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NUMERICAL SIMULATION OF GAS LIFT INJECTION AND ITS EFFECTS ON THE SLUGGING PHENOMENON IN OFFSHORE PRODUCTION

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Abstract. *Oil extraction is taking place in progressively more complex and inhospitable environments, which characterizes an engineering challenge on several fronts. One of these challenges is the stabilization of flow in marine risers, both to minimize risks and increase productivity. The slugging effect in particular, generated by the multiphase flow in the risers, in certain situations is potentially problematic, this happens due to the fact that it represents a variation in the flow rate and pressure in its usual regime. Severe intermittence and severe slugging occur under certain conditions of low gas and liquid flows in pipeline configurations with elevation gain, such as a riser. The main characteristic of severe intermittency is that it is pulsating due to the variation in pressure in the riser caused by alternating oil strokes, producing high volumes of oil and also alternating periods producing high volumes of gas. Several methods are applied to mitigate and even mitigate this phenomenon, leading to large investments in the development of new technologies for the optimization and mitigation of problems involving Exploration and Production activities. The injection of lift gas at the base of the riser is one of the alternatives for attenuating the slug pattern, and will be the alternative addressed in this work, with the aid of the computational tool Atificial Lift Flow Assurance Simulation - ALFAsim. Therefore, in this study, a graphical analysis of the parameters is proposed: oil flow std, holdup, flow pattern and elevation, to identify the occurrence of slugging in the pipeline. The mitigation of this flow pattern was done with the injection of a mass source (gas elevator) at the base of the riser. Finally, the work concluded the operational feasibility with the insertion of a mass source in the piping system, guaranteeing operational safety by changing the flow pattern of the riser, from slugs to annular.*

Keywords: *slugging, ALFAsim, flow assurance, multiphase flow.*

1. INTRODUCTION

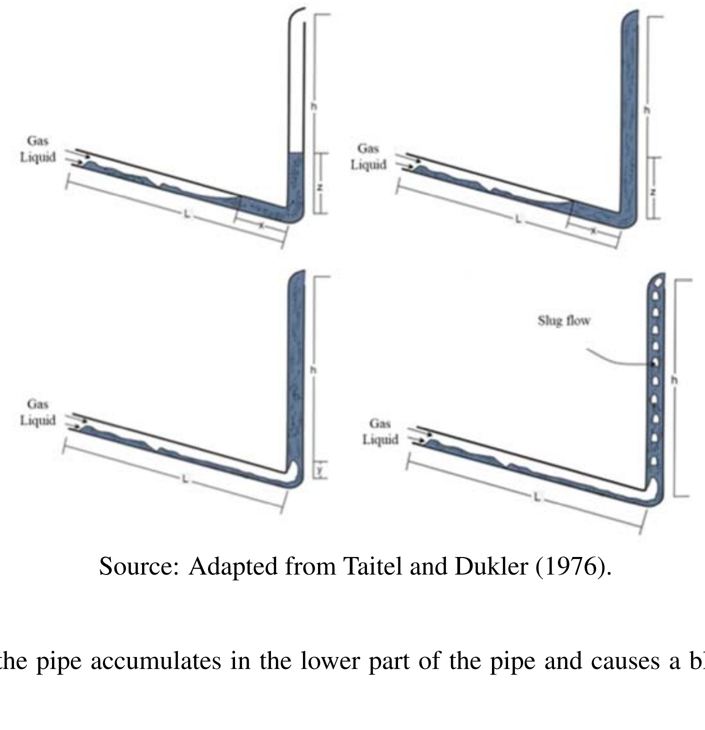
Multiphase flow can be defined as the simultaneous flow composed composed of two or more phases with different and immiscible properties in a pipeline. in this type of flow, no strict distinction is made between the concepts of phase and component, but rather between the number number of interfaces present in the flow. For example, two-phase flow means the presence of an interface, and can be an iminscible liquid-liquid type (oil and water) or a liquid-gas. In the case of oil-water-gas flow we have the presence of two interfaces, liquid-liquid-gas (water, oil and gas), although the mixture is considered biphasic (Silva *et al.*, 2000). In the oil industry, this type of flow occurs due to the reduction of pressure and temperature, causing the gas to be release before it is dissolved in the oil, depending on the chemical composition of the petroleum and will be produced together with oil and water from the formation Brill (1987). The presence of multiphase flow in pipes is quite frequent in different industrial activities, in the oil industry the occurrence of multiphase flowis common throughout the fluid path, production and transportation. This type flow occurs from the reservoir rock to the separation units, passing through the production column, risers and transfer lines to the refining. An important feature present in multiphase flow is the distribution physics of the phases within the pipeline, better known as flow patterns. The way each pattern presents itself depends on the forces acting on it. in each phase, these in turn strongly depend on the diameter, inclination and flow of each phase. The determination of flow patterns is the central problem in the study of multiphase flow, because parameters such as head loss, fraction of liquid are strongly dependent on flow patterns (Shoham, 2006). The phenomenon of slugs is a flow assurance problem in offshore production systems due to the irregularity of the surface of the seabed. Peculiar problems associated with such flow geometry are flow instabilities and production losses, pressure fluctuations at the base of the riser, separator flooding due to liquid spike accumulation, separator damage due to high liquid and gas flow rates Schmidt *et al.* (1980). Other slug flow issues include fatigue damage to marine structures Sultan *et al.* (2013) especially by severe slug flow which is generally associated with fluctuations in hydrostatic pressure and is significantly dominant at the base of an offshore production riser. The configuration or distribution of phases in a pipe depends on the flow of each phase and their relative velocities, hence their physical properties. These settings, known as flow patterns, can be described qualitatively for flows vertical and horizontal. Standards for horizontal flow, according to Darby and Chhabra (2016), are assumed to be more complex than those for vertical flows due to to the asymmetric effect of gravity. Boundaries or transitions between patterns have been mapped by several researchers, such as Taitel and Dukler (1976) based on observations of the behavior of various flow parameters and properties along the flowline and riser. The study was developed in Alfasim Artificial Lifting and Flow Assurance Simulation - ALFAsim, a 1D dynamic multiphase flow simulator that combines a Robust mathematical formulation with an advanced numerical strategy to provide a computationally efficient simulation experience with an intuitive interface. The software presents slugging mitigation techniques tools, as well as the parametric runs tool, which in a simulation can be done with different values of the same variable ESSS (2023a).

