Severe Slugging in pipelines: Modelling, Simulation and Mitigation

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Abstract

The petroleum industry heavily relies on the simultaneous transport of gas and liquid phases in a single pipeline. Due to the pipeline-riser system configuration, severe slugging might occur. This phenomena is unwanted and it is important to have a multiphase dynamic model capable of accurately represent it. A drift-flux model was developed with the purpose of predicting severe slugging. This dynamic and isothermal model based on the one dimensional conservation equations of mass and momentum used Shi correlation as the general slip law. The model was implemented in gPROMS, using the software internal implicit temporal discretization. For the spatial discretization it was developed a finite volume scheme with staggered grid, making this model numerically stable. A comparison was made against experimental data from different literature and the state of the art software, OLGA, showing very good results for the prediction of the cycle time and severe slugging type. Different mitigation strategies, such as gas-lift, increase in the separator pressure and pipeline design parameters, were studied. The model developed described correctly the behavior of such strategies.No paragraph breaks.

Keywords: Severe Slugging, Pipeline-riser system, Drift-flux model, gPROMS

1. Introduction

Multiphase transport is of great importance to the petroleum industry. A typical offshore pipeline follows the terrain topography, having uphill and downhill sections . Under certain conditions, the liquid accumulates at the lowest points of the pipeline, as shown in Figure 1, until it's blown out afterwards by the compressed gas, leading to high instantaneous flow rates. This phenomena is know as Severe Slugging and has received enormous amount of attention, because it leads to production losses and transient flow.

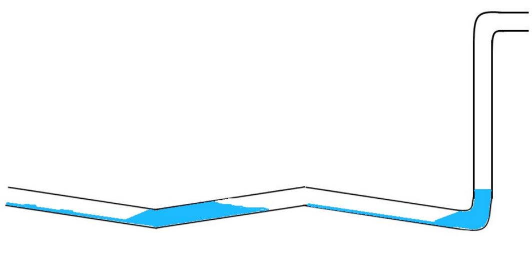


Figure 1: Liquid buildup during severe slugging.

Many companies model multiphase systems as a pseudo-homogeneous mixture. This approach to simulate complex phenomena like severe slugging. Process Systems Enterprise (PSE), the world's leading supplier of Advanced Process Modelling technology, is a company highly recognized in the industry and has showed interest in expanding their knowledge in the multiphase flow area. The current work was developed in PSE's Oil & Gas department with the main objective being the development of a multiphase model suitable for severe slugging studies.

2. Background

Severe slugging is a cyclical phenomena that might happen in pipelines with sections with different inclination, characterized by the accumulation of liquid at certain areas of the pipe and generation of long liquid slugs that are followed by a fast gas blowdown.

This phenomena was first reported by Yocum [15]. The key phenomena behind severe slugging are the liquid buildup at the bottom of the riser, local flow reversal and local phase disappearance.

The existence of severe slugging is a major issue for the production facilities as it increases the pressure at the wellhead, which leads to production losses, and causes high instantaneous outflow of liquid to the separator (see Fig. 6), which leads to large oscillations in the separator control system and might cause separator flooding.

By modelling this phenomena it is possible to know at which conditions severe slugging is going to occurs and determine the slug length and period, which are important for the design and control of the downstream facility. It is also possible to perform studies where different mitigation strategies are employed and determine by an optimization which is the best method to reduce severe slugging.

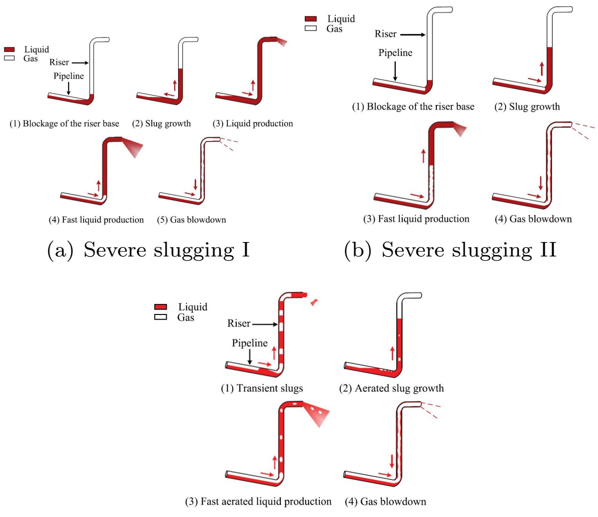
2.1. Classification

Severe slugging has been experimentally studied by several investigators [12, 14, 5, 10] at a laboratory scale to better understand it's characteristics. Schimidt [12] was the first to divide the severe slugging cycle into four main stages:

