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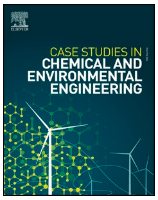

Case Report

Slug flow regime in a flowline with U-shape riser

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ABSTRACT

A suitable initial point for understanding multiphase flows is a phenomenological description of the mechanism of geometric distributions or flow patterns that are observed. The challenge however is the prediction of the flow patterns for a combination of flow operating conditions and the characteristics of the phases as well as points of transition from one pattern to the other. Different flow patterns occur in different pipeline configurations for which U-shape risers are part. In the quest to stabilise unstable slug flow in the U-shape riser, an experimental study of gas-liquid flow mixture is conducted to understand the behaviour of the flow in the riser.

This paper seeks to understand the flow dynamics in a 2-inch internal diameter U-shape pipeline riser system with much emphasis on unstable slug flow. The initiation of this flow instabilities in the U-shape pipeline riser system and the impact of the downcomer on the flow behaviour is investigated experimentally. Understanding the flow behaviour in the U-shape riser could help in developing effective control techniques to stabilise the multiphase flows in the flowlines. Experimentally, flow patterns observed from the U-shape pipeline riser configuration is used to develop a flow regime map which was then compared to that observed in literature and similarly to a purely vertical riser with similar pipe diameter. Thus, a slug envelope was developed for the U-shape riser to help identify which regions slugging could occur in the system.

1. Introduction

Understanding the flow behaviour is of great essence as this aid in the design of real slug control techniques. Many researches have been conducted on flow behaviours in either vertical or horizontal pipeline systems. In Refs. [1–6] some work in identifying flow regimes in horizontal pipeline systems was done while [7–10] studied flow patterns in vertical riser system. These flow regimes identified on a flow regime map are differently characterized by the interfaces between the liquid and gas phases and the distribution of the phases to form bonds with their likes [11]. Several works [9,12–16] have looked into the flow regimes and patterns in different pipeline configurations but less attention has been given to the flow behaviour in U-shape riser system which is a form of a platform to platform pipeline layout, usually seen in the offshore production fields.

While several flow pattern observations are available for vertical two-phase and horizontal two-phase flow, there are no flow regime studies available for U-shape two-phase gas-liquid flow, and as a result, there is no reliable and valid flow regime map available for U-shape configurations. Despite their industrial and technical importance, there have been comparatively few experimental studies focusing on flow regime observation in U-shaped configurations. To address this gap, a study was conducted to Ref. [17] establish a database of flow regime observations for two-phase gas-liquid flow in a U-shaped riser configuration [1], provide a flow pattern map as a resource for future research on U-shaped two-phase gas-liquid flow and [12] make a flow regime map comparison with already existing vertical two-phase maps to ascertain the slug envelope and investigate the initiation point of flow instabilities in the U-shape riser.

Experimentally, flow patterns observed from the U-shape pipeline riser configuration are used to develop a flow regime map which is then compared to that observed in the literature and similarly to a purely vertical riser with similar pipe diameter (2 inch). Thus, a slug envelope was developed in this paper for a U-shape riser to help identify in which regions slugging could occur in the system. With special interest in instabilities in the U-shape riser pipeline configuration, the initiation points of this instabilities were investigated. The procedure adopted for this study will be outlined in subsequent sections. The flow regime

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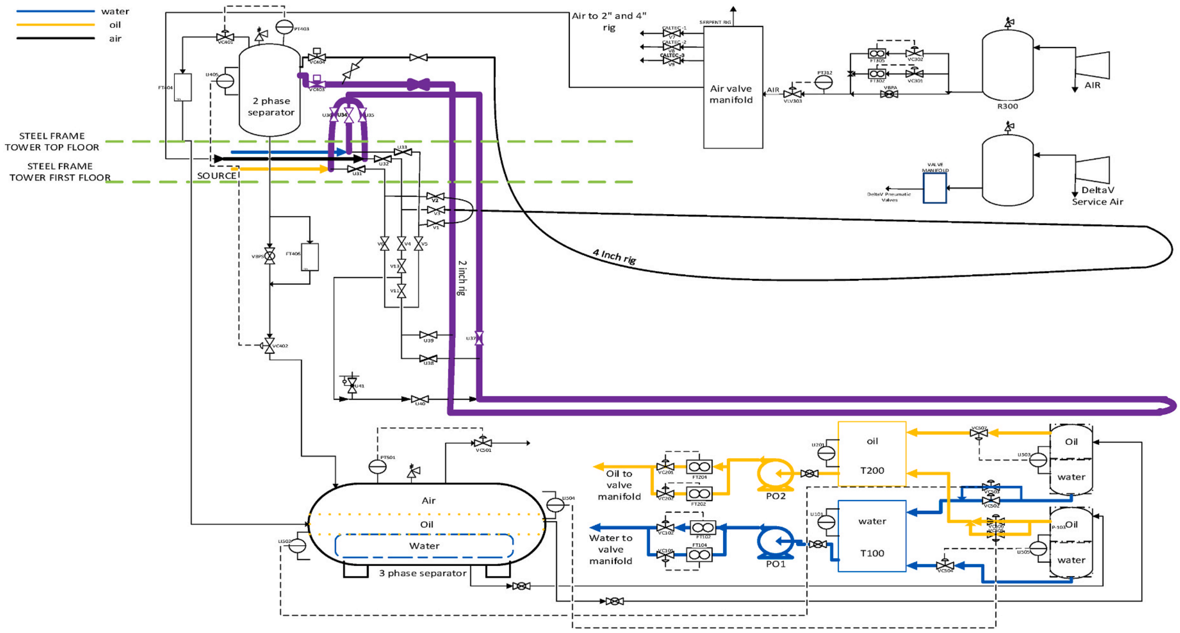