2. LITERATURE REVIEW

2.1 Slugging Flow Pattern

The slug flow pattern is defined as the flow of a known gaseous slug as a Taylor bubble, with smaller bubbles dispersed in its tail and in the liquid phase. A Taylor bubble, according to Abdulkadir *et al.* (2010), had its first mathematical model in relation to its ascending velocity presented by (Nicklin, 1962). Since then, studies have been developed with the aim of predicting and mitigating slugging. Taitel and Dukler (1976) report that several studies on slug flow comment on the dynamics of severe slugging. According to these authors, the liquid accumulates in the lower part of the riser blocking the passage of the gas, which causes the gas in the inlet of the riser to begins compressing the column of liquid. This will increase the pressure in the system. until it is sufficient to move the supporting column of liquid. When this happens, the column of liquid will explode at the outlet of the riser, which is known as a blowout.This effect can then be repeated, because with the rapid relief of pressure, it tends to drastically decrease again and cause another liquid retention. According to the authors, the flow with extreme slugs is formed by the respective stages of the flow as illustrated in the Fig. 1.

Figure 1. Steps of the extreme slug flow pattern



Source: Adapted from Taitel and Dukler (1976).

- The liquid entering the pipe accumulates in the lower part of the pipe and causes a blockage of the gas passage, causing the gas to be compressed at the inlet.

- When the height of the liquid column (z) equals the height of the pipe (h) we begin the entry of the liquid slug into the apparatus located at the top of the riser.

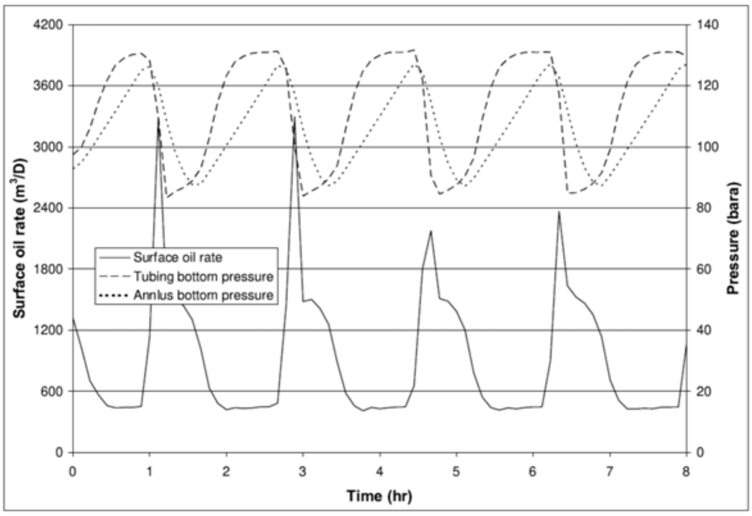
- When the gas that was compressed at the pipe inlet due to blockage caused by the liquid column reaches the base of the pipe the liquid starts to flow to the top with a very high speed, a phenomenon known as blowout.

- Finally, before the cycle starts again, there is a decrease in pressure which causes the liquid to fall back and accumulate at the base of the riser again restarting the process.