1. Slug formation: The accumulated liquid at the bottom of the riser will block the riser entrance to gas, generating a liquid slug. This initial liquid buildup can also arise as a result of liquid fall-back from the riser and transient hydrodynamic slugs from the pipeline.
2. Slug growth: The liquid level in the riser will increase as the slug grows. The gas is the pipeline will be compressed until its pressure becomes greater than the hydrostatic head of the liquid slug.
3. Blowout: The compressed gas will expand as it pushes the liquid out of the riser. According to Malekzadeh [10], this stage should be divided in two to better distinguish between different types of severe slugging:
   (a) Liquid production: If the liquid slug is bigger than the length of the riser then when the slug reaches the top of the riser the liquid will start to flow out with the gas pushing the slug tail from the pipeline to the riser.
   (b) Fast liquid production: When the compressed gas reaches the bottom of the riser, the hydrostatic head in the riser will decrease, making the gas expand and push the liquid out of the riser rapidly.
4. Liquid fall-back: The gas is expelled at a high rate, which will cause a quick system depressurization. When system reaches its minimal pressure the small liquid amounts that still remains in the riser will fall-back to the bottom.

Severe slugging can also be divided according to certain characteristics like slug length or riser blockage.

- Severe slugging I (SS1) : The maximum pressure at the bottom of the riser is equal to the hydrostatic head of the riser filled with liquid (neglecting other pressure drop terms) and the liquid slug length is equal or bigger than the riser length (see Figure 2(a)).
- Severe slugging II (SS2) : The liquid slug length is smaller than the riser length and there is a full blockage of the bottom of the riser until the blowout phase (see Figure 2(b)).
- Severe slugging III (SS3) : The bottom of the riser is never fully blocked so gas can still pass. Pressure and slug length are smaller compared to severe slugging I (see Figure 2(c)).
- Unstable oscillations (USO) : In this regime both gas and liquid flow into the riser and there isn't a vigorous blowdown. This type is not even considered severe slugging by some as it usually as very small pressure oscillations compared to the other types.



(a) Severe slugging I (b) Severe slugging II (c) Severe slugging III

Figure 2: Different types of severe slugging.

2.2. Mitigation

Since severe slugging affects the profitability and safety of a facility, much time as been spent on studying ways of eliminating or mitigating it.

Yocumm [15] demonstrated that increasing the separator pressure can eliminate severe slugging. Schmidt [12] and Jasem [8] suggested choking has an effective alternative. Both however will also decrease the production rate leading to a premature closing of the field.

The injection of gas in the pipeline system, , also known as gas-lift, is also capable of reducing or even eliminating severe slugging. One of the biggest drawbacks of this method is that it needs a large volume of gas to completely eliminate severe slugging [8]. Tengesdal [16] and Huawei [7] successfully eliminated severe slugging by using self-lift techniques.

2.3. Model Approaches

The first model of severe slugging was done by Schmidt [12]. This model can simulate the growth of a liquid slug for a downward pipeline-vertical riser system, however, the applications of these model, as explained on Chapter 3, are limited.

A more general approach, also used in the development of this work model is to model the gas-liquid flow using one dimensional equations of conservation of mass, momentum and energy.

These models can be categorized depending on how you model each phase, and most can be divided in two groups: Two-fluid models and Mixture models.

In the two-fluid approach both gas and liquid have their own conservation equations, making it a have a more rigorous and realistic model than mixture models. Bediksen [2] developed a two-fluid model, named OLGA, a dynamic multiphase simulator that is now considered the standard in the industry.

The drift-flux model is a mixture model where similar to the two-fluid model with the difference being the use of only one momentum equation, for the pseudo mixture-fluid. Much discussion has been heard about whether or not the drift-flux approach can have the same accuracy as the two-fluid approach, with some even saying that the drift-flux approach should be a better choice once the correct correlations are developed [4].

Two-fluid models have present in their equations terms that are difficult to define and get correlations for, such as the interfacial shear stress or the interfacial area, and numerical discontinuities when the regime changes or a phase disappears. In the Drift-flux approach there is no need to model the interface terms and it can be regime free. Also, due to being a simpler model than two-fluid model, the drift-flux model should be faster.

Masella, Malek and Osiptsov [11, 9] have successfully used a drift-flux model to simulate severe slugging in different conditions. Some commercial multiphase simulator like TACITE and ECLIPSE are also based on this approach.