Fig. 1. Schematic of the three-phase facility, purple line - U-shape riser. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

identification is presented first with the initiation of unstable flow (slug flow) presented later. In this work, an introduction is presented in section 1, followed by experimental setup and methodology in section 2, experimental results and discussion in section 3 and section 4 outlines the conclusions from this study.

2. The significance of flow regime identification

Researchers agree that understanding phase distribution, including flow regimes and transitions, as well as how they affect two-phase flow facilities, is critical to developing scientific methods to predict and comprehend (gas-liquid) flows. It has also been a source of significant concern in both industry and academia. Oil and gas, nuclear, and process industries are all primary players in this knowledge.

The flow behavior in the U-shape riser system is subject to the operating conditions of the process, geometry of the conduit, properties of the different phases and flowrate of the phases. One major challenge design engineers face with multiphase systems is the sensitivity of the fluid mass, momentum and energy transfer rate to the topology of the components in the flowing fluid which influences practically the geometric distribution [17]. Thus, the interfacial area available for the phases to exchange mass, momentum or energy is strongly affected by the geometry of the system.

The growing interest in this topic is intrinsically linked to the significant economic and engineering interests that would be served if no new technological modifications or advancements in this area were made. Some important areas that benefit from a better knowledge of phase distribution are listed below.

2.1. Design of equipment

During the early stages of projects that involve the construction of multiphase piping systems and other field production equipment such as pumps and slug catchers, designers typically require detailed data about pressure drop, liquid holdup, critical velocity, and so on.

And, since many pressures drop calculations are flow regime reliant, it is necessary to be able to identify the system's expected flow regime before progressing with the computation of the variables that are then employed to size transmission lines and design other field production equipment. Understanding and accurately predicting fluid behaviour provides useful data to design engineers and original equipment manufacturers (OEMs) when making these vital equipment and facility design decisions. Increased surface contact promotes more efficient and faster chemical reactions or extraction of chemical species in the chemical and process industries. One design focus for this application could be to enhance the surface contact area of the phases in the fluid. One method is to highlight conditions within the control volume that favour the pervasiveness of, presumably, the dispersed bubble flow regime. The dispersed bubble flow regime is distinguished by small mean-bubble sizes, which have a relatively larger surface area for a specified volume fraction than other flow regimes, particularly those with larger bubbles.

2.2. Efficient use of production plants

The dominant flow regime present in the pipeline affects the production rates in multiphase flow systems, such as hydrocarbon production plants. Each flow regime has a unique set of inherent hydrodynamic properties that control how flow parameters behave. For the systems to function at their best, it is crucial to have a comprehensive understanding of the nature and behaviour of these flow regimes because parameters like heat transfer, mass transfer, and pressure loss vary significantly between different flow patterns.

2.3. Developing safe operating boundaries

For particular flow systems or applications, each significant flow regime type has distinctive qualities that can be advantageous or disadvantageous. In some gas-liquid systems, such as pipelines, slug flow, for instance, displays unfavourable functionalities that lead to issues.

The following are some of the negative traits of this flow pattern: (i) It causes significant pressure drops along the channel; (ii) it causes vibrations, wear and tear, and eventually failure of critical process facilities; (iii) and it creates a vibrating effect (pressure surge). Design engineers may decide to alter certain parameters such as pipe diameters in order to guarantee that only specific favourable flow regimes occur throughout system operation once they are aware that slug flow may be an issue in a particular design. While slug flow is unpleasant in some situations, such as the one addressed, it has also been found to be helpful in other situations.

Using gas or liquid as a key driver to remove liquid or gas petroleum from reservoirs is one example of enhanced oil recovery, which occurs when a reservoir is flooded. Between 20 and 50° are the typical recovery factors from fully grown oilfields globally. Because of this, this practise is frequently necessary, particularly when oil prices are high. A sufficiently accurate knowledge of some system variables and parameters is typically required to predict the expected flow regimes in a fluid system. This includes, among others, (a) operational parameters (such as liquid and gas flow rates), (b) fluid physical characteristics (such as surface tension densities and viscosities) and (c) geometrical variables (pipe diameters and inclination angle). A designer could choose between two flow prediction techniques to determine the likely flow regime given these parameters.

3. Experimental setup

3.1. U-shape riser system configuration

The U-shape riser system which can basically be characterised by two vertical pipelines (down comer and riser) and a horizontal section. The U-shape riser can be described as or similar to an extended version of an L-shape riser, purely catenary riser, or even a vertical riser configuration. The flows through the two vertical pipelines are however opposite each other with the horizontal pipe serving as the link between both. The downward and upward flowing vertical pipeline of the U-shape riser system is known as the downcomer and riser respectively.

