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SLUG FLOW IN LARGE DIAMETER PIPELINE-RISER SYSTEMS: PREDICTION AND MITIGATION

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Abstract- Slug flow could pose serious threat to oil and gas production facility. The objective of the study was to gain better insight into the behaviour of slug flow in large pipe diameter pipeline-riser system. The influence of geometry configuration on the slug characteristics was also investigated. The understanding of these are very important in the development of effective slug control strategy. Numerical simulations were carried out on a 3.7 km long horizontal pipeline leading to a 0.13 km vertical riser using an industrial software package. The pipeline and riser are both of 17" internal diameter. Slug envelopes were developed for the pipeline-riser system and its constituents' pipes. A total number of 572 data points were investigated, covering superficial velocities ranging from 0.01 to 44.28 m/s for gas and 0.02 and 8.25 m/s for liquid. The results showed three distinct slug flow 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) where slug formation was predominantly due to the vertical pipe. The observed phenomenon is in consonance qualitatively with the experimental studies published in another paper, but quantitatively different and this may be due to diameter effect. The results also showed that choking can indeed be used to mitigate 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 therefore, the need to seek a better way of stabilizing slug flow bearing in mind the distinct behaviours of the identified regions.

Keywords: Slug flow, Choking, slug mitigation, Leda Flow, slug regions

1. Introduction

Slug flow is one of the challenges due to multiphase transportation of liquid and gas in a pipeline. This phenomenon can pose significant threat to oil and gas production facilities. Operational induced slug flow, hydrodynamic slug flow and severe slug flow are the widely known types. This study 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 to ensure that flow assurance demands are satisfied. The optimum design of the transporting pipelines and receiving facilities would be impossible without adequate understanding of the nature of slug flow expected in such system.

Hydrodynamic slug flow is known to occur in horizontal and near horizontal pipelines. In these pipelines, slugs can be formed from stratified regime by two main mechanisms. They are: growth of hydrodynamic instabilities and liquid accumulation due to instantaneous imbalance between pressure and gravitational forces caused by pipe undulation. The growth of hydrodynamic instability can be explained by the Kelvin Helmholtz (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 [1]. A good number of experimental and numerical works have been conducted to study slug initiation and evolution of two phase flows in horizontal pipes [1]–[6].

Previous studies have also provided significant understanding on the flow of hydrodynamic slug in horizontal pipes [6]–[11] and behaviour of severe slug flow in pipeline-riser system[12]–[17]. However, only few studies exist on hydrodynamic slug flow in pipeline-riser system and the impact of geometry [18], [19]. There is therefore the need to gain better understanding on the behaviour of slug flow in pipeline-riser system before an appropriate control strategy can be deployed.

Numerical tools provide an advantage of investigating industrial systems which are of larger sizes compared to the available experimental facilities. In this study, LedaFlow-one dimensional (1D) industrial multiphase code was used for numerical modelling and simulation of slug flow in pipeline-riser system. This helps to gain a good understanding of slug flow in pipeline-riser system. This understanding is needed for the development of an appropriate strategy for the slug attenuation. The well-established flow pattern maps were developed with special interest in the slug flow regime.

Flow regimes in Leda Flow 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. Details of the development and the mathematical models used in this software package have been previously presented in literatures [20], [21].

This paper is organized as follows: in section 2, the methodology adopted for this study was presented; In section 3, the results were presented and discussed while section 4 presents the response of the slug flow to choking as a mitigation method. The work was concluded in the last section.

II. Methodology

Extensive numerical studies were conducted on a large size pipeline-riser system. The pipeline-riser system 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 1. Slug studies were also carried out on the horizontal pipeline and the vertical riser with a riser top valve. These geometries were discretised and grid sensitivity studies conducted. A total of 1800 cells was observed to be the optimum mesh and was adopted for this study. A total number of 572 data points were investigated, covering superficial velocities ranging from 0.01 to 44.28 m/s for gas and 0.02 and 8.25 m/s for liquid.

In order to carry out a simulation study in 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 usually referred to as PVT file. The fluid properties and pipe materials properties are shown in Table 1 and 2 respectively.

Table 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}

Table 2 Properties of pipes and insulation materials

Material	Density [kg/m^3]	Specific heat [j/kg C]	Thermal conductivity [W/m C]
Material 1	7850	500	50
Material 2	2500	880	1

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.