Brevik [3] tried to model severe slugging using a two-fluid model on gPROMs, but failed due numerical instability issues. This comes up that numerical problems must be addressed for this type of phenomena in order to have a stable model and solution.

2.4. Drift-flux Correlations

The drift-flux model only as one momentum equation, so there is a need for an additional algebraic equation in order to be able to solve the model. This closure law also know as slip law relates the velocity of the gas to that of the the liquid, see eq. 11.

The parameters for the correlation started as constants but quickly evolved and became complex functions of many variables. Most of the correlations available in literature are not suitable as they are developed for specific flow regimes or limited to certain inclinations.

Shi [13] developed a correlation that is regime independent and the parameters were optimized using an oil and gas mixture in industrial size pipelines. Another advantage of this correlation is that it is possible to fit the parameters to experimental data, being able in this way to tune the model for each project.

3. Drift-flux Model

A drift-flux model was developed in this work to be able to simulate severe slugging. The drift-flux model is based on the mass conservation equation for each phase and a momentum equation for the mixture. Since the model was validated against isothermal experimantal data, the energy equation was not included.

3.1. Governing Equations

The mass equations for the gas and liquid phase are described bellow, respectively :

$$\frac{\partial \alpha_g \rho_g}{\partial t} + \frac{\partial \alpha_g \rho_g u_g}{\partial z} = \Gamma_{gl} + \Gamma_{gw} \,. \tag{1}$$

$$\frac{\partial \alpha_l \rho_l}{\partial t} + \frac{\partial \alpha_l \rho_l u_l}{\partial z} = \Gamma_{lg} + \Gamma_{lw} \,. \tag{2}$$

Where α_i, ρ_i and u_i are the volume fraction, density and velocity of phase i, respectively. The terms on the right side of Eq. 1 and 2 represent the mass flow rate transfer per volume from other sources. Γ_{iw} represents the quantity of phase i that entered the system through perforations in the pipe wall.

The other term represents the mass transfer due to phase change. The change of phase does not change the total mass, so the quantity that one phase lose must be the same as the other phase gains.

$$\Gamma_{lg} + \Gamma_{gl} = 0 \,. \tag{3}$$

The volume fraction of the phase i, α_i, is the fraction of the pipe cross section that phase i occupies. The sum of all fractions must then fill the pipe. Eq.4 express this relationship:

$$\alpha_g + \alpha_l = 1 \,. \tag{4}$$

The momentum conservation equation for the mixture is defined as

$$\frac{\partial p}{\partial z} = -\frac{2f}{d}\rho_m u_m |u_m| - \rho_m g \sin\theta \,. \tag{5}$$

Where the variables on right side terms represent the pressure drop due friction and gravity, respectively. The mixture density, ρ_m, and the mixture velocity, u_m are defined, respectively, by:

$$u_m = \alpha_g u_g + \alpha_l u_l \,. \tag{6}$$

$$\rho_m = \alpha_g \rho_g + \alpha_l \rho_l \,. \tag{7}$$

In the chemical area almost every model takes the physical properties with utmost importance in order to get the good results. Usually, the mixture is complex making this properties hard to predict correctly. In that case, specialized third party software are usually used, which increases the simulation time. Another solution is define in the model the physical properties without using a external package. A good approximation for the gas density is the use the ideal gas law, with the compressibility factor, z. It can be rewritten as:

$$\rho_g = \frac{p}{R_g T} \,. \tag{8}$$

Where R_g is the individual gas constant, give by,

$$R_g = \frac{zR}{M_g} \,. \tag{9}$$

Since the model is isothermal, and it's assumed that there is no mass transfer, the density of the liquid phase will only change due to the pressure. One way to express this relation is:

$$\rho_l = \rho_{l,0} + \frac{p - p_{l,0}}{a_l^2} \,. \tag{10}$$

Where $\rho_{l,0}$ is the reference liquid density at the reference pressure, $p_{l,0}$ and a_l is the sound velocity in the liquid phase.

3.2. Shi Correlation

In order to solve the model there is need for a closure correlation. The slip law, a correlation that relates the velocities of both phases.

$$u_g = C_0 u_m + u_{drift} \,. \tag{11}$$

The relationship between the velocities can be described as a combination of two mechanism, as shown on eq. 11. The distribution parameter, C_0, represents the distribution of gas over the pipe cross section. The other mechanism represents the tendency of the gas phase to rise vertically due to buoyancy effects.

