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Strategic Slug Flow Attenuation in Pipeline-Riser Systems

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***Abstract*:** Oil and gas activities across the globe now take place deep offshore. To operate in this harsh environment, there are numerous challenges. These can be in the form of high cost of production, space constraints, operational and technological demands. The co-transportation of oil and gas in same pipeline is one of the operational and technological approaches adopted in the industry to meet the transportation of produced crude. This approach comes with its attendant flow assurance difficulties. Slugging is one of such problems which can constitute operational hitches resulting in production reduction and sometimes eventual plant shutdown. Existing attenuation techniques are limited in various ways. Therefore, seeking a reliable solution to this problem is highly desired. In this study, an experimental study of multiple techniques for slug attenuation was attempted. A passive device-the intermittent slug absorber, strategically combined with topside choking as well as topside separator were investigated. The theoretical analysis showed that slug attenuating devices can be combined in parallel to reduce the resistance posed on flow, leading to increased flow. The experimental results showed that a combination of the methods proves to be more effective compared to individual techniques. A significant reduction in riser- base pressure of up to 39% was achieved. This is advantageous and translates to an increase in oil recovery. Thus, the proposed strategy helps to achieve system stability and improved production at a lower cost.
***Keyword*:** Decision matrix, slugging, flow assurance, slug mitigation, bifurcation map

1. Introduction

Flow assurance in petroleum production systems is of immense importance. The operators desire economical, environmentally safe, and continuous flow of oil and gas. A deviation from this could translate into billions of dollars loss which are either paid in fines or loss due to downtime. One of the flow assurance difficulties facing producers is slugging. This is an alternating flow of oil and gas characterised by pressure and flow fluctuation. This intermittence could result in a number of operational problems including topside separator's trip and eventual shutdown. Existing efforts to curb this menace have either have limited applicability or negatively impact production [1–3]. There is therefore a continual search of techniques for its control and attenuation.

Substantial studies have been devoted to understanding slug flow phenomenon [4–13]. Others investigated the control and attenuation of slug flow and many approaches have been proposed [3,14–19].

These techniques have been classified as active and passive control strategies[20]. The active slug control involves the use of external influencer to achieve slug control while the passive methods achieve slug attenuation without any external influence.

The manual or automated choking and gas injection are good examples of active slug flow attenuation strategies. In manual choking and automated choking, the operator and the controller are the external influencer. For gas injection, the compressor system serves to externally influence the process. The literature is replete of existing works on active slug control and an attempt to review the progress made is made next.

The foundation works for the control and attenuation of slug flow were done between 70s and late 1980s. Significant efforts have been made after to optimise the proposed methods and new methods have been proposed recently. The use of choking as a slug control technique and its attendant downside of excessive back pressure resulting in flow capacity was reported [1,21,22]. This shortcoming has been further worked upon by automating the process and the results of such automation has shown that with the use of controllers, the pressure drop could be reduced and production could be positively enhanced [14,22–25].

The last two decades have witnessed noteworthy progress in developing control systems for slug attenuation. Both linear and non-linear control algorithms have been developed [26–32]. Although momentous advancements have been witnessed in the application of control techniques for slug attenuation, efforts are still ongoing in the areas of controllability, measurements and optimization of control systems [28,33].

Gas injection is another active slug mitigation approach that has been widely employed in the industry. Although, the related cost of gas injection could be extortionate, significant advancement have been recorded in this technique [34–37].

The passive slug control can be achieved by using many devices or techniques such as pipeline reduction [21], multiple risers [38], self-gas lift method [39,40], flow conditioners [41,42], bubble breaker [43], mixing device [44] and more recently the intermittent absorber[25,45].

Other techniques include the use of topside pipeline specially designed for slug attenuation [17], subsea separation [46], homogenization of multiphase flow using emulsifier[47] and the use of surfactants for slug attenuation [48]. Although this technique showed some promising results, its applicability is limited.

There is no doubt that significant progress has been made in slug flow attenuation. However, it has been reported recently that no single method can achieve excellent result. It was therefore, proposed that, to optimise slug flow attenuation, more than one technique must be employed [45,49]. Efforts are thus geared towards seeking strategies to attenuate slug flow at the same time meeting production system stability and enhancement.

In this study, a new strategy for slug mitigation has been presented. A passive device-the intermittent slug absorber and topside separator were investigated.