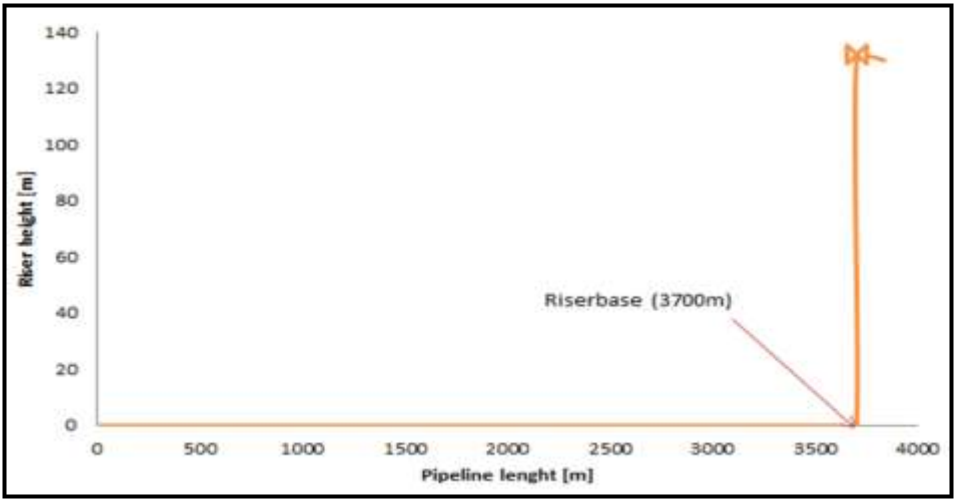


Fig. 1: Geometry of pipeline-riser system.

The numerical simulations of the pipeline-riser, horizontal and vertical pipes were carried out for various flow conditions using the various models (Unit cell, and slug capturing). A total number of about 572 simulations were done and a good number of the results fall within the slug region. The flow regime indicators in the software package were used to judge the presence or absence of slugging for the unit cell model while the fluctuation of the flow variables like pressure, mass flow rate and so on were used for the slug capturing. The superficial velocities were used to generate the flow envelopes which were analyzed to understand the behaviour of slug flow in pipeline-riser system.

III. **Results and Discussions**

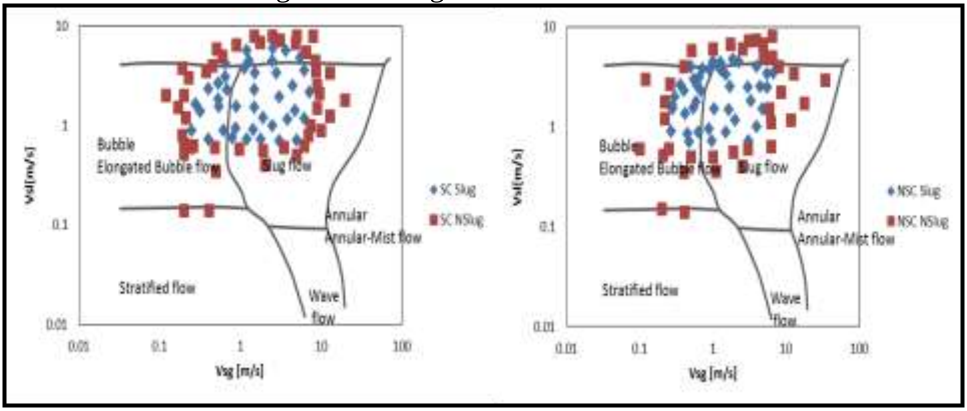
The slug envelopes obtained from horizontal pipeline, vertical pipeline, pipeline with riser downstream were discussed and comparisons of these systems have been made. Comparisons were also made between the envelopes obtained for various models.

Slug Flow Envelopes for the Horizontal Pipeline

The pure horizontal 3.7km, 17’’ internal diameter pipeline described in section 2 was investigated and 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 2 shows the slug envelopes for the horizontal pipeline as predicted by slug capturing and unit cell models 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. 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 the slug capturing models.

Figure 2 also shows the slug flow regime obtained from these models compared with the flow regime map provided by Mandhane et al. [22]. The Figure shows that considerable amount of data investigated for slug fall within the slug region of [22] 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.