The 2" U-shape flow loop used in the experimental study for this work consists of a 10 m vertical downcomer connected to a 40 m horizontal pipeline leading to a 10.5 m vertical riser. The U-shape riser system is made from pipes (stainless steel and plastic) with a uniform internal diameter of approximately 50.4 mm. The flow enters the system through the downcomer and exits through the riser into a vertical two-phase separator at the top of a steel frame tower, where gas and liquid are separated. The riser is joined at the top to a purely horizontal pipe (topside) with sections of steel and PVC pipes leading to the two-phase separator. The total length of the topside is about 3.5 m and it is equipped with a valve (choke valve), 0.3 m from the 2-phase separator where initial separation of liquid and gas takes place prior to the 3-phase horizontal separator.

Fig. 1 shows a schematic of the three-phase facility with the U-shape riser layout shown as the purple trace. The horizontal section of the U-shape riser has no inclination or declination. This serves as the channel through which the fluids are introduced into the riser and it is made from a 2-inch stainless steel schedule 20 pipe. A transparent and Perspex pipe section is fitted in the horizontal and near vertical riser base section of the U-shape riser respectively to aid in the observation of the dynamics of the fluids through the pipe. In addition, an extra clear pipe, 1.0 m in length, is fitted in the downcomer (about a meter from the base) to ease flow behaviour observation in the downcomer.

3.2. Experimental procedure for flow regime identification

There are mainly two methods used in identifying flow regimes when constructing flow regime maps namely: direct observation thus visual inspection and extraction of characteristic variable from phase fraction signal fluctuations [18]. The procedure for identifying the flow pattern is by visual inspection and an analysis of unsteady pressures of the spectral content is used even though the fluctuations of the volume fractions as devised in some of these circumstances are established in Ref. [19].

Liquid flowrates within the range of 0.1 kg/s to 5 kg/s corresponding to superficial liquid velocities of 0.05 m/s to 2.47 m/s respectively were investigated against gas flowrates of 7 Sm^3/h to 150 Sm^3/h also corresponding to a superficial gas velocity of 0.18 m/s to 19.87 m/s. Liquid (water) was pumped into the pipeline system by a 30 Hz frequency drive pump. Compressed gas flow was contacted with the pumped liquid before both transported through the downcomer of the pipeline riser system.

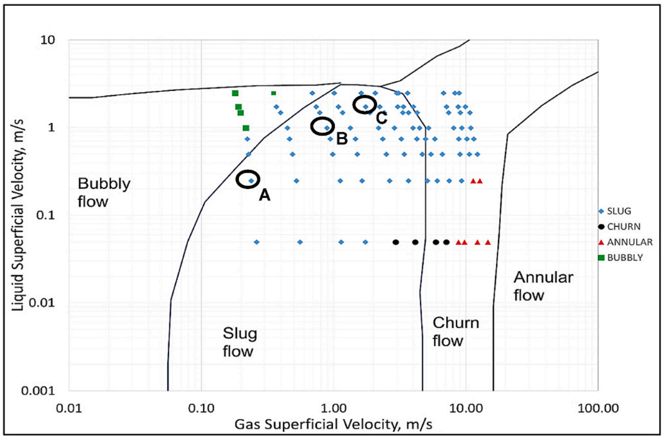

Fig. 2. Flow regime map for the 2 inch U-shape riser loop with flow pattern boundaries from Ref. [21], black line – Barnea boundaries.

The flow dynamics of each condition was observed through the Perspex glass located on the vertical section of the pipeline riser system (above the riserbase). The superficial velocities of both liquid and gas were varied stepwise and each flow pattern visually observed and recorded. From the observations made, a flow regime map was developed identifying each flow pattern for the pipeline riser system.

3.3. Procedure for flow stability in open loop

A bifurcation analysis (manual choking) was done to identify the stability point of the different slugging conditions chosen for further investigation work. From the flow regime map produced, three flow conditions within the slug regime were identified and investigated using the bifurcation analysis [20].

An unstable slug flow condition with superficial velocities of 0.24 m/s and 0.25 m/s for gas and liquid respectively, representing a low flowrate exhibiting a severe slugging condition was run. A stepwise decrease in the choke valve opening was done from a valve opening of 100%–10%. Riserbase pressures for each condition were recorded. The minimum, average and maximum riserbase pressure of each condition were plotted against their corresponding percentage valve opening (bifurcation map) where the critical bifurcation point was identified.

Consequently, the same process was done for the two other chosen unstable flow conditions. Bifurcation maps were developed for these operations identifying the critical bifurcation points. Same conditions were run for the purely vertical riser system to investigate the effect of configuration on flow stability.

4. Results and discussion

4.1. Observed gas - liquid dynamic flow in U-shape riser system

With the point of interest in this study being the control of unstable slug flow, the identification of the slug flow region was key. Different sub-regimes observed within the slug flow regime region exhibiting different characteristics were considered for further investigation.