Thus, the severe slugging flow pattern is possible due to the compressibility property of the gas. Taitel and Dukler (1976) then developed a stability condition, where it is not possible for severe slugs to occur and consequently for blowout.

The intermittent operation scenario can generate operational and safety problems for industrial installations, since the intermittency of the phases causes large pressure oscillations in the system. Due to the multiphase characteristic, it is not feasible in real systems to perform dynamic monitoring of direct production parameters such as flow and density. The production ratio as a function of pressure is sensitive to the intermittency mechanism. As illustrated in Fig. 2, for the Annular Heading mechanism in a case generically, slugs can cause pressure oscillations of up to 50 bar at the bottom of the well during a 1.5 h cycle. So, the alternation of high oil production and low gas production is reversed, with low oil production, gas production and this which characterizes the slug flow pattern.

Figure 2. Monitoring of oil production through the dynamic pressure of the steps of the Annular Heading Mechanism: 1-Filling the Annular; 2-Injection of gas in the Tubing; 3-Propagation of the gas followed by the transfer of injection; 4-Resumption the filling of the Annular



Source: Hu (2005).

2.2 Mathematical equations

Techniques to mitigate severe slugging use basic physical principle the increase in the velocity of the phases. This guarantees a continuous upward flow inside the riser and prevents the transmission of liquid in the riser's duct-base transition. Some mitigation techniques that can be adopted both together how much are they in particular Meng and Zhang (2001):

- Geometric change with the reduction of the internal diameter of the pipe and ou the riser;

- Division of the duct into multiple pipes;

- Gas injection in the gas-lift riser

- Use of a mixer at the base of the riser;

- Subsea phase separation;

- Choke Valve and Flow control;

- Increased back pressure in the system.

The gas injection increases the velocity of the flowing gas, causing the liquid to be lifted, avoiding the formation of liquid flow (slug) and originating in a continuous flow. Gas injection also has the great advantage of facilitating the increase in oil by reducing the hydrostatic column in the riser. However, in most cases, it is necessary to install compressors on the Campos *et al.* (2006) platform.

The continuous gas injection method is still the most used method in production in offshore systems, as it allows continuous production of hydrocarbons through a simple physical principle, the decrease in average density. As the density of the gas is much lower than that of the liquid, mixing the injection gas with the hydrocarbon flow from the reservoir results in a final mixture with a lower average density. CWith this, the pressure gradient from the injection point is reduced and the gradient curve is no longer linear. This is due to the compressibility of the gas, which, as it is depressurized as it rises, expands Campos *et al.* (2006).The gas and oil velocities required for a continuous and stable at pattern to be achieved are part of the production process, and the flow is only stable from certain gas velocities and at a certain value. Any increase in injection speed and pressure does not result in a significant increase in oil production, but only in an increase in compression cost. On the other hand, low gas flows have a direct impact on the amount of oil produced and on the flow pattern, which may turn out to be an undesirable intermittent pattern or severe slugging.

The developed models aim to predict the production flow behavior in the riser and the unstable flow condition based on the balance of forces, and the second method is a simplified transient model assuming quasi-equilibrium forces, based on the work of Taitel and Dukler (1976). The injection of gas results in a decrease in the length of the bubble and its cycle, leading to higher production and lower pressure variation in the system, eliminating severe slugging by increasing speed and reducing liquid hold-up in the riser, but a large amount of gas is required to stabilize the flow. In contrast to control via a choke valve, in which gas injection reduces system pressure and stabilizes flow in the direction of surface gas velocity.

Flow pattern identification is significantly important for multiphase flow assurance in deepwater oil and gas pipelines Xu *et al.* (2023). The authors conducted a study with the aim of selecting signals to identify multiphase flow patterns offshore. The system is composed of a horizontal pipe of 1657 m length and an S-shaped riser of 16.7 m length. Therefore, a new sample preparation method using only liquid accumulation stage data was proposed to identify severe slugging. A set of signal evaluation and selection criteria covering the effects of signal recognition and practicality are proposed for the identification of severe slugging, oscillating flow and steady flow. They concluded that when using a single signal, the recognition rate of the pressure signal is generally lower than that of the differential pressure signal. The differential pressure reflects rich information about the flow characteristics in the pipe section between the two measurement points, and the pressure signal contains limited flow information.