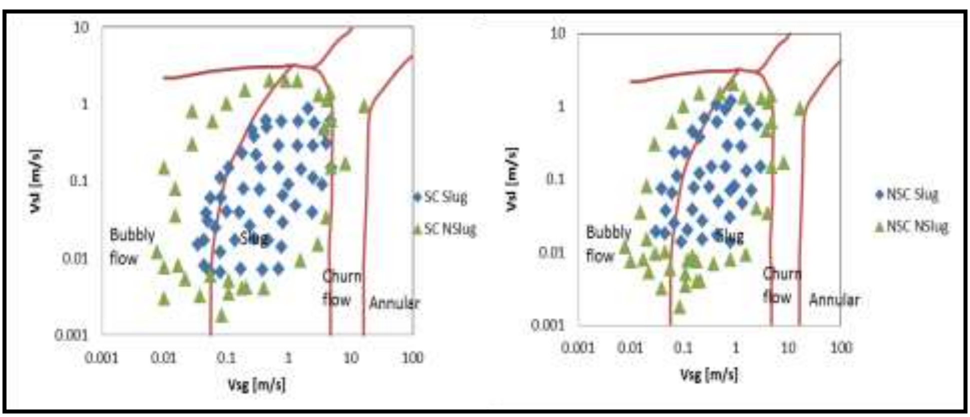


(a) Slug capturing model (SC) (b) Unit cell model (NSC)

Fig. 2 Numerical flow regime compared with Mandhane et al. [22] flow regime

Slug Flow Envelopes for the Vertical Pipe

The slug flow envelope for the vertical pipe is as shown in Figure 3. 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 and not likely to occur at high flow rates. Though the envelope seems tilted compared to what was reported in the literatures for example Barnea [23].



(a) Slug capturing model (SC) **(b) Unit cell model (NSC)**

Fig. 3 Numerical flow regime compared with Barnea [23] flow regime

Figure 3 also shows the slug flow regime obtained from the numerical studies compared with the flow regime map of Barnea [23]. The Figure shows that considerable amount of data fall within the slug region as predicted by Barnea [23]. However, some region predicted as slug by the models fall within the non-slug region and vice versa. This again could be as a result of the effect of the difference in pipe diameter. Again, it was observed that 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.

Slug Flow Envelopes for the Pipeline-riser System

The pipeline-riser system described in section 2 was studied 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.

Figure 4 shows the slug flow envelope developed for this pipeline riser system compared with flow regime map of Schmidt et al.[13]. Considerable number of data points investigated fall within the slug flow regime while the rest fall within the non-slug regime. Severe slug flow was reported in Schmidt et al.[13], however, such was not observed in this study. The region where hydrodynamic slug was observed in this study covers significant parts of regions reported as dispersed, bubble and transition to severe slug flow in Schmidt et al.[13]. This may be due to difference in pipeline-riser geometry

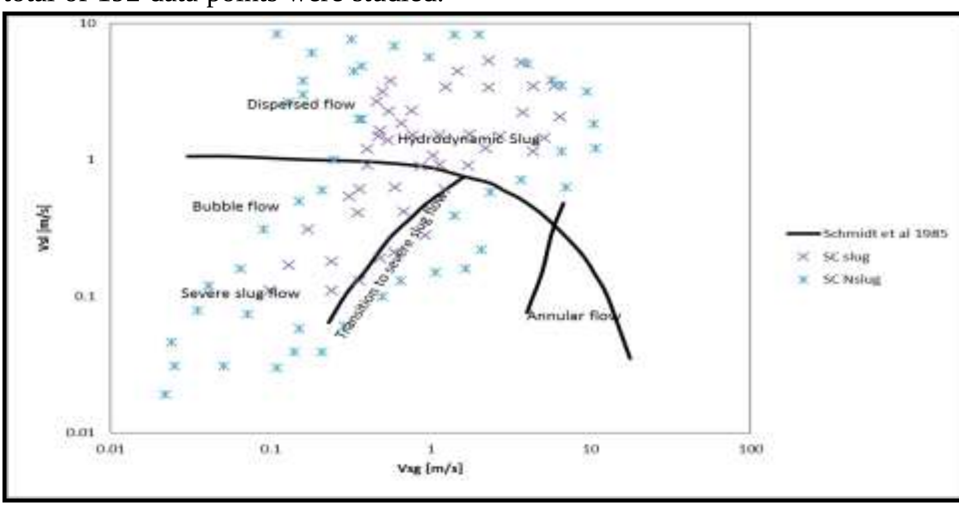


Fig. 4 Numerical flow regime compared with map of Schmidt et al. [13]

Slug Flow Envelopes for the Pipeline-riser System

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

From Figure 5, it was 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 [24] and Schmidt et al. [18].