4.1.1. U-shape flow regime map

A total of about 100 data points were studied covering a gas superficial velocity of 0.18 m/s to 19.87 m/s and a liquid (water) superficial velocity of 0.05 m/s to 2.47 m/s on the 2 inch U-shape flow loop described earlier. Fig. 2 shows the flow regime map obtained experimentally from the U-shape riser pipeline system. This is however compared with a flow regime map obtained from Ref. [21] (black line representing the transition regions).

From Fig. 2, it could be observed that for gas superficial velocities greater than 10 m/s and high liquid superficial velocities, a slugging flow regime was still present. This indicates that the visual observations over predicts the slug flow region relative to that seen in Ref. [21].

Again, the slug envelope is wider and tapers towards the top compared to that observed from the literature, which could possibly mean that the slug flow from literature are mainly formed from low to medium flowrates as compared to higher flowrates. However, a considerable amount of the experimental data falls within the slug region when compared with the literature. Similar observation is made for a considerable amount of non-slugging flow conditions when compared to the literature [9]. This could however be attributed to the difference in configuration, pipe diameter or even the mode of assessment.

4.1.2. Riserbase pressure trends

To understand the unstable dynamics of the flow in the U-shape riser system, three flow compositions observed to be within the unstable region are chosen to study the trend of the fluctuations or oscillations. From Fig. 2, the three flow conditions represented by A, B and C corresponding to 0.24 m/s, 1.34 m/s and 2.23 m/s superficial gas velocities and 0.25 m/s, 0.99 m/s and 1.73 superficial liquid velocities exhibit different flow characteristics. To fully understand the dynamics and the effect the downcomer has on the flow, a slug envelope with similar flow condition was performed on a purely vertical riser system. Results of this is shown as Fig. S2 in supplementary.

Similarly, points A, B and C from Fig. 2 fall within the unstable region in Fig. S2 in supplementary. With the point of interest in this study being stabilising unstable slug flow regime, the identification of the slug region was key and different points within the slug region exhibiting different characteristics were considered for further investigation.

Figure S3, S4 and S5 in supplementary represent the riserbase pressure trend in the U-shape riser system and on the purely vertical riser for the flow conditions A, B and C from Fig. 2.

Fig. S3 (a) and (b) in supplementary, representing low gas – low liquid flowrate riserbase pressure trend on both U-shape and purely vertical risers respectively, behave similar to the characteristics of severe slugging type 2 and 3 as shown in Ref. [22]. Thus there exists no period where the entire riser is filled with liquid. However, the shape of fluctuation in the pressure trends represents different liquid levels translating to different volumes of produced fluids. The fluctuations in the riserbase are 0.3–0.4 barg in magnitude. However, the magnitude of oscillation in the U-shape is slightly higher compared to that seen in the purely vertical riser. This dissimilar behaviour is traced to the geometry of the pipeline riser configuration.

Fig. S4 (a) and (b) in supplementary, represent medium gas – medium liquid flowrate riserbase pressure trend on both U-shape and purely vertical risers respectively. The riserbase pressure fluctuates within a magnitude of 0.2–0.3 barg with low frequencies. Thus, within a period of 600 seconds there were 2 complete slug cycles observed in both risers. However, the pressure magnitude in the U-shape riser pipeline was slightly higher than that observed in the purely vertical riser.

Similarly, Fig. S5 (a) and (b) in supplementary, represent high gas – high liquid flowrate riserbase pressure trend on both U-shape and purely vertical risers respectively. The riserbase pressure fluctuates within a magnitude of 0.2–0.25 barg. The frequency of oscillation is comparatively higher than that seen for medium gas – medium liquid flowrate producing about 3.5 slug cycles per 600 seconds. Again, the magnitude of oscillation in the U-shape riser is higher than that observed in the purely vertical riser. This signifies that the pipeline configuration surely has an impact on the instabilities in the system hence the investigation of the cause a necessity. A stability analysis for flow conditions A, B and C on both risers will be assessed next.

4.2. Stabilising unstable flow condition

The flow behaviour for different flow compositions has been studied in previous sections. From the literature it has been established that an increase in the downhole pressure of the system can help in slug mitigation. This however has been one of the common and most used method for slug elimination in the hydrocarbon industry. In this part of the study, this concept would be further explored for each of the flow conditions (low gas – low liquid flowrate (A), medium gas – medium liquid flowrate (B) and high gas – high liquid flowrate (C)) chosen from the slug envelope with the aid of a choke valve. The choke valve located at the topside of the riser was used to increase the pressure in the system. Riserbase pressure trends resulting from manual choking was used to generate bifurcation maps for the various slug conditions or different forms obtained from the flow regime map. This would aid in the understanding of the slug behaviour as well. Bifurcation maps are produced for the typical unstable slug flow conditions shown above to gain an advanced understanding of the behaviour of these slug types.

