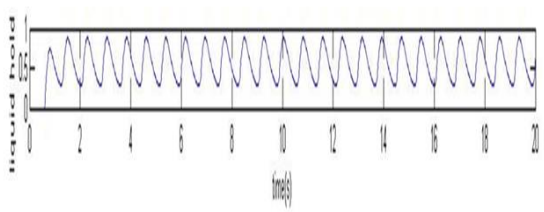
A.3.6 **Wave growth**

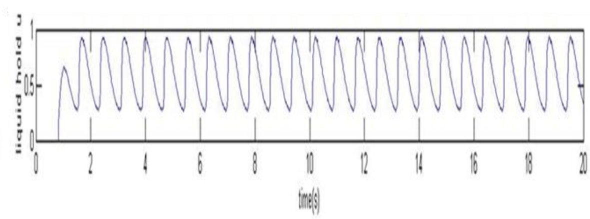
The contours of volume fraction are as shown in Figure A 8. This wave was observed to start growing as early as 1s and eventually blocked the pipe cross section at 1.80s for the first time at 5m as shown in Figure A 9. The rate of growth of the wave was estimated at 0.11. This was estimated using the logarithm of maximum liquid hold up against pipe length.





(a) (b)





(c) (d)

Figure A 8 Liquid hold downstream pipe inlet (a) 1m (b) 2m (c) 3m (d) 4m

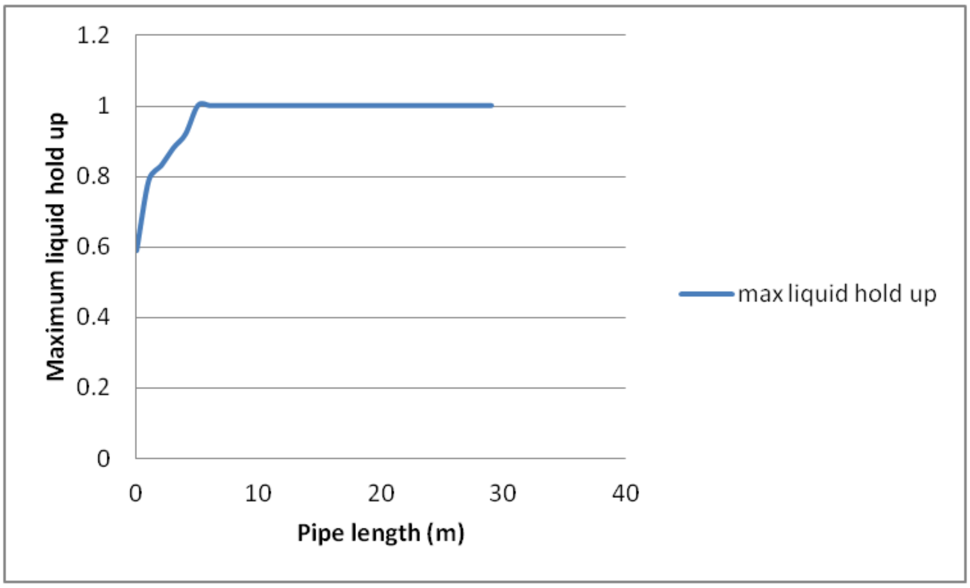


Figure A 9 wave growth along pipe length

A.4 Conclusions

Although considerable insight has been gained into slug flow initiation, growth, stability and collapse in horizontal pipes using of state of the art CFD tool-FLUENT, it was observed that the computational cost can be prohibitive.

The initial results indicate that slug flow and indeed other flow regimes could be modelled using FLUENT. However applicability for long pipeline might not be feasible [94].

Appendix B

Numerical investigation of slug flow and attenuation

B.1 Geometry description

This was a 3.7 km long horizontal pipeline leading to a 0.13 km vertical riser; both pipeline and riser are of 17” internal diameter as shown in Figure 3-2. Apart from the pipeline-riser system, the horizontal section was also modelled without the vertical riser and vice versa. Their geometries are shown in B1 and B2 respectively.