Distribution Parameter

The distribution parameter peaks on bubbly and slug flow regime, reaching a value of 1.2. As the void fraction increases the distribution parameter approaches unity. The distribution parameter is expressed according to:

$$C_0 = \frac{A}{1 + (A-1)\gamma^2} \,. \tag{12}$$

Where A is the value of the distribution parameter on bubble and slug flow regimes and γ is a term that makes C_0 reduce to 1.0 at high values of void fraction or mixture velocity, and is defined by:

$$\gamma = \frac{\beta - B}{1 - B} \,. \tag{13}$$

where β approaches 1.0 at high values of void fraction or mixture velocity. B is the value of void fraction at which the the distribution parameter drops below A.

$$\beta = MAX\left(\alpha_g, F_v \frac{\alpha_g u_m}{u_{sgf}}\right) \,. \tag{14}$$

Shi choose the transition to the annular regime to eliminate the phase slip velocity. This transition occurs when the gas superficial velocity is higher than the flooding velocity, defined in eq. 15, being sufficient drag the liquid film.

$$u_{sgf} = \alpha_g K_u (\frac{\rho_l}{\rho_g})^{0.5} u_c \,. \tag{15}$$

Where u_c is the characteristic velocity, defined in eq. 16, and K_u is the critical Kutateladze number, which is related to the inverse of the adimensional pipe diameter, La, according to eq. 17:

$$u_c = \left[\frac{\sigma_{gl} g \left(\rho_l - \rho_g\right)}{\rho_l}\right]^{\frac{1}{4}} \,. \tag{16}$$

$$K_u = \begin{cases} 3.2 & \text{if } La \leq 0.02 \\ 0 & \text{if } La \geq 0.5 \\ 12.6La^2 - 13.1La + 3.41 & \text{else} \end{cases} \tag{17}$$

The inverse of the adimentional pipe diameter is given by

$$La = \left[\frac{\sigma_{gl}}{g\left(\rho_l - \rho_g\right)}\right]^{0.5} \frac{1}{d} \tag{18}$$

Where σ_{gl} is the superficial tension the the mixture.

Drift velocity

The vertical rise of the gas bubbles due to buoyancy effects is accounted on the slip law by the drift velocity term. It can be expressed as:

$$u_{drift} = \frac{(1-\alpha_g)C_0 K u_c}{(\frac{\rho_g}{\rho_l})^{0.5}\alpha_g C_0 + 1 - \alpha_g C_0}\Phi(\theta)\,. \tag{19}$$

Where K is a term that ramps down the flooding curve at low void fractions in order to account for the bubble rise and is defined by:

$$K = \begin{cases} \frac{1.53}{C_0} & \text{if } \alpha_g \leq a_1 \\ K_u & \text{if } \alpha_g \geq a_2 \\ \frac{1.53}{C_0} + \left(K_u - \frac{1.53}{C_0}\right)\frac{\alpha_g - a_1}{a_2 - a_1} & \text{else} \end{cases} \tag{20}$$

The change between curves are done by the ramping parameters a_1 and a_2.

To account for other inclination that are not vertical there was need to add the following correction term to Eq. 21.

$$\Phi(\theta) = n_1 \text{sgn}(\theta)|\sin\theta|^{\ n_2}\,(1 + |\cos\theta|)^{n_3}\ . \tag{21}$$

It should be noted that the parameters used in this expression stayed the same. Further studies on the effects of inclination on the drift velocity are advised.

4. Numerical Schemes

The modelling of multiphase phase flow as long been known for have numerical issues. Some came from single phase flow like the velocity-pressure coupling in the momentum equations, while others like numerical discontinuities when changing flow regimes are exclusive for multiphase flow. The phenomena of severe slugging brings another layer of complexity and numerical challenges because there is local flow reversal of each phase separately as well local phase disappearance.

The drift-flux model variables are function of both time and space. There is need to discretize both the temporal and spacial domain with suitable methods.

The temporal discretization is done by DAE solver, a internal gPROMS solver that uses an implicit scheme. The use of implicit scheme makes the solver more robust and usually allow it to that larger time steps than the explicit counterpart.

Although gPROMS also has some discretization methods like finite differences, they are not suitable for reversible flow. So unlike the temporal discretization where the method was already implemented, a finite volume method was developed and implemented.