2. Materials and Method

The multiphase facilities at the Oil and Gas engineering Centre of Cranfield University was used for the experimental studies. The two-inch Pipeline-riser system part of a completely computerised high-pressure test experimental facility containing three major segments. The metering unit, the test segment which includes the horizontal pipe, vertical riser and the two-phase test separator, and the third segment where separation of the multiphase working fluids takes place in a horizontal three-phase separator. Figure 1 shows the test area used for this study. The vertical two-phase test separator is of 1.2 m height and 0.5 m diameter where the fluids from the pipeline-riser systems are discharged. More details, operations and procedure for this facility can be found in [25]. In this study, bifurcation maps were developed for slug flow conditions using topside choke and separator gas outlet valves to study the attenuation capability of the device and the separator and their combined operation modes. This method has been previously adopted by Ehinmowo et al. [45] to investigated the potential use of intermittent absorbing device for hydrodynamic slug flow mitigation.

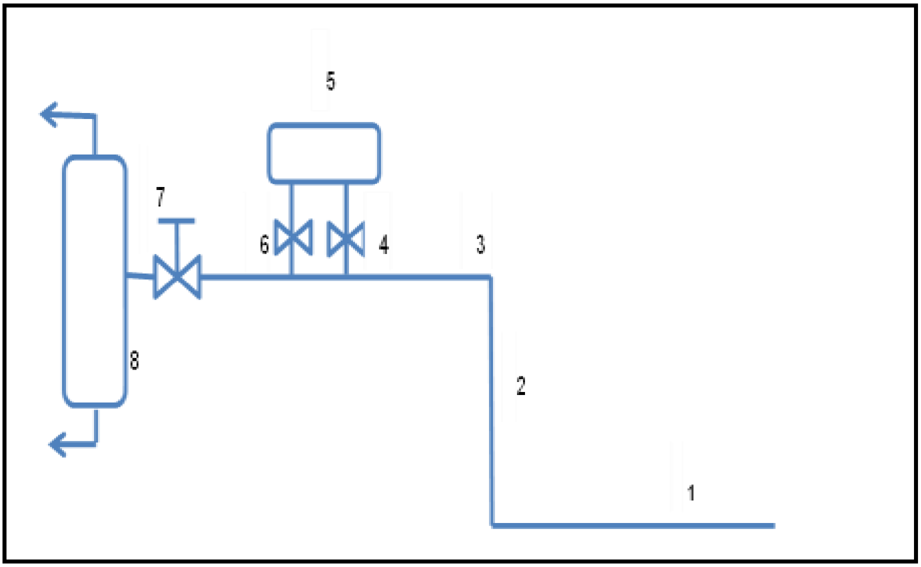

Figure 1: The test section of the Pipeline-riser system ((1) *40 m long purely horizontal pipe , (2) Vertical riser which is 11 m high , (3) horizontal section which is about 3 m, (4) the upstream isolation valve, (5) the intermittent absorber , (6) downstream isolation valves, (7) topside choke valve and (8) two-phase test separator*)

Following the experimental work of Ehinmowo et al. [45], various flow conditions including slug flow and non-slugging regimes were investigated in this study. A representative slug flow condition of 1.95m/s and 1.0m/s superficial velocities (30 Sm^3/hr and 2 kg/s) of air and water respectively was investigated for the combination of intermittent absorber and topside separator and their individual performances were investigated for slug flow mitigation.

3. Strategic stabilization of slug flow for increased oil production

Considering a pipeline-riser system shown in Figure 1, Ehinmowo [24] has shown that the riser base pressure is a function of the liquid head, frictional head, acceleration head, and pressure drop across the valve and the separator pressure. In this study, there will be additional pressure drop due to the intermittent absorber and the pressure drop at the gas outlet choke valve represented as ΔP_{int} and ΔP_{sgo} respectively. The statement of Ehinmowo [24] can be written as equation (1).

$$P = \mathrm{f}\left(\Delta P_h, \Delta P_f, \Delta P_a, \Delta P_v, P_s, \Delta P_{int}, \Delta P_{sgo} \right) \quad (1)$$

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

It is desired to minimise P in order to achieve unhindered and increased flow. This can be shown mathematically, by considering the general linear well model given in equation (2). This model described the oil production rate as a function of pressure drop across the production system [25,51].

$$Q = K(\Delta P) \quad \textbf{(2)}$$

The well production rate is Q, ΔP represents the pressure drop across the production system and can be given as equation (3) . K is the productivity index

$$\Delta P = (\mathrm{Pr} - \mathrm{Pw}) \quad \textbf{(3)}$$

where P_r is the average reservoir pressure and P_w is the well head pressure. The well head pressure is a function of all the pressure downstream including those contribute by the pressure drop across the line, equipment and choke valves as detailed in the right-hand side of equation 1. These terms determine the resistance to flow that must be minimised in order to maximize production.