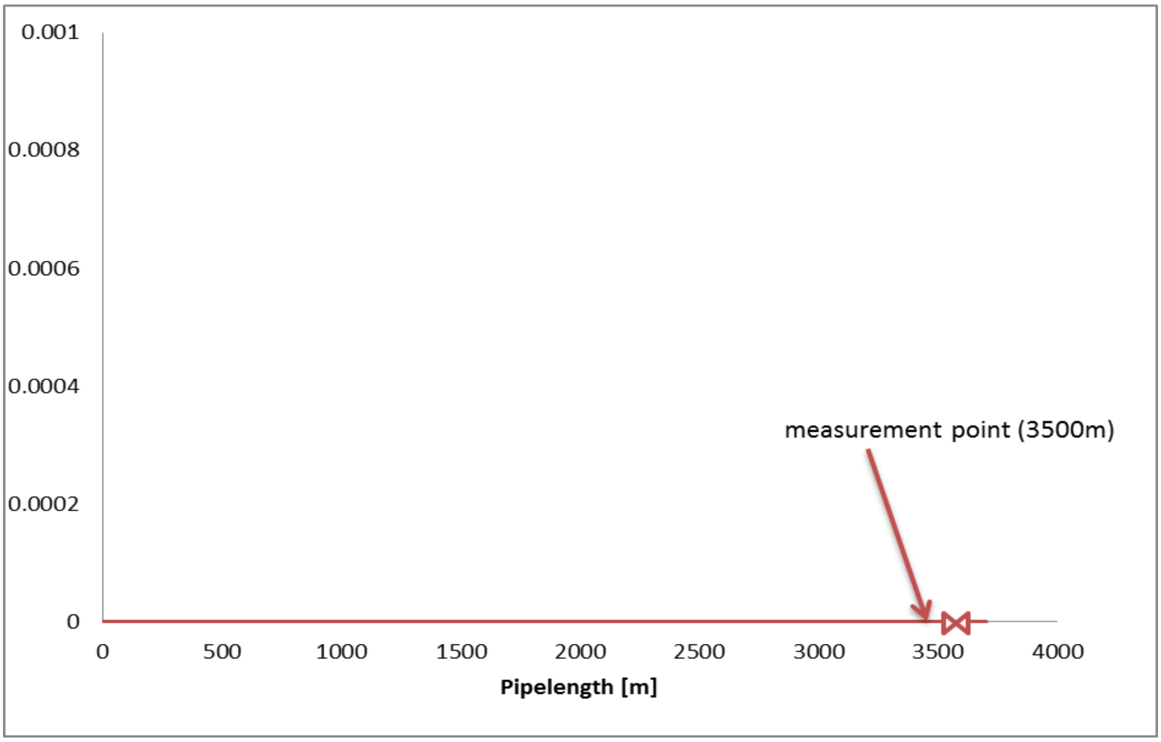


Figure B 1 Geometry of pure horizontal pipeline

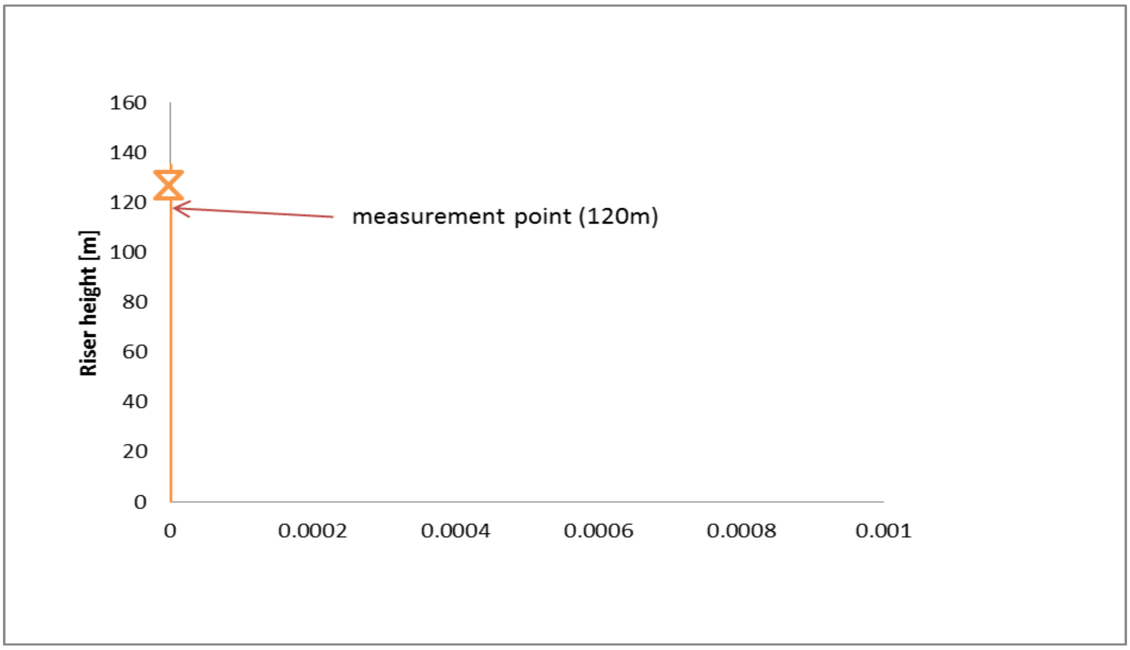


Figure B 2 Geometry of pure vertical riser pipe

B.2 Pre-processing

The pre-processing describes the activities carried out before the actual numerical solution of the problem. One of the pre-processing activities is the The details of the fluid properties as shown in shown in Table B1 and the fluid compositions were used to generate the file using the PVTsim.

Table B 1 Fluid Properties

Component	Gas	Oil	water
Density [kg/m^3]	23	780	1000
Viscosity [kg/m-s]	1.3×10^{-5}	1.1×10^{-3}	3.5×10^{-4}

In order to carry out any simulation study, the geometry must be modelled and all the properties of material used for the pipes specified. Table B 2 shows the properties of materials used for the pipe in this study. Materials 1 and 2 are the steel pipe and the insulation respectively. The heat transfer coefficient and pipe roughness values of 10 W/m^2-K and $4.572e^{-5}$ m were used respectively.

Table B 2 The properties of pipe and insulation materials

Material	Density [kg/m3]	Specific heat [j/kgC]	Thermal conductivity [W/mC]
Material1	7850	500	50
Material 2	2500	880	1

