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Experimental Investigation of Hydrodynamic Slug Flow in Pipeline-Riser Systems

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Abstract
Activities in oil and gas industry have shifted deep offshore. There is therefore the need to envisage and accurately provide for flow assurance challenges that might be encountered throughout the life of a field. Slug flow is one of the flow assurance concerns confronting the industry. The objective of the study was to gain insight into the behaviour of hydrodynamic slug flow in pipeline-riser system. This understanding is needed for the development of appropriate slug control strategy.
Experimental studies were conducted in a 2” pipeline-riser system and a 2” horizontal two-phase flow facility. Slug envelopes were developed for the pipeline-riser system, the vertical and the horizontal pipes. The results revealed three distinct slug flow behaviours. The first type of slug was formed in the horizontal pipeline and transported through the riser pipe nearly unchanged, the second type of slugs were formed in the horizontal pipe but also experience growth in the riser pipe while the third are slugs formed in the vertical pipe without the influence of the upstream horizontal pipe.
There is therefore the need to develop appropriate slug control strategies based on the observed behaviour of the identified regions.

Keywords: Hydrodynamic slug flow, slug prediction, slug regions, Flow assurance

INTRODUCTION
Slug flow is one of the flow assurance challenges confronting the oil and gas industry. This phenomenon can pose significant threat to oil and gas production facilities. The three known types of slug flow: hydrodynamic slug flow, operational induced slug flow, and severe slug flow have been widely investigated.
Hydrodynamic slug flow is generally said to occur in horizontal and near horizontal pipelines. In these pipelines, slugs can result from growth of hydrodynamic instabilities 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 Kelvin Helmholtz (KH) instability 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[18,19]. There is therefore the need to understand the behaviour of this type of slug in pipeline-riser system before an appropriate control strategy can be deployed. The objective of this study was to gain more insight into the behaviour of hydrodynamic slug flow in pipeline-riser systems. This understanding is crucial to the development of appropriate slug control strategy to ensure that the production facility is operated in a stable manner. 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. In this study, the well-established flow pattern map was employed with special interest in the slug flow regime. Slug envelopes were produced and flow regimes were identified using physical observation and time response of the riser base pressure.
This paper is organised as follows: in section 2, the methodology adopted for this study is presented; In section 3, the results are presented and discussed. The last section presents the conclusion.

METHODOLOGY
Multiphase flow and indeed slug flow has been studied widely using both experimental and computational methods. In this study, experimental studies were conducted using a state of the art facility to gain practical insight into the behaviour of hydrodynamic slug flow in pipeline-riser systems.

The Three-phase pipeline-riser system
The Oil and Gas Centre of Cranfield University houses a number of experimental facilities. Two of these facilities were employed in this study. They are: the 2” Three- phase pipeline-riser system shown in Figure 1 and the 2” two- phase (Air/Water) horizontal rig shown in Figure 2. The three phase rig was used to carry out studies that pertain to pipeline-riser system. It was also adapted for the vertical pipe study.