4.0.1 Staggered Grid

Due to the velocity-pressure coupling in the momentum equation, if both variables are defined at the node a cell it can give rise to non-physical simulations. Harlow [6] used a staggered grid for the velocities as a solution for this problem. In this approach the velocities are defined using a different control volume, and the node where the velocity is defined matches the face of the cell of the normal grid, as shown on figure 3.

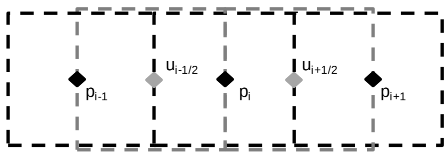


Figure 3: Staggered grid.

The momentum equation is discretized over the staggered grid domain while the continuity equations are discretized over the normal domain.

4.0.2 Cell-surface quantities

The value of the variables at the position $i + 1/2$ was approximated using a upwind scheme. This scheme causes strongly diffused solutions, so there is need to use a higher resolution on zones of high gradient. However, this scheme is much more robust and stable due to his diffusional part.

In this upwind scheme, also known as donor-cell scheme, the property to be approximated at $z_{i+1/2}$ is either the value at the node behind or the node ahead, depending on a condition. In this case, the condition is the direction of the specific phase flow. Eq. 22 shows an example of how the density of gas is calculated at the cell boundary:

$$\rho_{g\ i+1/2} = \begin{cases} \rho_{g\ i} & \text{if } u_g \geq 0 \\ \rho_{g\ i+1} & \text{if } u_g < 0 \end{cases} \tag{22}$$

5. Model Validation

The the model developed was validated against experimental studies from literature [14] and the industry standard in multhiphase dynamic simulation, OLGA.

Taitel [14] studied severe slugging occurrence in a downward pipeline connected to a vertical riser, a typical setup for a offshore production facility. The experimental setup, extensively explained in is work, consists in a buffer tank where only gas passes and gives an additional length of 1.69m to the pipeline, followed by a 9.1m pipeline with an inclination of -5 and a then by a vertical riser of

3m. Figure 4 shows the gPROMS representation of the experimental setup.

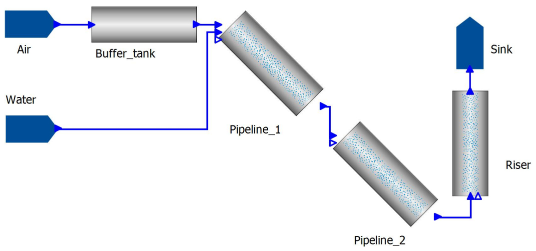


Figure 4: Taitel experimental setup.

Others researchers including Taitel also developed their own severe slugging models and compared it against Taitel experimental points. Table 1 shows a summary comparison between the different models in order to compare the drift-flux performance.

It is possible to see that the drift-flux model developed in the present work is capable of predicting within a small margin of error the cycle time of severe slugging when it exists an can also predict that there won't be severe slugging, and the discrepancy between the stable cases reported is explained further ahead.

The pressure changes with time in the pipeline allow to better understand and categorize severe slugging. Figure 5 shows the pressure at the end of the pipeline for case 1.

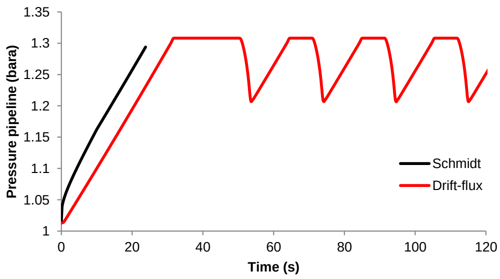


Figure 5: Pressure profile. (Taitel case 1)

Besides the higher pressure drop caused by during severe slugging, other maybe even more important consequence is the intermittent inlet that the separator downstream receives. Figure 6 shows the simulation results of the liquid outlet with time for case 1.

As expected, it is possible to see in Fig. 5 that liquid production starts to happen at the same time the pressure reaches it's maximum, this is when the slug reaches the top of the riser. It is then pushed by the compressed gas at a steady rate until the gas penetrates the bottom of the riser and accelerates due to the pressure drop decrease, spiking the

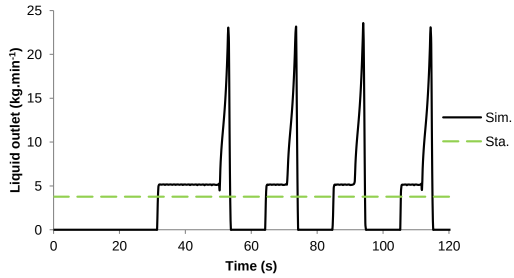


Figure 6: Liquid production profile.

liquid production for a few seconds before the gas slows down and the remaining liquid fall back to the bottom of the riser again.