4.2.1. Low gas – low liquid flowrate bifurcation map

Using the topside riser choke valve as the manipulating variable and the riserbase pressure as the controlled variable, a bifurcation map was generated for low gas – low liquid flowrate. A bifurcation map obtained from the U-shape riser system for a 7 Sm^3/h gas and 0.5 kg/s liquid corresponding to a 0.24 m/s and 0.25 m/s gas and liquid superficial velocities respectively is shown in Fig. S6 from supplementary. From Fig. S6, a bifurcation point of 19% valve opening was observed corresponding to a riserbase pressure of 2.8 barg. The region beyond the 19% opening (increasing valve opening) is considered as unstable whiles that to the left side of that (decreasing from 19% valve opening) is a stable region. Again, the variation in valve opening (reducing the valve opening) causes an increase in the riserbase pressure of the system. The increased riserbase pressure causes the unstable low gas – low liquid flowrate to be relatively stable a resultant of increased pressure drop across the choke valve. This explains the bane for choking to be used to stabilise unstable slug flow condition.

Similarly, Fig. S7 from supplementary, represents the bifurcation map obtained from the 2 inch vertical riser system for the low gas – low liquid flowrate (7 Sm^3/h gas and 0.5 kg/s liquid). This corresponds to a 0.24 m/s and 0.25 m/s superficial velocities of gas and liquid respectively. From Fig. S7, it was observed that the pressure oscillation magnitude reduces significantly as the choke valve opening was reduced from 100% to 19% opening. Valve closure beyond 19% opening showed a relatively constant oscillation even though the magnitude increases. A bifurcation point of 19% valve opening corresponding to a riserbase pressure of 2.7 barg was seen for the low gas – low liquid flowrate on the 2 inch purely vertical riser. The region above the 19% valve opening (right side - increasing valve opening) is considered an unstable region while that to the left side of that is a stable region.

The bifurcation maps produced in Fig. S6 and Fig. S7 from the U-shape riser and the purely vertical riser respectively for low gas – low liquid flowrate yielded the same critical bifurcation point, thus, 19% choke valve opening. However, the 2 inch U-shape riser system produces a slightly higher corresponding riserbase pressure compared to the 2 inch purely vertical riser.

4.2.2. Medium gas – medium liquid flowrate bifurcation map

The riserbase pressure bifurcation map for medium gas – medium liquid flowrate on the 2 inch U-shape riser flow loop is illustrated in Fig. S8 from supplementary. Medium gas – medium liquid flowrate was represented by 30 Sm^3/h gas and 2 kg/s liquid which is equivalent to 1.34 m/s and 0.99 m/s gas and liquid superficial velocities respectively. From Fig. S8, a 29% choke valve opening was seen to be the bifurcation point of the system corresponding to a 3.35 barg pressure at the base of

Table 1
Result summary for stability analysis (critical bifurcation points and riserbase pressure) for operating conditions through the U-shape and vertical riser.

Flow Condition	U-Shape Riser		Purely Vertical Riser	
	Critical Bifurcation Point, %	Riserbase Pressure, barg	Critical Bifurcation Point, %	Riserbase Pressure, barg
A – 0.25 m/s Liquid and 0.24 m/s Gas	19	2.8	19	2.7
B – 0.99 m/s Liquid and 1.34 m/s Gas	29	3.35	31	3.1
C – 1.73 m/s Liquid and 2.23 m/s Gas	38	3.7	39	4.0

the riser. At 29% choke valve opening, the maximum and minimum valve openings connect and consequently the point which differentiates the stable and unstable region of the system.

Again, the same flow condition was run on the 2 inch purely vertical riser and the resulting bifurcation map shown in Fig. S9 from supplementary. The bifurcation point was seen to be at 31% valve opening which corresponds to a 3.1 barg riserbase pressure. There was a decrease in the riserbase pressure from 3.35 barg at 29% choke valve opening as seen in Fig. S8 for the U-shape riser to 3.1 barg at 31% choke valve opening in Fig. S9 for the purely vertical riser. This indicates that an increase in the topside choke valve opening, eases of the pressure in the pipeline system.

The pressure fluctuation observed at the bifurcation point is of minimum fluctuation compared to that at a 100% choke valve opening for the U-shape and purely vertical riser. The increased pressure drop across the choke valve as a results of the valve closure explains the relatively stable flow oscillation observed.

4.2.3. *High gas – high liquid flowrate bifurcation map*

Fig. S10 from supplementary, shows the bifurcation map obtained from the U-shape riser for a high gas – high liquid flowrate represented by a 75 Sm^3/h gas flowrate and 3.5 kg/s liquid flowrate. This flowrate corresponds to a 2.23 m/s superficial gas velocity and 1.73 m/s superficial liquid velocity. From Fig. S10, a bifurcation point of 38% choke valve opening corresponding to a 3.7 barg riserbase pressure was observed. The choke valve operating range beyond 38% opening was considered an unstable region thus to the right of the critical bifurcation point while that to the left side of the critical stable opening was considered stable. Again, after reducing the valve further into the stable region, it was observed that the system becomes unstable again which was due to the slugging induced by over choking, thus over-choking induced slugging.

Fig. S11a from supplementary, shows the pressure trend in the U-shape riser system at stable condition (38% choke valve opening). Comparatively, Fig. S11a shows a much more stable flow behaviour than observed in Fig. S5a, thus at 100% valve opening. This is because of the attained increased pressure drop across the valve resulting from the closure of the choke valve (38% choke valve opening).