B.3 Mesh sensitivity studies

For 1 hour simulation time in Ledaflow, the case 400 did not show any slug at all whereas case 800 shows 1 slug/hr. while case 1600 has frequency value of 9 slug/hr.

Table B 3 Mesh sensitivity study

Case	Domain	No of cells	Grid size	Estimate slug frequency/hr.	CPU run time (s)
case400	1D	400	21 ID	0	172.40
case800	1D	800	11 ID	1	923.09
case1600	1D	1600	5.36ID	9	4654.3
case1800	1D	1800	4.76ID	13	4657.4
case2200	1D	2200	4ID	14	9324.4

The slug frequency of case 1800 is about 13 slugs /hr. while that of case 2200 stands at 14/hr. For additional 200 cells added to case 1600, 4 slugs were observed whereas 400 cells were added to case 1800 to yield case 2200 and additional 1 slug observed. Also for these two scenarios, additional 3.1s and 4,667s were required to complete the simulation. From the above, it is clear that case 1800 appears to be the optimum mesh. This is in consonance with the suggestion in the online LedaFlow user manual that a mesh size of less than 5ID is fine enough for hydrodynamic slug study. The details of these meshes are shown in Table B 3.

B.4 The Intermittent absorber

Figure B3 describes in detail the intermittent absorber presented in chapter three.