2.3 Mathematical Modelling

2.3.1 Conservation of Mass

The one-dimensional nonlinear system of equations are obtained through an averaging process from the 3d local instantaneous equations. The resulting mass balance equation 1 for each field k is where αk is the volume fraction, ρk is the mass density, uk is the velocity ESSS (2023b).

$$\frac{d(\alpha_k \rho_k)}{dt} + \frac{d(\alpha_k \rho_k u_k)}{dx} = 0 \tag{1}$$

2.3.2 Conservation of Momentum

The momentum balance equation 2 for each field k is given by:

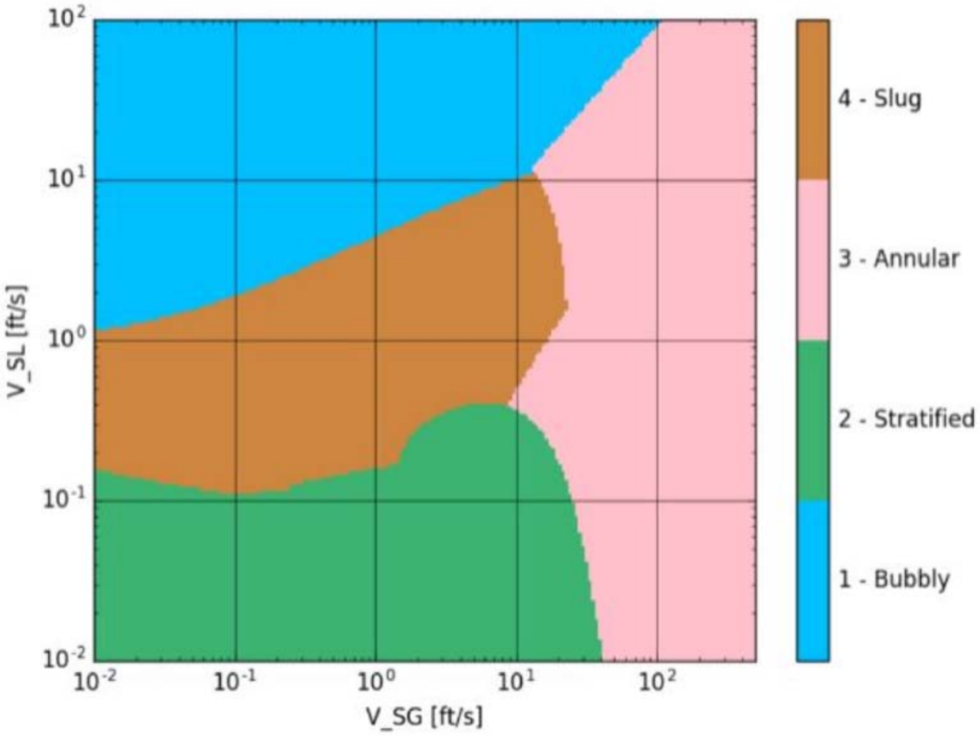
$$\frac{d(\alpha_k \rho_k u_k)}{dt} + \frac{d(C_k^u \alpha_k \rho_k u_k u_k)}{dx} = -\alpha_k \frac{dp_k}{dx} - \alpha_k \rho_k g sen\theta + (p_{ki} - p_k)\frac{d\alpha_k}{dx} - \frac{\tau_{wk} S_{wk}}{A} \pm \frac{\tau_i S_i}{A} \tag{2}$$

where θ is the pipe inclination, A is the cross section area, $\tau_{wk} \cdot S_{wk}$ is the wall shear stress, $\frac{\tau_i Si}{A}$ is the interfacial shear stress, S_{w_k} is the wall wet perimeter, S_i is the interface wet perimeter and C_k^u is the distribution parameter of phase k which is set to 1 by default. u_{ks} is the reference velocity that will account for the momentum transported by the mass source $\gamma_{k,s}$ ESSS (2023b).

2.3.3 Flow Regimes

The software ALFAsim considers five flow patterns: stratified, annular, slug, bubbly and dispersed bubbly. The Unit Cell Model is used as the central model for flow pattern determination. If the model succeeds in the evaluation of the slug flow variables then the flow regime is slug, otherwise (if it fails) the regime is defined depending the type of failure. The horizontal flow pattern map available in the software is shown in Figure 10

Figure 3. Flow pattern map horizontal flow using the UCM mode



Fonte: ESSS (2023b).

In the case where no root is found for the film liquid volume fraction, the flow is defined as stratified if $\theta \leq 10$, otherwise it is bubbly. Besides that, if

$$F = \frac{L_S}{L_S + L_f} \pm 1 \tag{3}$$

the flow is bubble. If $F \leq 0$ the flow is separated defined as:

- stratified, if $\theta \pm 10$
- annular, if $\theta > 10$

Furthermore, there is 2 more conditions for the stratified flow definition and 2 more for the annular flow definition. So, to stratified regime, we have:

$$|u_g - u_l| \leq \left(1 - \frac{h_l}{D}\right) \sqrt{\frac{(\rho_l - \rho_g)\, g A_g \cos\theta}{\rho_g \frac{dA_l}{dh_l}}} \tag{4}$$

$$|u_l| \leq \sqrt{\frac{gD\left(1 - \frac{h_l}{D}\right)\cos\theta}{f_{wl}}} \tag{5}$$

For transition to annular regime, it is given by:

$$\tilde{h}_L = \frac{h_L}{D} < 0.35 \tag{6}$$

in which h_L is the liquid height. If the flow is vertically downward, then the condition applies to the liquid volume fraction ($\alpha_l < 0,35$). The software quantifies the flow patterns as follows:

- 0 - Closed pipeline;
- 1 - Stratified;
- 2 - Bubbles;
- 3 - Slug;
- 4 - Annular;
- 5 - Single-phase.