5.1. Performance vs. OLGA

In this section the drift-flux model developed in the present work is compared against OLGA. This performance test was done using Malekzadeh [10] experimental and numerical investigation of severe slugging in a long pipeline-riser system.

Malekzadeh reported in is experimental investigation the type of severe slugging for each case. This allows to evaluate the models ability to predict the correct severe slugging regime. Table 2 shows a summary of the results produced by both models for Malekzadeh dataset (see Table 5.

The unstable flow regime is the one that is less well described by the developed model, but is more important to refer that OLGA simulator mispredicted every unstable flow regime as severe slugging II sometimes with dual slugging occurrence.

Both models had a similar performance in guessing the correct regime, with the drift-flux model coming slightly ahead. To have a fair comparison between the average error in both models all the unstable flow regime cases were neglected and a new average error was determined. With this change, the drift-flux model average error went down almost 10% while OLGA model was lowered by around 4%. This supports the supposition that the unstable flow regime is the one that gives rise to bigger errors and that the developed model can have similar performance as the industry standard, OLGA.

Figure 7 shows the pressure profile for case 1 of Malek (Table 5. The first thing to conclude it that both models follow reasonably well the experimental pressure profile, with the developed model getting a very good match with the experimental data. OLGA predicts a slower cycle time, delivering minus one slug for the timespan showed.

6. Mitigation Strategies

Severe slugging causes production losses and unstable and intermittent production of liquid to the separator. For getting the highest profit and for

Table 1: Summary of results for Taitel data.

	Experimental	Drift-flux	Schmidt	Balino [1]	Taitel [14]
Period Average Error (%)	-	6.3	15.9	4.9	13.8
Stable Cases	16	7	0	6	18

Table 2: Performance of the drift-flux model and OLGA model.

	Drift-flux	OLGA[10]
Period Error (%)	23.6	15.9
Period Error (without USO) (%)	15.6	12.3
Cases with correct SS type	27	24

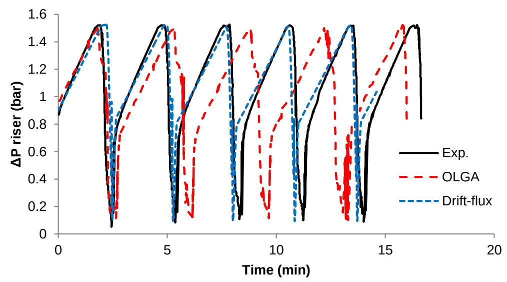


Figure 7: Pressure profile Taitel.

safety reasons this phenomena must be eliminated.

6.1. Choking

Choking is a viable option for eliminating severe slugging by increasing the back pressure proportionally to the velocity at the choke. Malekzadeh [10] used a choke valve in the experimental setup. In order to test the model performance in the last section, there was a need for develop a simple valve model.

6.2. Choke Valve Model

The choke valve creates a pressure drop that is usually proportional the velocity square. The pressure drop across the valve can be estimated by the definition of the flow factor.

$$\Delta Pchoke = \frac{1}{K_v^2}\frac{\rho_m}{\rho_{ref}}Q_v^2 \tag{23}$$

Where ρ_{ref} is the water reference density and equal to $1000kgm^{-3}$. Since there is two phases flowing thorough the choke, an expression for the volumetric flow rate must be defined.

$$Q_v = \alpha_l u_l A \tag{24}$$

Eq. 24 assumes that the only the liquid phase is important for the estimation of the pressure drop across the valve. This is generally a good approximation as the gas density is low. It is also important to note that the flow factor provided was obtained using only water as single phase. The usage of this flow factor to calculate the pressure the pressure drop of air passing the choke would be wrong.

6.3. Gas-lift

Gas-lift is a method well known in the petroleum industry and it's also effective at reducing severe slugging by decrease it's hydrostatic head in the riser. Another benefit is that it will increase the production as the pressure drop is related with the inlet flow rates to the pipeline-riser system in the industry.

Table 3 shows the cycle time for the case 1 of Taitel experiments for the different scenarios with gas-lift.

Table 3: Gas-lift scenarios definition

	Gas injected (kg.hr^{-1})	Period (s)
Base case	0	20.4
Scenario 1	0.9	7.1
Scenario 2	1.3	5.6

Figure 8 shows the pressure profile for the different scenarios when air is injected at the bottom of the riser.