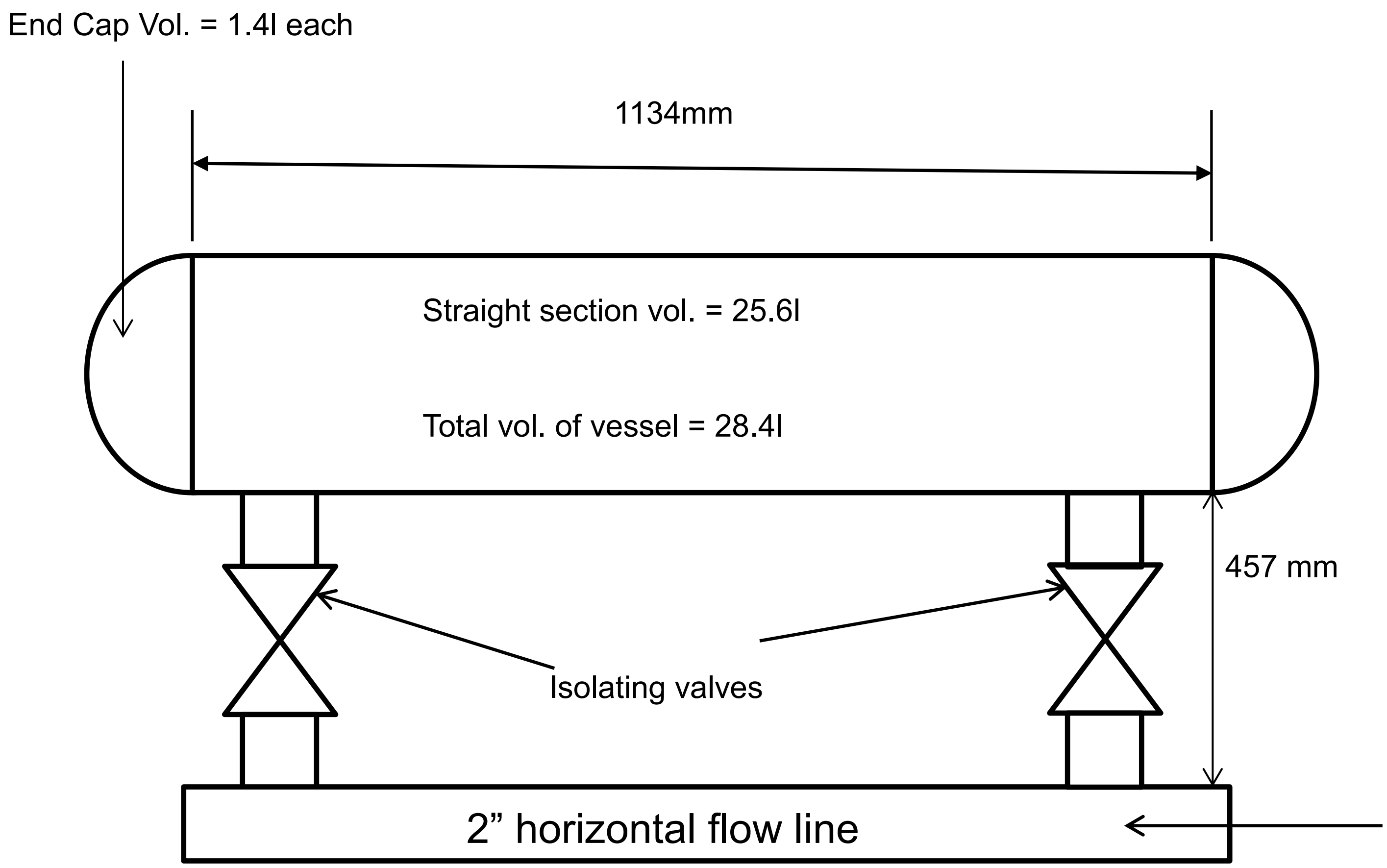


Figure B 3 Intermittent absorber