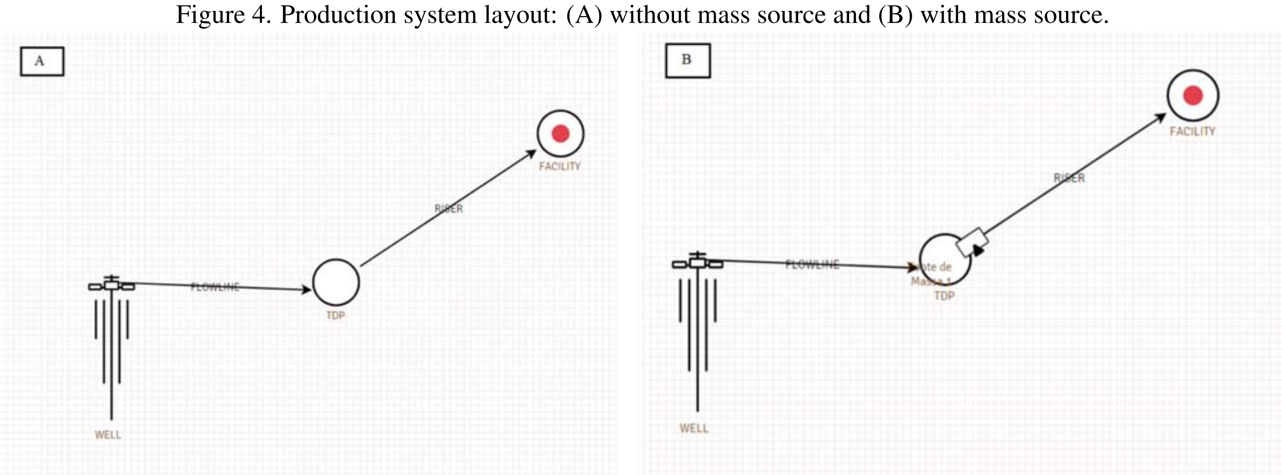
3. Methodology

The study was developed in the Artificial Lifting and Flow Assurance Simulator - ALFAsim software, a 1D dynamic multiphase flow simulator that combines a robust mathematical formulation with an advanced numerical strategy to provide a computationally efficient simulation experience with an intuitive interface. The software presents slugging mitigation techniques tools, as well as the parametric rounds tool, which in a simulation can be performed with different values of the same variable ESSS (2023a).

Pressure, temperature, solubility ratio, volume formation factor, oil and gas viscosity, oil and gas density, compressibility factor, available in a file *.tab obtained through RFDAP FASE were adopted. ESSS@ 2023 and inserted into ALFAsim containing information from the PVT model of the fluid used in all simulations. The Figure 4a and 4b and also the Table 1 illustrates the scenario and conditions modeled for the well flow simulation of 800m³/day. The simulation of gas injection in the base riser must be done by adding the ALFAsim tool called mass source, so it is possible to inject gas into the annular space of the well and release the valve by pressure, injecting gas into the production column with a water depth of 2000 meters in both systems.

The mass source was added at the base of the riser and a gas flow variable in m³/day was created in the flow rate parameter under standard conditions, then in the parametric rounds tool the injection flow values of 600 thousand m³ were defined /day to 660 thousand m³/day, with intervals of 30 thousand m³/day, in search of a gas flow that would mitigate the effect of slugs.

Figure 4. Production system layout: (A) without mass source and (B) with mass source.



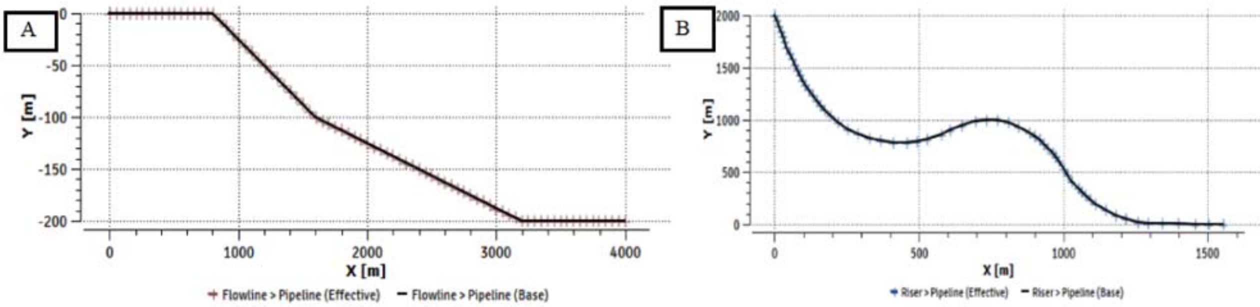
Fonte: Autor.