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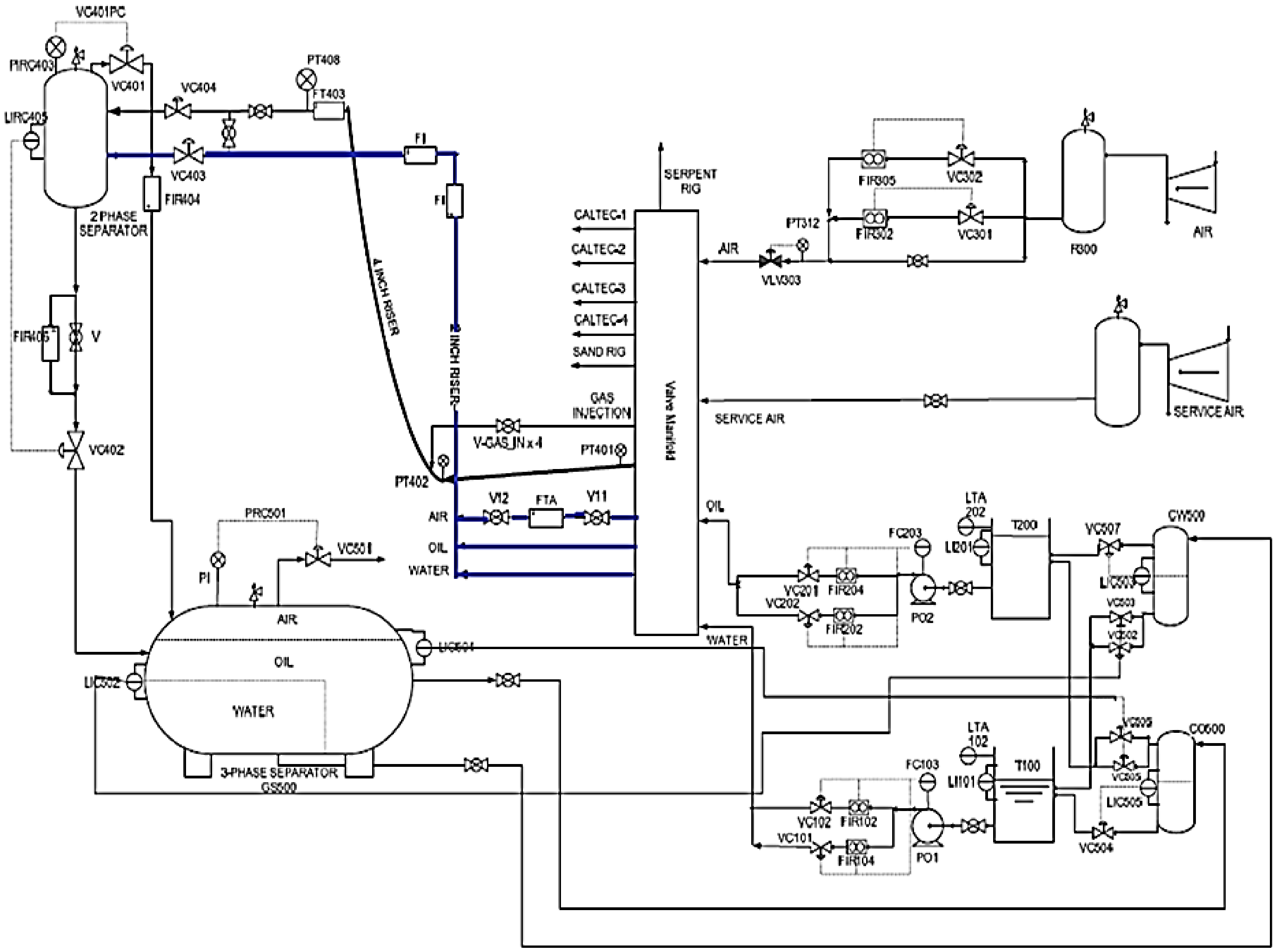

Figure 1: Cranfield University Three phase multiphase facility[20]

The three-phase facility is a fully automated high pressure test experimental rig comprising of three main sections. The metering section where working fluids are measured and supplied into the test section. The test section comprises of the pipeline-riser system and the test separator. In the third section, 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 DeltaV system from Emerson was used to set the various flow conditions and acquire data in the three-phase facility .More on the facility can be found in literatures [20,21].

The two-phase horizontal rig

The horizontal two phase facility shown in Figure 2 was used for horizontal pipeline studies. The air was supplied to the two-phase horizontal rig directly from Cranfield University central compressors and through a needle valve to the metering section. The water was supplied into the horizontal pipe from a 4.4m^3 water tank.

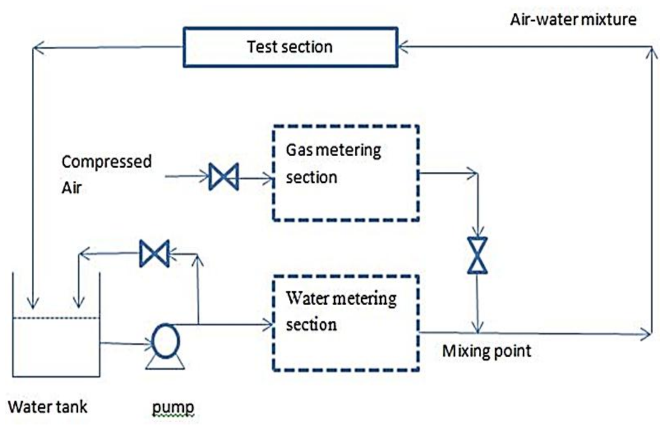

Figure 2: Schematic of two-phase horizontal rig [21]

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. Labview® from National

Instrument was the data acquisition system for the two-phase rig. Detailed information about this rig can be found in [21].

RESULTS AND DISCUSSION

The experimental campaign described in section 2 was used to gain insight into the behaviour hydrodynamic slug flow in pipeline-riser system. Slug flow envelopes were developed for horizontal pipeline, vertical pipe and pipeline-riser system.

Slug flow behaviour in pipeline-riser system

Figure 3 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.