As the gas is injected, the hydrostatic head of the riser is smaller and the pressure drops. Even if the amount of gas injected is not enough to make the system stationary, the cycle time and amplitude of the fluctuations are much smaller.

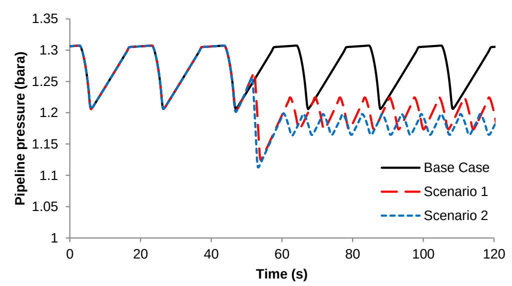


Figure 8: Pressure profile gas-lift.

The stability map a plot defined by superficial liquid velocity towards superficial gas velocity, and it is possible to show regions where different types of severe slugging can occur as well as the regions of stable flow. This maps play an important role in mitigation strategies. By determining the stability curve for the different scenarios, as shown bellow in Fig. 9, it is possible to determine area were severe slugging was completely eliminated.

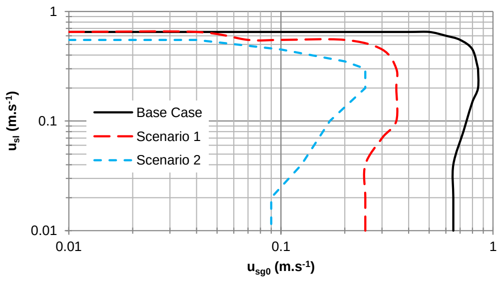


Figure 9: Stability map gas-lift.

As expected, the injection of gas at the bottom of the riser moves the stability curve to the left, so even with smaller flow rates of gas at the inlet the system might be steady state.

6.4. Pipeline Diameter

The design of the system also plays an important effect on severe slugging, so this might also be a viable way of preventing severe slugging if the project is still on the early stages.

During the design phase, the choice between the pipe diameters for the configuration has several alternatives. It is expected that this parameter will have an affect on severe slugging, as it also affects the velocities.

For a constant mass flow rate of both phases, four scenarios were defined with different only by changing the pipeline diameter in order to study the influence of the diameter on severe slugging.

Table 4: Diameter sensitivity

	d(cm)	Period (s)
Base case	5.08	133
Scenario 1	6.10	81
Scenario 2	4.06	175
Scenario 3	2.54	Stable

Table 4 shows the decrease in pipe diameter also decreases the intensity of severe slugging and scenario 3 shows that the phenomena can even be eliminated. Figures 10 and 11 show the pressure profile and the liquid production profile, respectively.

As the diameter of the pipeline lowers, for the same mass flow rates, the velocities inside it increase. This increase in velocities make the slugs smaller, decreasing the cycle time of severe slugging. If the velocities continue to increase the liquid will no longer accumulate at the bottom of the riser and steady state will be reached.

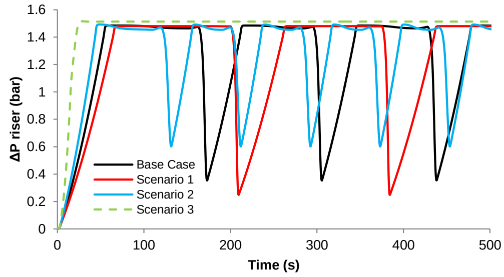


Figure 10: Pressure profile diameter.

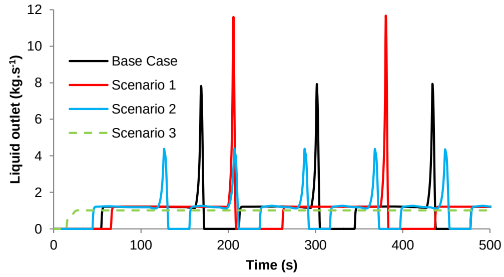


Figure 11: Liquid outlet diameter.

The liquid profile shows us that the time without liquid production is also shortened with the decrease in the diameter. This is because the slug reaches the top of the riser faster.

In the end, the decision of which strategy to apply will depend on a economical analysis that should weight the loss in gains due to production losses (choke valve and separator pressure) with the increase of operating costs (gas-lift) in order to maximize profit. Future studies on the optimization of eliminating severe slugging using one or more strategies are encouraged to be done.