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 Figure 5. 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 [11], [25] 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 [18] .

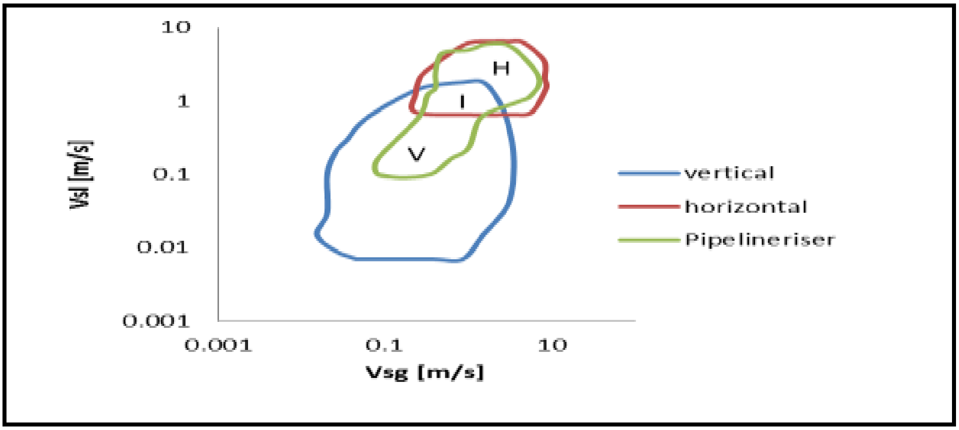


Fig. 5 Slug flow behavior in pipeline-riser system

The Figure also shows 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 [13].This type of behaviour was reported for a gas-liquid flow in large pipeline-riser system where the effect of upstream configurations was investigated [26].

It can also be seen from the Figure 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 [26].

Figure 5 ultimately provides a clearer picture of the slug behaviour in pipeline-riser. The software package predicts three regions designated as head/horizontal (H), intersection/neck (I), and vertical/handle (V).

The region H shows the region due to 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[18], [26].

Slug flow in H-region. From Figure 5, it is observed that the area designated as H region of the pipeline-riser slug envelope falls largely within the slug region of horizontal pipe. This region appears not to suffer slugging in the 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. A representative case in this region has been studied to observe the behaviour of slug in these systems.

Table 3 Properties of case study in 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

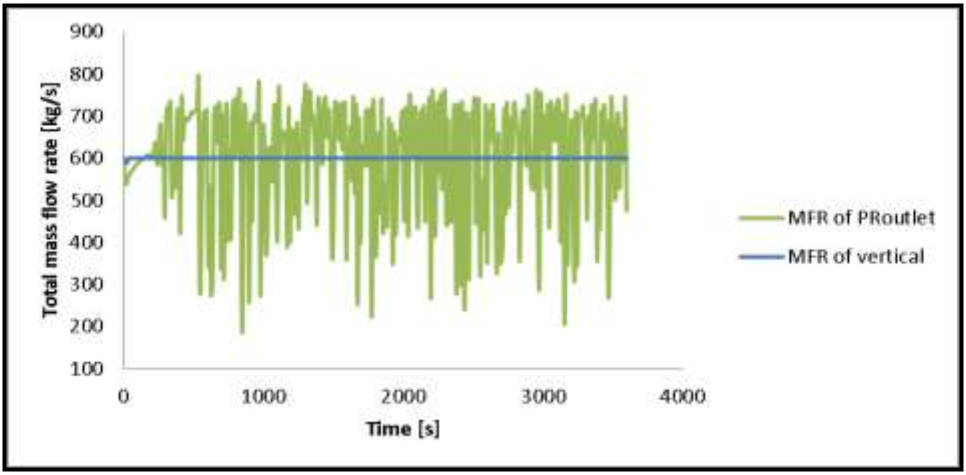


Fig. 6 Comparison of total mass flow rate for pure vertical pipe and pipeline-riser system

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 3. This representative flow condition corresponds to 2.48m/s and 4.50 m/s superficial velocities of gas and liquid respectively.