Bifurcation map generated from the pure vertical riser for the same flow condition (high gas – high liquid flowrate) is shown in Fig. S12 from supplementary. From Fig. S12, a 39% choke valve opening was identified as the bifurcation point which corresponds to a riserbase pressure of 4.0 barg. For this operating condition, valve openings above 39% was seen to be an unstable region whiles valve openings 39% and below was seen to be in the stable region. Fig. S11b represents a relatively stable pressure trend obtained at a 39% valve opening on the purely vertical riser for the same high gas – high liquid flowrate compared to the trend seen in Fig. S5b for the same flow condition but at 100% valve opening.

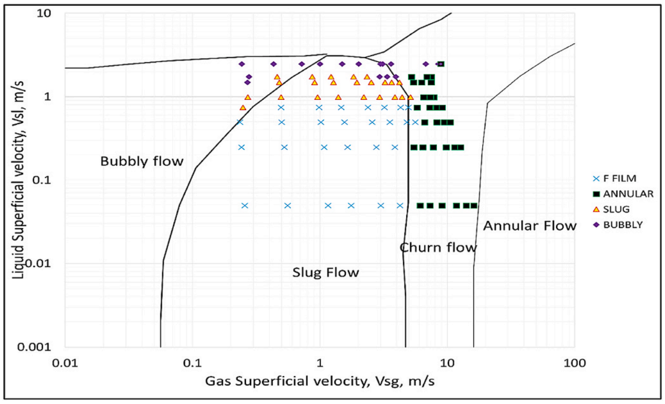

Fig. 3. Flow regime map for a 2 inch U-shape downcomer determined experimentally.

It has been presented that significant choking was required to alleviate the unstable slug flow in the pipeline riser system which unfortunately could translate to less production of fluids. It is therefore important to advance the approach to stabilising the unstable slug flow at a considerably larger valve opening. Conclusively, considering the flow conditions run on both the U-shape riser system and the purely vertical riser system, there was an obvious similarity between the stability points, however the extra riser system volume caused by the downcomer affects the stability point. Thus the valve opening had to be closed further before the system could be stabilised. This raised concerns where the actual flow instabilities in the U-shape riser system could be from and this would be investigated next. Table 1 presents a comparison of the outcome for the three flow conditions through both the U-shape and purely vertical riser in terms of stability analysis, thus critical bifurcation/stability valve opening and the corresponding riser base pressure.

4.3. *Initiation of flow instabilities in U-shape riser*

Studying the dynamics of gas-liquid flow in the U-shape riser yielded a flow regime map which helped identifying the region where slug flow pattern was observed when viewed through the Perspex glass located on the vertical section of the pipeline riser system (above the riserbase). Even though the obtained flow regime map identified on the U-shape riser does not vary from that on a purely vertical riser, the stability point for some flow conditions exhibiting unstable slug flow differ in both the U-shape and the purely vertical risers hence the need to investigate this cause. To understand this concept, an investigation on the unstable slug flow region was performed to establish the initialization of slug flow in the riser.

A justification for the cause for this flow dynamics was necessary hence some further modifications were made on the U-shape riser system. These modifications included introduction of extra visual section and extra pressure transducers on the downcomer as shown in Fig. S1 in supplementary.

The slug flow pattern behaviour observed in the U-shape riser was of great concern since the initialization of slug flow in the riser was not understood. The boundaries of the slug flow regime were assessed to know the initialization stage of slugging in the U-shape flow riser. An experimental run of the flow conditions exhibiting unstable slug flow in the U-shape riser was assessed. Flow pattern in the downcomer of the U-shape riser system was observed and the resulting flow regime map is shown in Fig. 3. From Fig. 3, four distinct and unique flow behaviours were observed in the down comer of the U-shape riser.

For very low gas and liquid flowrate, a free fall flow was seen in the downcomer. Increasing the liquid flowrate (mid flowrate) showed a slug

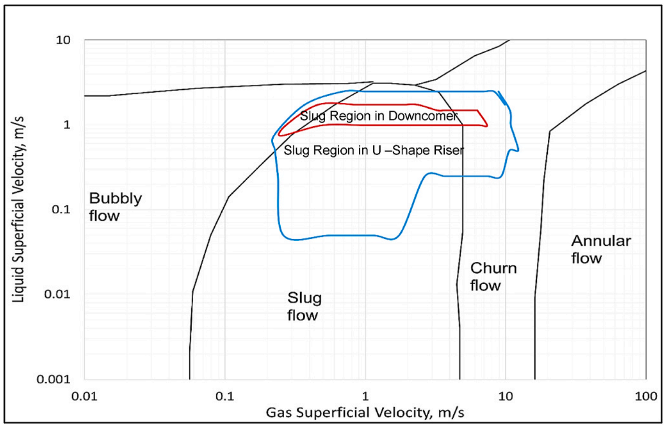

Fig. 4. Slug region comparism for both downcomer and riser system in a 2″ U-shape loop.

flow regime in the down comer. A further increase to higher liquid flowrate showed a dispersed bubble flow.