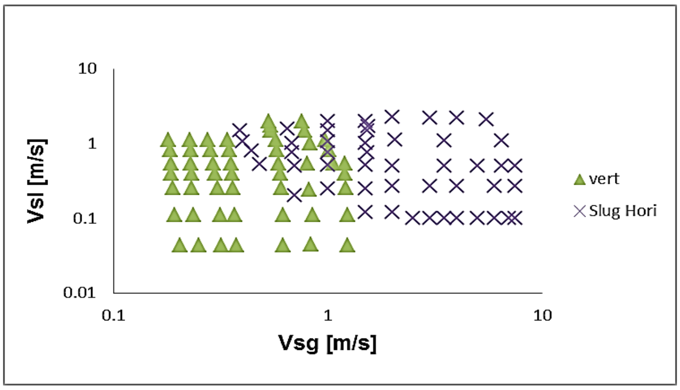

Figure 3: Comparison of slug flow maps for pure horizontal and vertical pipelines

Figure 4 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. Here, the slugs were formed in the horizontal pipeline and transported through the riser. This behaviour is in consonance with what was observed and reported in literature [13,22].

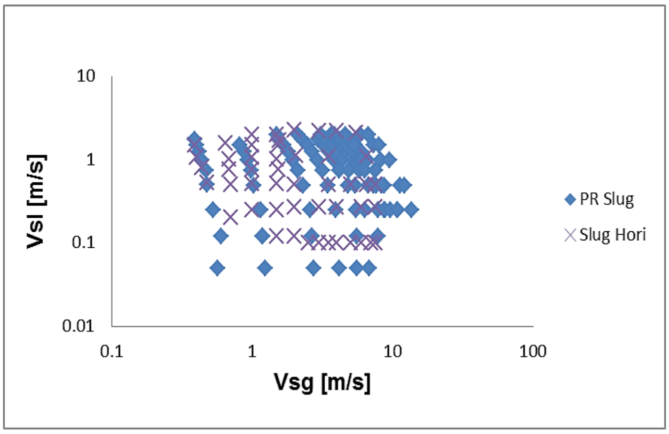

Figure 4 : Comparison of slug flow map for pure horizontal pipeline and pipeline-riser

Figure 5 shows the comparison between the vertical and pipeline-riser system slug maps. It is shown that the slug region at low flow rates in the pipeline-riser intersect with the vertical pipe map. This shows that the region at low flow rate in the pipeline-riser system is due to slug in vertical pipe.

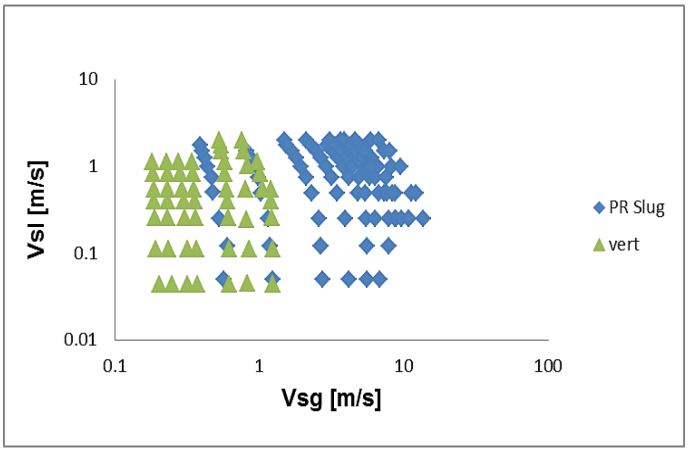

Figure 5: Comparison of slug flow map for pure vertical pipe and Pipeline-riser system

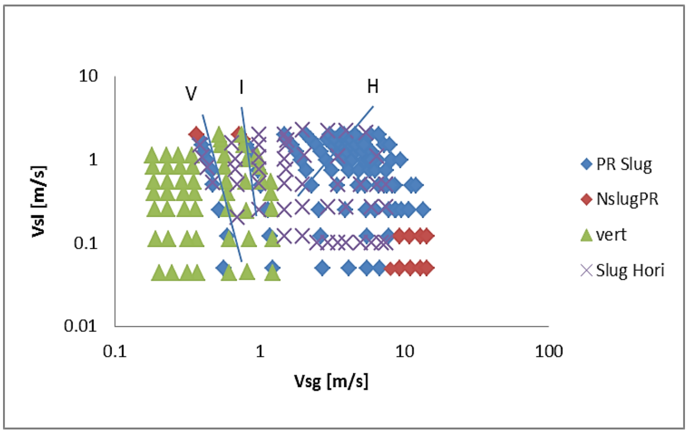

Figure 6 : Comparison of slug flow map for pure horizontal, vertical pipes and Pipeline-riser system

Figure 6 shows the combination of all the slug flow maps. This Figure provides a good picture of the hydrodynamic slug behaviour in pipeline-riser system. Three regions designated as horizontal (H), intersection (I), and vertical (V) were observed. 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 hydrodynamic slug flow.