Assuming a series arrangement of the attenuating devices, valves, intermittent absorber, the fluid resistance being the ratio of pressure drop to flow rate can be written as equation (4).

$$F_R = \frac{\Delta P_h}{Q} + \frac{\Delta P_f}{Q} + \frac{\Delta P_a}{Q} + \frac{\Delta P_v}{Q} + \frac{\Delta P_s}{Q} + \frac{\Delta P_{int}}{Q} + \frac{\Delta P_{sgo}}{Q} \quad \textbf{(4)}$$

Assuming the gravity and frictional terms are enormously greater than the acceleration term, and the acceleration term is neglected, Equation (4) can be written in terms of the fluid resistance of each component to obtain equation (5).

$$F_R = \mathrm{R}_h + \mathrm{R}_f + \mathrm{R}_v + \mathrm{R}_s + \mathrm{R}_{int} + \mathrm{R}_{sgo} \quad \textbf{(5)}$$

where F_R is the resistance the fluid experienced, R_h, R_f, Rs , R_v, R_{int}, R_{sgo} are the resistance due to hydrostatic head, frictional head, , separator , topside valve, intermittent absorber and separator gas outlet respectively.

But, the intermittent absorber is not in series with other components as shown in Figure 1. It is in parallel with the topside valve. Thus Equation (5) now becomes equation (6).

$$F_{RP} = \mathrm{R}_h + \mathrm{R}_f + \frac{\mathrm{R}_v \mathrm{R}_{int}}{\mathrm{R}_v + \mathrm{R}_{int}} + \mathrm{R}_s + \mathrm{R}_{sgo} \quad \textbf{(6)}$$

An inspection of equations (5) and (6) shows that F_R is greater than F_{RP} . Thus, the strategic placement of the intermittent absorber in parallel with the topside valve will increase the valve opening required for slug stability leading to a reduction in the resistance posed to flow. This in turns lead to increase in production rate.

Also, the additional volume provided by the separator helped to reduce the resistance to flow when using the gas outlet valve as the slug attenuating device. This is in consonance with the observation of Ehinmowo et al. [17].

4. Results and Discussion

Slug flow occurs within a wide range of conditions as shown in Figure 2. The slug flow condition chosen for attenuation occurs at the core of the map. The blue markers indicate conditions for slug flow while the red represent the non-slugging region. The slug flow region has been previously characterised and described [19], [50] .