For a vertical pipe, this case did not experience any slugging as can be seen in Figure 6 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 Figure 7.

Figure 7 (a) shows the trend plot of the total mass flow rates at 1km for pipeline-riser system (PR) and the horizontal pipeline (Horiz). It was observed that at 1 km from the inlet of the pipeline, the horizontal case has developed interfacial waves of peak in the 684 kg/s 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 kg/s.

Figure 7(b) 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 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. The initiation and development of slugs have been studied previously by many authors[3], [6], [11], [27], [28]. Ujang et al. [6] 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 7(b) and 7(c). 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 [29].

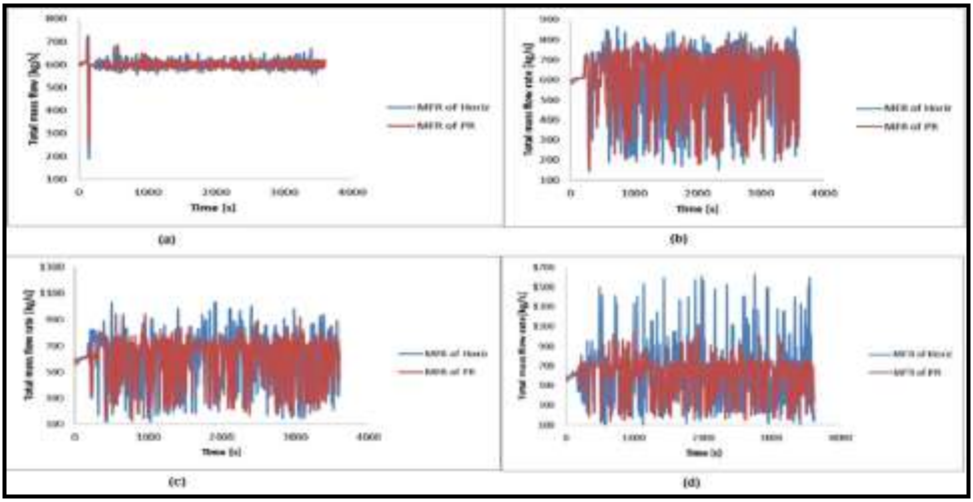


Fig. 7 H-region total mass flow rate (a) at 1 km from inlet, (b) at 2 km from inlet, (c) at 3 km from inlet, (d) 3.7 km (riser base)

Figure 7(c) 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 7(b).

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 [30], [31].

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.[32] that hydrodynamic slug could be severe with length greater than the riser.

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 7(d). The 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.

Slug flow in I-region. From Figure 5, 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 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 behavior 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 summarized in Table 4.

Table 4 Properties of case study in 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 8(a) 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.

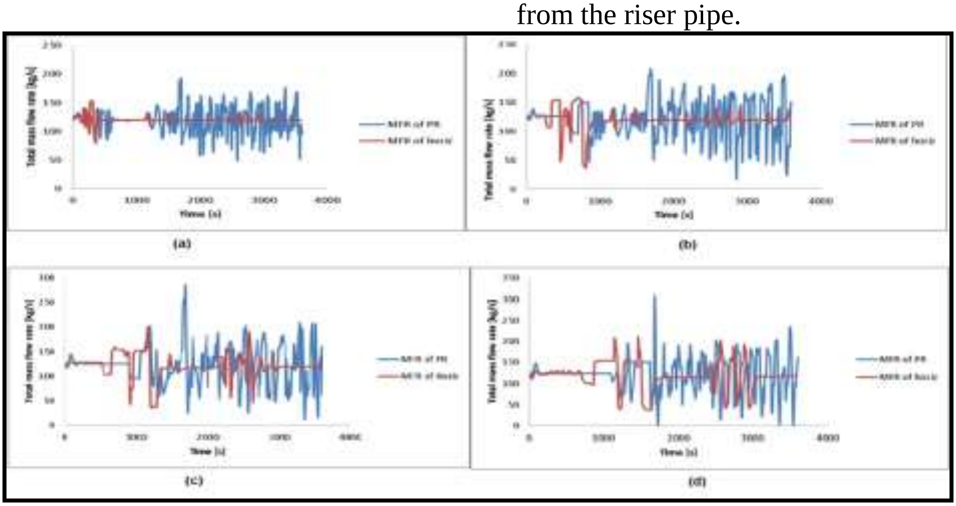


Fig. 8 I-region total mass flow rate (a) at 1 km from inlet, (b) at 2 km from inlet, (c) at 3 km from inlet, (d) 3.7 km (riser base)

Figure 8(b) 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. 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 riser base reduces from the inlet.