Similarly, increasing the gas flowrate at constant liquid flow rate resulted in an annular flow regime. This was observed however for relatively medium gas flowrate. Again, for high flow rate for both gas and liquid, annular flow pattern was observed, while reducing the gas flowrate at high liquid flowrate showed dispersed bubble flow.

Fig. 4 shows a comparison of the slug behaviour regions in both the riser and the downcomer. It was observed that the slug region in the downcomer (red sectioned area) falls perfectly within the slug region of the riser (blue sectioned area). This shows that all the flow conditions exhibiting slugging flow in the downcomer, exhibits slugging flow in the riser.

However, not only flow conditions exhibiting slug flow in the downcomer translate to slug flow in the riser, since there were other flow regimes in the downcomer that also exhibited slug flow in the riser. This could means that, the initialization stage of slug flow in the riser is not necessarily from the downcomer but could be from either the flow condition itself or might also be from the horizontal section of the flow loop as established by several researchers.

4.3.1. *Downcomer pressure trends*

Different flow patterns are observed for the different flow pattern characterization. Fig. S13 from supplementary, represent the transient flow behaviour of a free fall flow, slug flow, dispersed bubble flow and an annular flow pattern in the downcomer.

The slug flow characteristics observed in the downcomer behave like type 2 and 3 severe slugging described in Ref. [22], however there was no time period where the entire downcomer was completely filled with liquid. However, the liquid in the downcomer build up to an extent since there is an oscillating flow observed in the system which is a resultant of the different liquid heights. The downcomer pressure fluctuates with an amplitude of about 0.1 barg which is a considerable oscillation in the 2-inch U-shape riser hence we consider to stabilise the system next using the downcomer pressures.

4.3.2. *System stability study using downcomer top pressure*

To verify the slug initiation, point in the U-shape riser, pressure stability test (bifurcation maps) was developed using different pressure points (downcomer top pressure, downcomer base pressure and riserbase pressure) on the U-shape riser. This study aims to establish any similarity in system response in both the riser and the downcomer of the U-shape riser with regards to the choke valve openings.

4.3.2.1. Low gas – low liquid flowrate bifurcation map using downcomer top pressure. From Fig. 2 an operating condition (7 Sm^3/h gas and 0.5 kg/s of liquid) represented by point A was investigated to determine the stable and unstable operating regions in the riser and in the downcomer when varying the choke valve opening. Again, this helps in understanding the dynamic unstable slug flow behaviour in the U-shape riser system. Figs. S14–S16 from supplementary, represent the bifurcation maps, a resultant of a parameter variation technique (using choke valve opening), obtained using the pressure at the top of the downcomer (downcomer top pressure), pressure at the base of the downcomer (downcomer base pressure) and the pressure at the base of the riser (riserbase pressure) respectively. Addressing the setbacks associated with measurement signals from the base of the riser or downcomer, the downcomer top pressure bifurcation map was of great interest as both base signals are not readily accessible especially for already existing fields.

From Figs. S14–S16, a 19% choke valve opening was registered as the bifurcation point, thus, the point which transitions from the stable to unstable operation mode for the downcomer top pressure, the riserbase pressure and the downcomer base pressure bifurcation maps. This flow condition however represents a low gas – low liquid flowrate condition.

Beyond 19% choke valve opening, thus, increasing the percentage valve opening, the system loses its stability while for valve openings below 19% the system was stable. For the stable region, the maximum pressure curve and minimum pressure curve converge hence follow the same trend. On the contrary, for valve openings greater than 19% valve opening, there was divergence in both the maximum and minimum pressure curves which signifies instabilities or oscillations in the system pressures (riserbase pressure, downcomer top pressure and downcomer base pressure). This explains why for all the pressure signals used the system losses its stability when the valve opening was greater than 19%. Again, as observed from Fig. S14, Fig. S15 and Fig. S16, the pressure measurement signals reduced as the valve opening reduced, signifying that reduction in the valve opening reduce the severity of the fluctuation in the pipeline system.

4.3.2.2. Medium gas – medium liquid flowrate bifurcation map using downcomer top pressure. Similarly, Fig. S17, Fig. S18 and Fig. S19 show the bifurcation map obtained for the flow condition (30 Sm^3/h gas and 2 kg/s of liquid (Point B on Fig. 2)) representing medium gas – medium liquid flowrate using the downcomer top pressures, downcomer base and riserbase pressure respectively.

From Fig. S17 and Fig. S18, a bifurcation point of 31% was observed for the downcomer base pressure and downcomer top pressure bifurcations. Again, the riserbase pressure bifurcation map as shown in Fig. S19 registered a bifurcation point of 29% choke valve opening. This implies that the downcomer becomes stable at a 31% choke valve opening however for the entire system to be stable the choke valve opening needed to be closed a further 2% since the riserbase pressure only becomes stable at 29% choke valve opening. The regions beyond these respective critical choke valve openings was considered an unstable region due to the oscillations in the pressures while the regions to the left side of these valve opening was considered stable. Comparatively, the pressures in the downcomer base for the different valve openings are high relative to that seen in the riserbase pressure. This could be associated with the horizontal section aiding accumulation of liquids at the base of the downcomer.