The slug 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 [23].

The slug region V is the portion of the envelope below both H and I. The slug flow occurs at low flow rates. This type of slug is believed to be due the vertical section of the pipeline-riser

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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[18,22].
The riser base 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.

Characteristics of slug flow in Pipeline-riser system

Characteristics of H-region slug flow :

Figure 7 shows the riser base pressure response of a representative flow condition in the H region. The condition investigated was 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 7.
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.

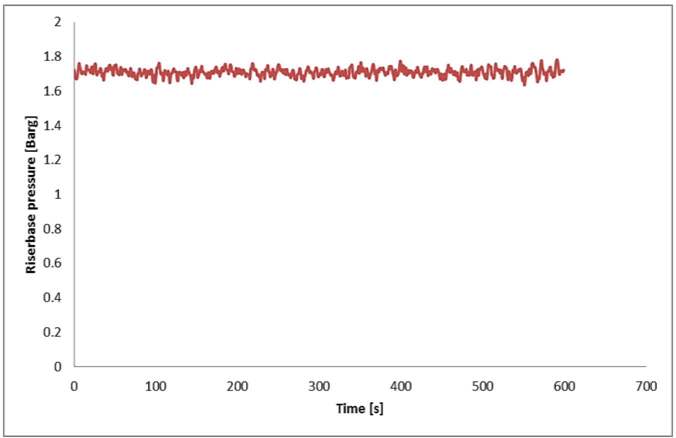

Figure 7: Experimental riser base pressure response for H-region

The riser base pressure fluctuations are of small amplitude in the neighbourhood of 0.2 bar in our experiment.

Characteristics of I-region slug flow:

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.[17], 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 8. The riser base pressure fluctuations are of considerable amplitude magnitude in the neighbourhood of 0.5 Bar. The riser base 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 8.

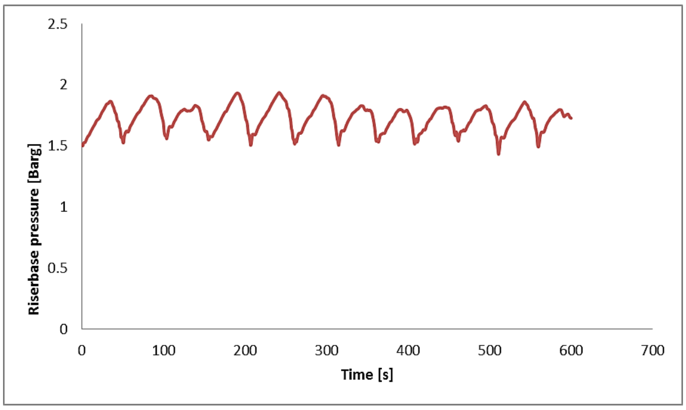

Figure 8: Experimental riser base pressure response for I-region

Characteristics of V-region slug flow :

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.

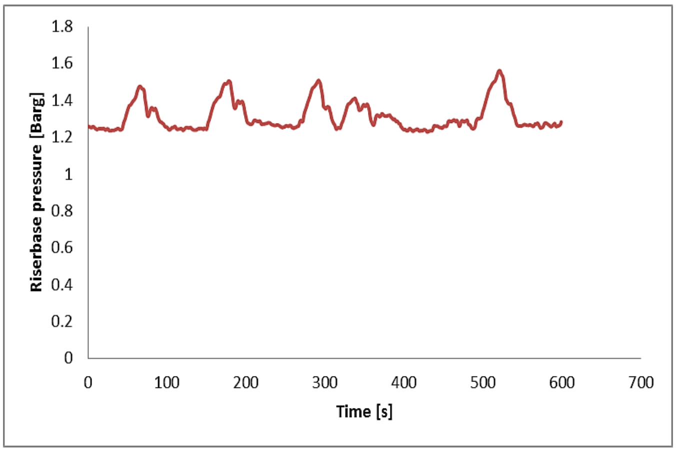

Figure 9 : Experimental riser base pressure response for V-region

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 like 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. [24] and Schmidt et al. [13] 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 riser base 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 9.

CONCLUSION

The need to understand the nature of slug flowing in a pipeline-riser system necessitated this study. Slug envelopes were experimentally generated for a pipeline-riser system 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. The understanding derived from this study can provide a good basis for the development of appropriate slug control strategy for a pipeline-riser system prone to hydrodynamic slug flow.

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