4. RESULTS AND DISCUSSIONS

Considering a well flow of 800m³/day, which resulted in unstable std oil flow values as shown in Figure 6a. The results illustrated in the sequence 6b a 7b complement the analysis carried out, analyzing other variables: riser elevation, flow pattern in the riser and in the flowline and holdup. Figure 6b illustrates the slug flow pattern along the entire length of the riser and it can be seen that the severe slug pattern occurs in regions of the riser with elevation gain, as confirmed by literature. Figure 7a shows the flow pattern of slugs at the top riser and at the end of the flowline in 24 hours of simulation, it can be seen that the flow pattern in the flowline does not change, keeping it always in a stratified pattern, as there is no elevation gain in this pipe, unlike what happens in the riser. Figure 7b illustrates the liquid holdup along the entire length of the riser and the other holdup portion represents the fraction of gas released by reducing the pressure gradient.

The following figures illustrate the values of std oil flows and flow pattern, simulated for injection flow values from 600 thousand to 690 thousand m³/day, with variation in intervals of 30 thousand, with a fixed well flow of 800 m³/day in the simulations.

Figure 5. (A) Profile of flowline and (B) Profile of riser.



Fonte: Autor.

PROCESS TIME	
24H	
WELL CONDITIONS	
Depth	3200 m
Temperature	60° C
Absolute Pressure	320 bar
Diameter	8.5 in
Flow rate	800 m^3/dia
FLOWLINE CONDITIONS	
Length	4000 m
Elevation	- 200 m
Internal Diameter	6 in
Absolute Pressure (0 m)	200 bar
Absolute Pressure (4000 m)	125 bar
Volume Fraction (0 m)	0.2 gas/0.8 oil
Volume Fraction (4000 m)	0.4 gas/0.6 oil
Temperature	4° C
RISER CONDITIONS	
Length	3187.61 m
Elevation	2000 m
Internal Diameter	6 in
Absolute Pressure (0 m)	125 bar
Volume Fraction (0 m)	0.4 gas/0.6 oil
Temperature (0 m)	4° C
Temperature (3187.61m)	25° C

Table 1. Operation conditions

Figure 6. (a) Oil production in std for a well flow of 800m³/day; (b) Flow pattern along the entire length of the riser.

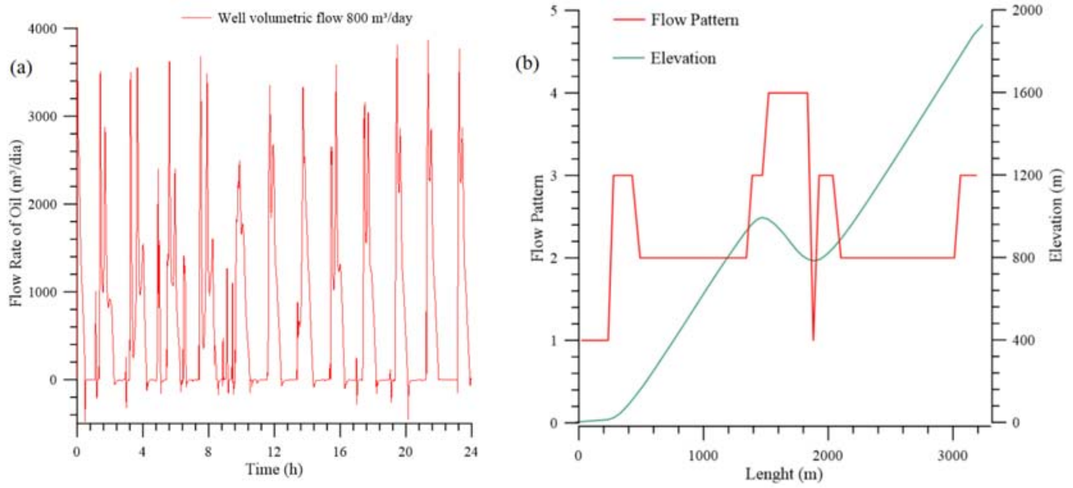


Figure 7. (a) Flow pattern at the top of the riser and at the end of the flowline; (b) Liquid holdup along the entire length of the riser.