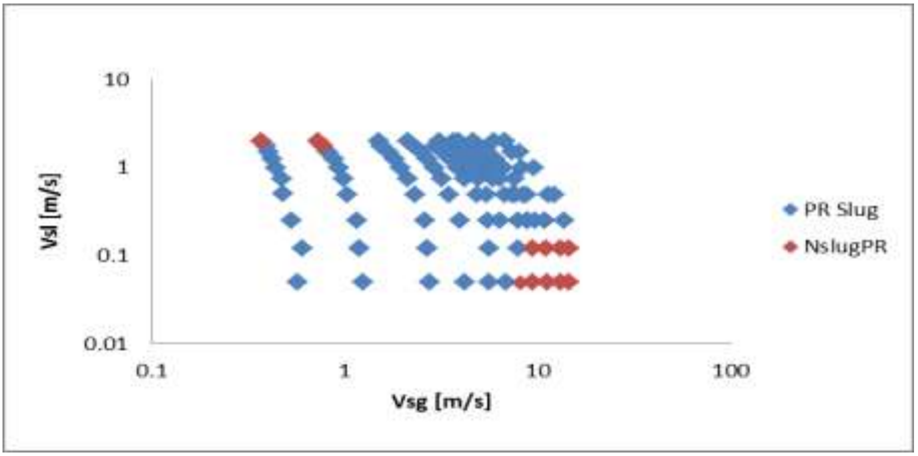

Figure 2: Flow regime map for the experimental study

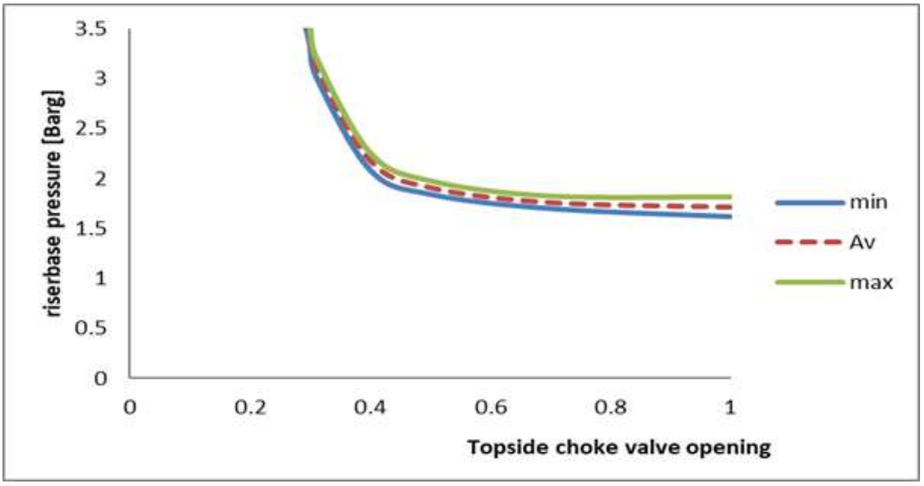

Figure 3: Topside choking for slug flow mitigation

Figure 3 shows the bifurcation plot for the case for topside choking for slug flow attenuation. The slug flow was stabilized at a bifurcation point of 31% valve opening. The riser-base base pressure at stability point was 3.21 barg. Similar results have been previously obtained [25,45] . The slug flow was attenuated but at a high pressure and small valve opening which is detrimental to production. It is therefore desired to have the slug flow stabilized at low pressure and large valve opening. From equations (2) and (3), it is clear that the lower the P_w, the higher the Q which is the oil production.