Figure 8(c) 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 8(b). 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 8 (b). 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 [33]. 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 [6].

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 8(d). 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 [33], and Zoeteweij [34]. Zoeteweij [34] observed that this type of slug that keeps growing till the end of the pipeline is characterized by continuous change in length and can be difficult to predict and control. However, this view was not substantiated with any control study.

Slug flow in V-region. From Figure 5, it was 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 summarized in Table 5. 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 Figure 9. However, both the vertical and pipeline-riser system was observed to suffer from slugging.

Table 5 Properties of case study in 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 9(a) 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[13], [35]. 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 9(b) 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.

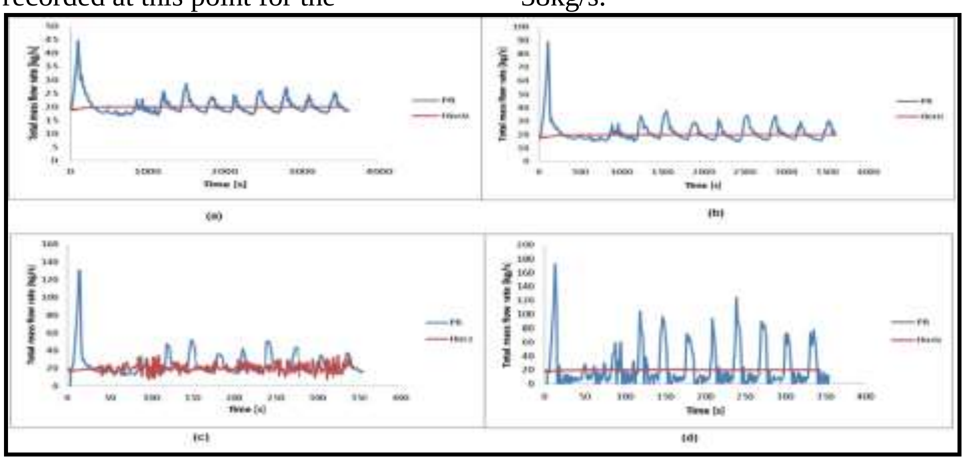


Fig. 9 V-region total mass flow rate (a) at 1 km from inlet, (b) at 2 km from inlet, (c) at 3 km from inlet, (d) 3.7 km (riser base)

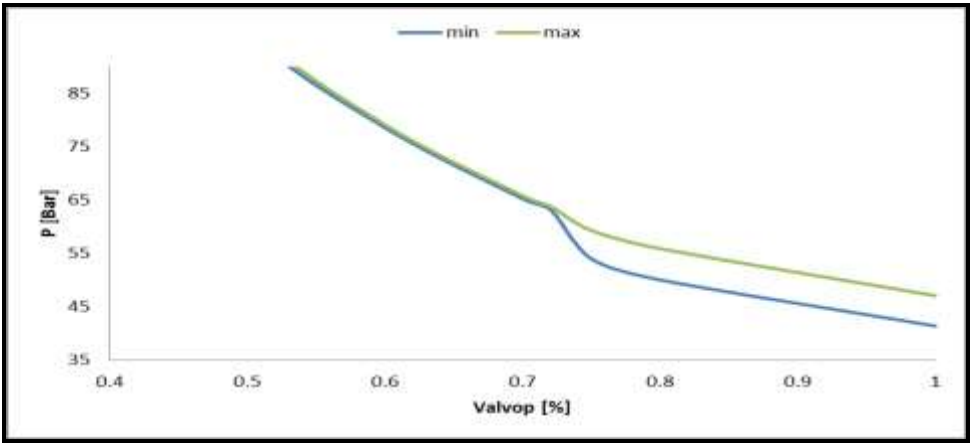
Figure 9(c) shows the trend plot of total mass flow rates of the pipeline-riser system (PR) and the pure horizontal pipeline (Horiz) at 3km from the inlet. As can be seen the frequency of the slug precursors observed in the pipeline-riser system remain the same while the fluctuation in the total mass 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 wave dissipated before the outlet as can be seen in Figure 9(d). This could be because the available liquid height in the pipeline is not high enough to bridge the pipe for slug formation[36], [37].