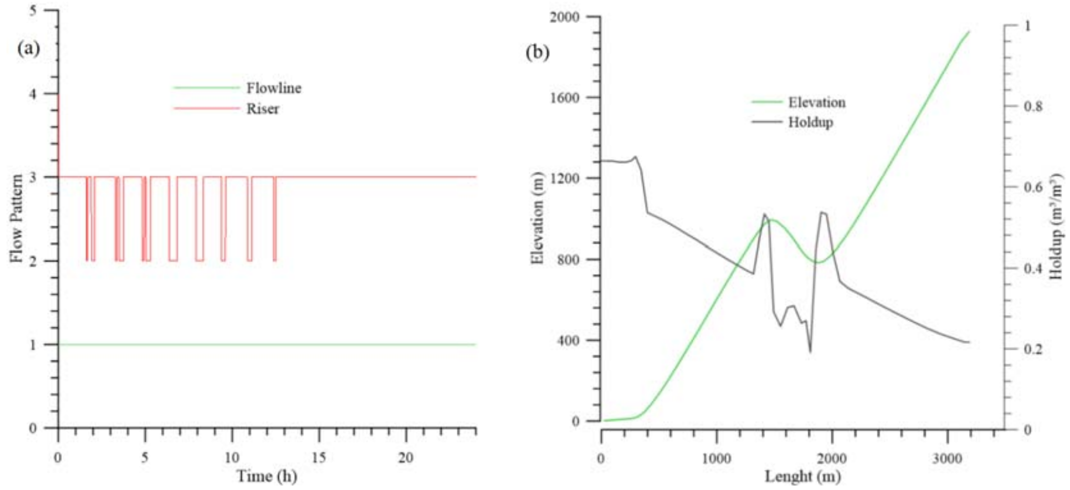
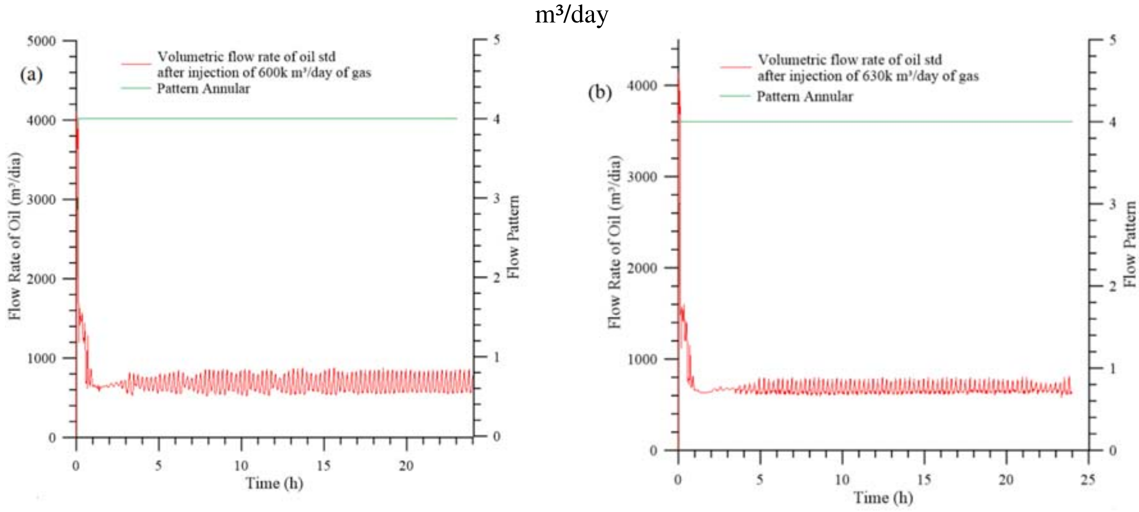
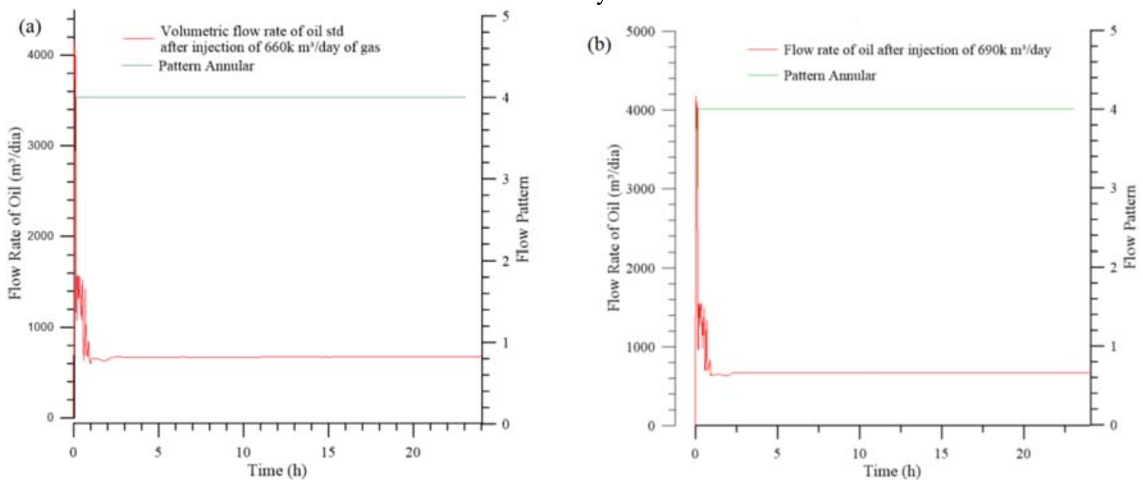