It could be deduced from this case that slugs in the riser could be formed as a result of the flow through the horizontal section of the pipeline and are not dependent on the downcomer of the U-shape riser. As shown in the medium gas – medium liquid flow condition, at 31% valve opening, the downcomer was stable but the riserbase was not stable since it requires an extra 2% valve closure for it to be stable as the stability point of the riserbase was at 29% valve opening.

4.3.3. *Validation of slug initiation in U-shape riser*

From previous sections, it was observed that the flow conditions

Table 2
Flow observations in a riser system for a 2 inch purely vertical riser.

Liquid flowrate, kg/s			1.5	2	3	3.5
Liquid volumetric flowrate (m^3/s)			0.00150	0.00200	0.00301	0.00351
Superficial liquid velocity per second (m/s)			0.74	0.99	1.48	1.73
Gas Flowrate sm3/h	Gas Flowrate nm3/h	Superficial gas velocity (m/s)				
5.00	2.42	0.33	slug	slug		
10.00	4.83	0.66		slug	slug	slug
20.00	9.66	1.32		slug	slug	slug
30.00	14.50	1.99		slug	slug	slug
50.00	24.16	3.31		slug	slug	slug
70.00	33.83	4.64		slug	slug	slug
100.00	48.32	6.62		slug	slug	
120.00	57.99	7.95		slug	slug	
150.00	72.48	9.93		slug	slug	
200.00	96.65	13.24		slug	slug	
250.00	120.81	16.55		slug	slug	

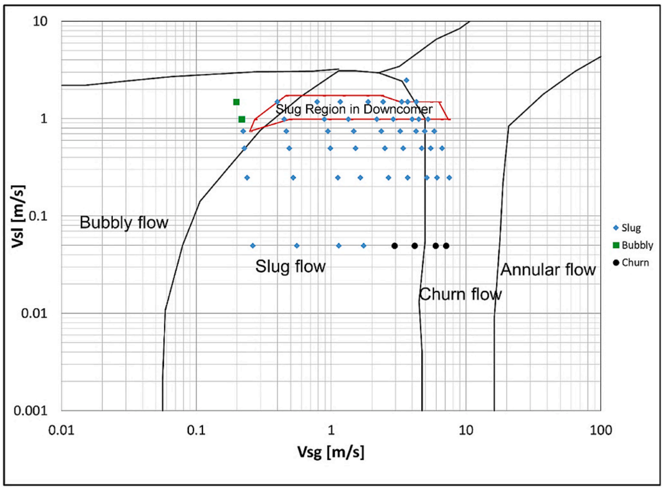

Fig. 5. Slug region comparism for U-shape downcomer and a purely vertical riser system.

exhibiting slug flow in the downcomer also exhibited slugging in the riser, hence the validation of the slug initiation point on the U-shape riser. To confirm these findings, the same flow conditions as shown in Table 2 was run on a 2 inch purely vertical riser (without a downcomer) to investigate if these conditions also exhibit slugging in the purely vertical riser.

Table 2, shows the observations made from the various flow conditions in a 2 inch purely vertical riser. Slug flow pattern was observed in the riser of the 2 inch purely vertical loop for the flow conditions that exhibited slugging flow in both the downcomer and the riser of the 2-inch U-shaped riser. This illustrates that the downcomer of the U-shape loop has minimum influence on the slugs produced in the riser of U-shape riser as represented on Fig. 5.

From this section, it could be deduced that for flow conditions exhibiting slugging characteristics in the riser of the U-shape, its initiation may not necessarily be from the downcomer of the U-shape riser loop but from the horizontal section of the flow loop. This is shown in the study above as all the flow conditions showing a slug flow characteristics in both the riser and downcomer of the U-shape flow loop also showed slugging in the riser for a 2 inch purely vertical riser as shown in Fig. 5.

5. Conclusions

In this paper the necessity of flow loop geometry has been established. The slug envelope from both the 2-inch vertical riser and the 2 inch U-shape riser has been seen to be nearly unchanged. Most of the slug flow predicted from the experimental run on both riser match significantly with that in Ref. [21]. Even though in some instance there was an over prediction of certain regimes, there was a great match from both the experiments and the flow regimes from the literature.

Again, choking can be used to mitigate slug for different slug characteristic or behaviours. The choke valve needs to be closed considerably, to attain a stable flow. The degree of closure depends however on the flow characteristics. For both the U-shape riser and the purely vertical riser, there was a considerable increase in the riser base pressure due to choking even though the pressure at the base of the riser was on the high in the U-shape compared to that of the purely vertical riser. Choking however comes with a certain degree of cost baring due to the reduced valve opening which tends to reduce the flow of the system on a whole. Therefore, there is a need to seek better ways or methods of stabilising unstable flows in flow loops for distinct flow behaviours.

Also, it could be deduced that, for flow conditions which exhibit slugging characteristics in the riser of the U-shape, its initiation may not necessarily be from the downcomer of the U-shape riser loop but from the horizontal section of the flow loop. This is shown in the study above as all the flow conditions showing a slug flow characteristic in both the riser and downcomer of the U-shape flow loop also shows slugging in the purely vertical riser.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cscee.2022.100265.

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