Figure 9(d) shows trend plot for the total mass flow rate at the outlet of the pure horizontal pipeline and the riser base of the pipeline-riser system (3.7 km from the inlet). The horizontal pipeline experienced no slug at the outlet but slugging was observed at the riser base of the pipeline. 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 as shown in increase in fluctuation amplitudes. The additional growth could be as a result of liquid fall back from the riser pipe and the inability of the incoming flow 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.

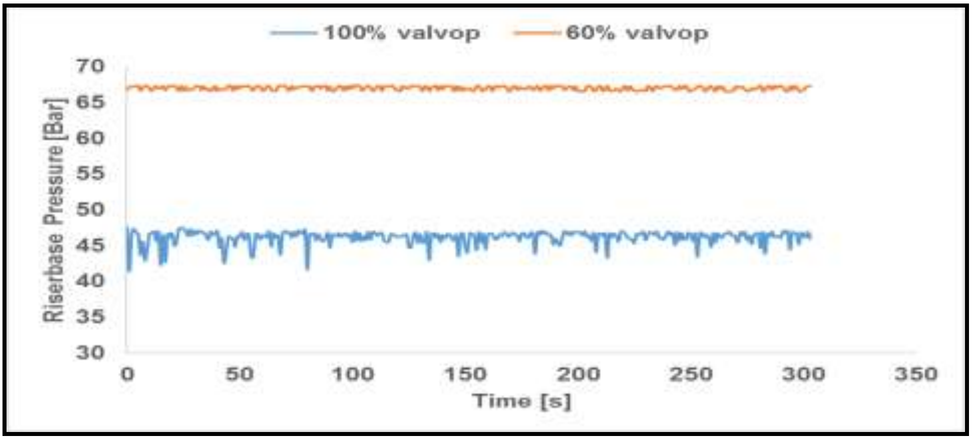
Stabilizing Slug Flow in Pipeline-riser System using Choking Method

Three slug flow regions have been identified in the previous section and the behaviour explained. In this section, the potential of using increase in the downstream pressure to attenuate slug flow was investigated. This concept is investigated for each of the representative flow condition in the regions. The riser top 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 slug mitigation potential of this traditional method is investigated for the slug regions identified in this study. Bifurcation maps are generated for the representative slug flow conditions in these regions to further understand the behaviour of these slug types.

Bifurcation map for H-region. Figure 10 (a) shows the riser base pressure bifurcation map of the industrial pipeline-riser system described in section 2. The flow and boundary condition for the representative flow condition is as shown in Table 3.



(a)



(b)

Fig. 10 H-region riser base pressure (a) bifurcation map of pipeline-riser system, (b) Riser base pressure trend at 100% valve opening and Riser base 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 10 (b) shows the riser base 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 stabilize the unstable flow.

Bifurcation map for I-region. The riser base pressure bifurcation map of the case described in Table 4 is shown in Figure 11. 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.