Figure 8. (a) Oil flow std for injection flow of 600 thousand m³/day; (b) Std oil flow for injection flow of 630 thousand m³/day



It can be seen that with the injection of 600,000 m³/day, Figure 8a, the severe slugs were minimized and the flow pattern was changed to annular, but it is still possible to observe instability in the oil flow std and this can be a production risk. At a flow of 660,000 m³/day, figure 9a, it is possible to observe greater stability in production, mitigating the appearance of slugs in the riser, with a greater flow of gas than oil, but it does not present any operational risk. With injections of

Figure 9. (a) Oil flow std for injection flow of 660 thousand m³/day; (b) Std oil flow for injection flow of 690 thousand m³/day



660,000 m³/day and 690,000 m³/day, there was no change in their stability, so these values do not bring better results, but more costs for the injection operation.

Figure 10. (a) Flow pattern along the entire length of the riser; (b) Liquid holdup along the entire length of the riser

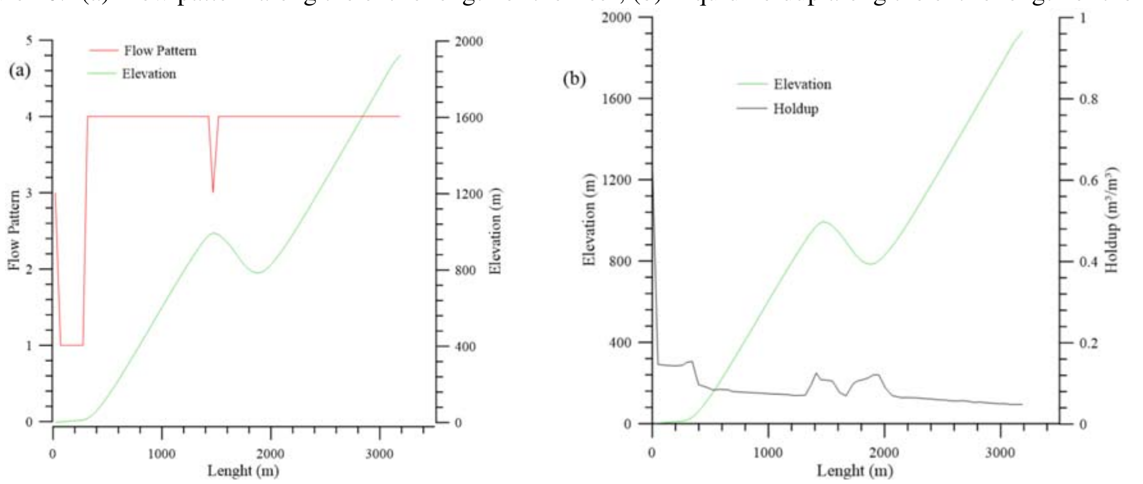


Figure 10a shows the flow pattern along the entire length of the riser, it is possible to observe the pattern of slugs less present throughout the riser when compared to figure 6b. Figure 10b illustrates the result of the injection in the riser holdup, when compared to Figure 7b, it can be noted the reduction of this parameter, since the gas, because it has a lower density, has a higher velocity in vertical pipes, thus changing the flow pattern to annular. Therefore, after gas injection at all injection rates (600K, 630K and 660K) it proved to be efficient, demonstrating a correct methodology that can be applied in flow assurance studies, such as multiphase flow stability.

5. CONCLUSION

The results obtained from numerical simulations carried out in ALFAsim allow us to conclude that:

- The well flow of 800m³/day shows the severe slugging flow pattern;
- The injection flow that inhibits the slug flow pattern and maintains stability in the production of std oil was 660 thousand m³/day.
- The computational tool ALFAsim showed efficiency in the use of the implantation of offshore production compounds, being able to predict possible technical problems and consequently anticipate corrective solutions, avoiding higher production costs, and helping in the development of more efficient plants.

Thus, the use of a mass source, injecting lift gas at the base of the riser, is an alternative to mitigate severe slugging, as stated in the literature used in this study.

6. ACKNOWLEDGEMENTS

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