7. Conclusions

The petroleum industry heavily relies on the simultaneous transport of gas and liquid phases in a single pipeline. Due to the pipeline-riser system configuration, severe slugging might occur. This phenomena is unwanted and it is important to have a multiphase dynamic model capable of accurately represent it. This model can also be used to simulate other multiphase flow regime for different pipeline configurations, either in steady state or dynamic.

Shi correlation was successfully extended to allow negative inclination. However, the parameter were not change for steeper negative inclination the model results get worse.

Different mitigation strategies typically used to eliminate severe slugging were discussed and the model showed is capability of simulating these methods. Injecting gas at the bottom of the riser or increasing the separator pressure successfully reduce severe slugging. The latest method, however, will cause production losses as an side effect.

The choice of the design parameters will influence severe slugging. Smaller pipes both in diameter and length will help mitigating severe slugging. More importantly, the pipeline section should not have a downward inclination, as that will greatly help the liquid accumulation for the generation to severe slugging.

A drift-flux model was developed, validated and it was found that it can predict accurately the occurrence of severe slugging and characteristic properties like the cycle time and slug length. This showed capability of achieving the similar performance other model used in the present.

7.1. Future Work

This work was created to serve as base for a new and better multiphase model capable of predicting severe slugging. Due to the large applications of this model there are many ways the model can be extended/improved. Some suggestions for future work are listed bellow:

- Extend the model to include the energy balance.
- Improve and extend Shi correlation by making some of the parameters inclination dependent.
- Estimate the Shi new parameters with industrial data.
- Study the model performance in typical multiphase flows.
- Compare the different friction models available for multiphase flow.
- Use the model for the design and operation of pipeline systems.
- Study self-lift as an method to eliminate severe slugging.
- Perform economical analysis and optimization in order to find which are the optimal variables for the mitigation methods in order to reduce severe slugging.

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Table 5: Experimental and numerical results.

Case	Experiment		Drift-flux			OLGA [9]		
	t_{exp}(s)	Type	Type	t_{sim}(s)	Error (%)	Type	t_{sim}(s)	Error (%)
1	179	SS1	SS2	171	-4	SS1	211	18
2	135	SS1	SS1	150	11	SS1	154	14
3	109	SS1	SS1	126	16	SS3	105	-4
4	78	SS1	SS1	83	7	SS3	77	-1
5	95	SS1	SS1	118	24	SS3	95	0
6	185	SS1	SS1	182	-1	SS1	211	14
7	101	SS1	SS2	98	-3	SS1	108	7
8	148	SS1	SS1	154	4	SS1	138	-7
9	173	SS1	SS1	224	30	SS3	143	-17
10	90	SS1	SS1	97	8	SS3	85	-6
11	92 and 138	SS2	USO	72	NA	SS2	76 and 191	NA
12	72	SS2	USO	100	38	SS2	108 and 160	NA
13	96	SS2	SS2	87	-10	SS2	98	2
14	68	SS2	SS2	55	-19	SS2	63	-7
15	227 and 159	SS2	USO	837	NA	SS2	138 and 286	NA
16	119	SS2	USO	330	177	SS2	211	77
17	93	SS2	USO	179	92	SS2	143	54
18	82	SS2	SS2	62	-24	SS2	72	-12
19	72	SS3	SS1	76	5	SS3	72	0
20	69	SS3	SS1	73	6	SS3	70	1
21	63	SS3	SS1	70	11	SS3	67	6
22	60	SS3	SS3	68	13	SS3	66	10
23	72	SS3	SS3	80	11	SS3	73	1
24	64	SS3	SS3	70	9	SS3	66	3
25	57	SS3	SS3	65	14	SS3	63	11
26	113	SS3	SS3	158	40	SS3	98	-13
27	86	SS3	SS3	110	28	SS3	89	3
28	64	SS3	SS3	77	20	SS3	68	6
29	57	SS3	SS3	63	11	SS3	59	4
30	64	USO	USO	89	38	SS2	98	53
31	64	USO	USO	88	38	SS2	98	53
32	65	USO	USO	83	28	SS2	95 and 191	NA
33	53	USO	USO	43	-18	SS2	86 and 155	NA
34	60	USO	SS2	47	-22	SS2	60 and 236	NA
35	43	USO	USO	34	-20	SS2	60	40
36	72	USO	USO	99	38	SS2	56 and 111	NA
37	73	USO	USO	63	-13	SS2	95	30
38	67	USO	USO	49	-26	SS2	87 and 174	NA