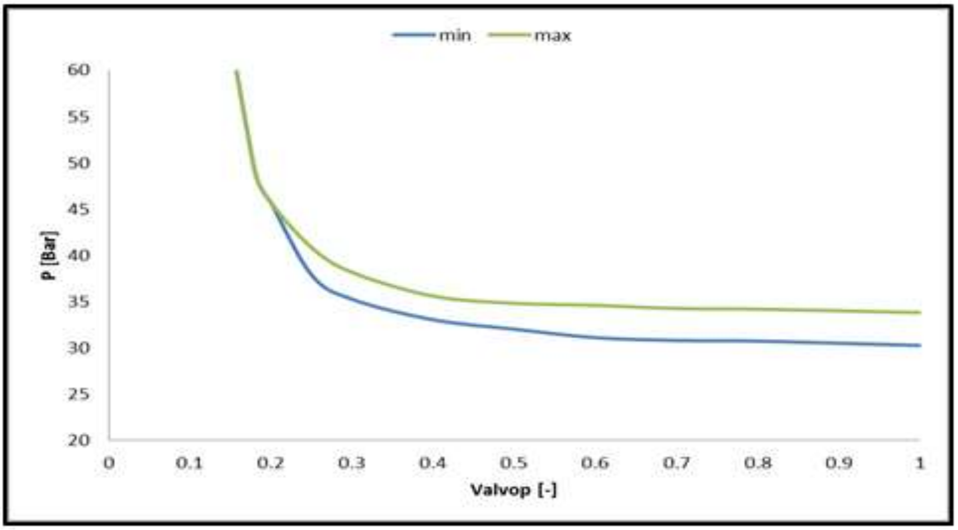


Fig. 11 I-region riser base pressure bifurcation map for pipeline-riser system

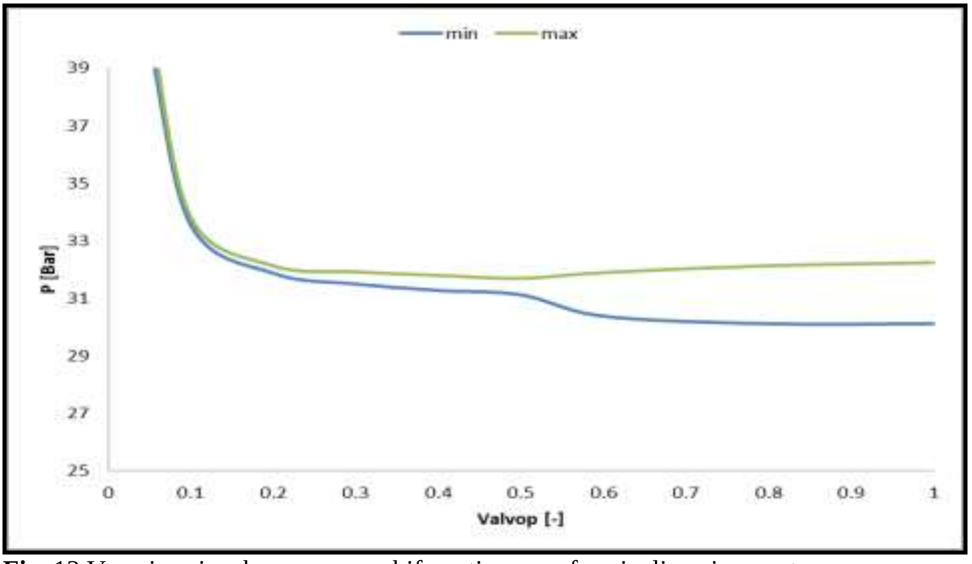


Fig. 12 V-region riser base pressure bifurcation map for pipeline-riser syste

Bifurcation map for V-region. Figure 12 shows the riser base bifurcation map of the pipeline-riser system in the 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 neighborhood of 2 Bar, the valve opening required to stabilize 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[35]. 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[38]. It has been shown that significant choking was needed to stabilize the unstable hydrodynamic slug flow which unfortunately could mean less production [39]. It is therefore important to develop an approach to stabilizing the slug flow at larger valve opening.

The numerical results presented in this work and indeed the observed phenomenon is in consonance qualitatively with the experimental studies [40], but quantitatively different and the difference could be due to diameter effect. Although the software package used in this work predicted slug flow for a large vertical pipe, as opposed to churn flow that has been reported by several authors including Ali [41], 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.

IV. Conclusion

The need to understand the behavior of slug flow in large diameter pipeline has necessitated this study. The understanding derived from this study can be pivotal to the design and operation of pipeline-riser system where slug flow is expected. Considerable insight has been gained from the results and the following conclusion can be drawn.

- There is significant reduction in the area prone to slugging in a vertical pipe compared with the pipeline-riser system. This could be due to the interaction between the pipeline and riser pipe. This suggests the upstream horizontal pipeline has significant effect on the slug flow in the pipeline-riser system.
- Three distinct slug regions and behavior were identified: 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.

- Choking can indeed be used to mitigate the slug flow in all the regions identified but at varying and considerable loss in production. The valve must be choked down at various degrees depending on the regions (flow conditions).
- The understanding of slug behavior in various regions of the envelopes could be useful in seeking a better way to stabilize slug flow in pipeline-riser system.

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