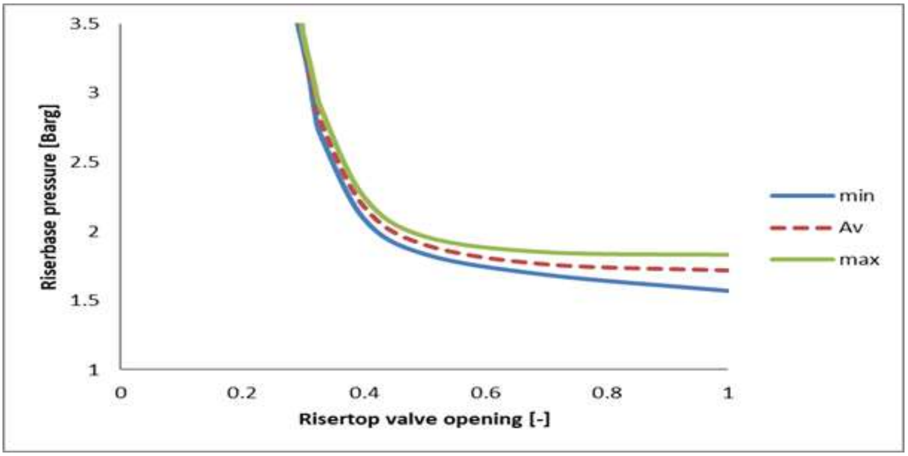

Figure 4 Intermittent Absorber for slug flow mitigation

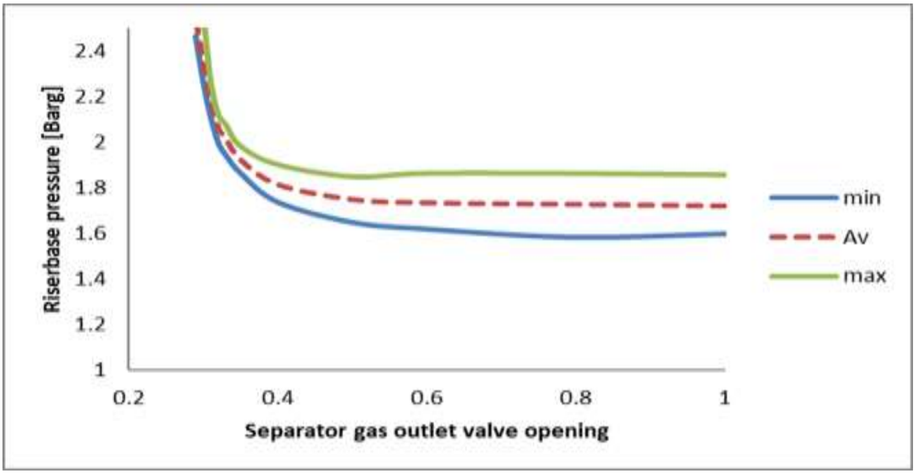

Figure 5: Separator gas outlet valve operation for slug flow attenuation

Figure 4 shows the bifurcation map for intermittent absorber for slug flow mitigation. Slugging disappears at 33% valve opening and a riser-base pressure value of 2.88 barg. This is a larger valve opening and lower pressure when compared with 31 % for topside choking and 3.21 barg. The further 2 % valve opening translated into a pressure difference of 0.33 barg. This is a gain in production as shown in equation (2) and similar quantification has been reported [25].

In a quest for optimized slug flow mitigation, the use of the gas outlet valve as the parameter variation was attempted. Figure 5 shows the bifurcation map using this strategy.

The slug flow was stabilized at 32% valve opening and the riser base pressure value reduced to 2.1 barg. This bifurcation point was more desired when compared with topside pressure as the varying parameter, the result showed that the gas outlet valve was a more desirable one.

The focal objective of this study is to seek a reliable approach to attenuating slugging in pipeline-risers. Figure 6 shows the bifurcation plot for intermittent absorber combined with separator operation as slug control strategy. The slug flow mitigation was achieved at 35% valve opening and a very low riser-base pressure of 1.96 barg. This provides a huge profit of about 38.94% when compared with topside choking, 31.94% when compared with vessel added to topside choking and 6.67% when compared with separator gas outlet choking as the slug control technique.

This benefit of gas outlet valve choking over topside choking and topside choking coupled with intermittent absorber can be traced to additional volume provided by the separator which serves to provide attenuation capacity for the slug flow. These results showed that the combination of more than one technique is more reliable for slug flow attenuation compared with a single approach. This is in consonance with the previous observations of [49,52].

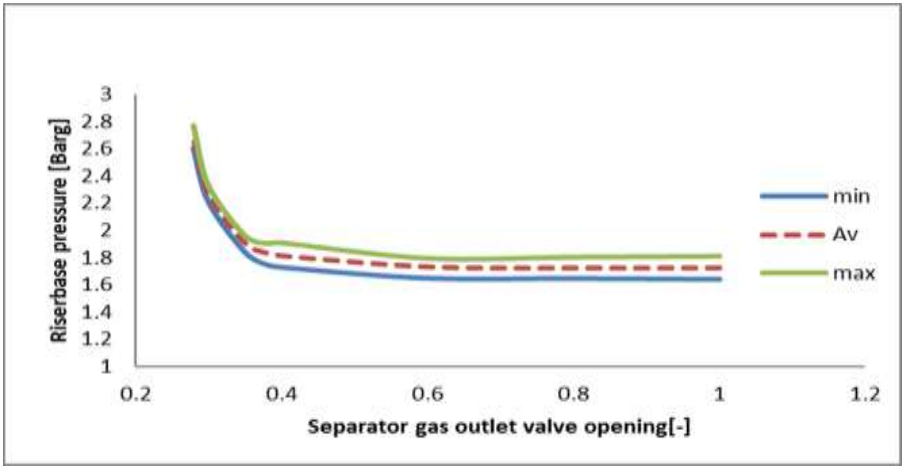

Figure 6 Separator and intermittent Absorber for slug flow attenuation

4. Conclusions

A reliable strategy for slug flow attenuation was investigated in this study. Based on the findings, the following deductions can be made.

- For effective mitigation of slug flow, a minimum of two techniques must be combined
- The use of the separator gas outlet choking and intermittent absorber outperforms the combination of topside choking and intermittent absorber.
- The theoretical analysis revealed that slug attenuating devices arranged in parallel outperforms those arranged in series for slug mitigation and enhanced production capacity.

- The proposed strategy in this study can provide up to 39% reduction in riser-base pressure which signifies an increased oil production.

5. Recommendations

Although, the proposed strategy has been shown to outperform existing techniques, there is the need to further optimise the volume of the separator for enhanced performance.

A numerical study can also be carried out to further strengthen the understanding of the proposed techniques. This is a subject of future studies

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