MODELING AND SIMULATION OF SEVERE SLUGGING IN PIPELINE-RISER SYSTEMS

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Abstract. *A mathematical model, numerical simulations and a stability map corresponding to severe slugging in catenary risers, commonly used in offshore petroleum production systems, are presented. In the simulations air and water were used as flowing fluids, in order to make a comparison with experimental results. The mathematical model considers continuity equations for liquid and gas phases, with a simplified momentum equation for the mixture, neglecting inertia. A drift-flux model, evaluated for the local conditions in the riser, is used as a closure law. The developed model predicts the location of liquid accumulation front in the pipeline and the liquid level in the riser, so it is possible to determine which type of severe slugging is occurring in the system.*

Keywords: *severe slugging, pipeline-riser system, stability, multiphase flows, petroleum production technology.*

NOMENCLATURE

Letters:
a: constant.
A: cross sectional area of pipeline and riser.
C: parameter.
D: diameter.
g: acceleration of gravity.
j: superficial velocity.
K: time step.
L: length.
$\dot{m}$: mass flow.
N: number of nodes.
P: pressure.
Q: volumetric flow.
R: constant.
S: wetted perimeter.
s: position along the riser.
t: time.
T: absolute temperature.
u: velocity.
U: parameter.
v: volume.
x: position of the liquid accumulation front.
X: abscissa of top of the riser.
z: local height.
Z: height of top of the riser.

Subscripts:
0: at pipeline inlet.
b: at the bottom of the riser.
d: drift.
e: equivalent.
g: gas.
i: at the gas-liquid interface.
l: liquid.
m: mixture.
p: at the pipeline.
r: at the riser.
s: at the separator.
t: at the top of riser.
u: at the liquid level in the riser.
w: wall.

Greek letters:
α: void fraction.
β: pipeline inclination angle.
Δ: increment.
ϵ: rugosity.
μ: dynamic viscosity.
ρ: density.
θ: local riser inclination angle.
τ: shear stress.

1. INTRODUCTION

Severe slugging is a terrain dominated phenomenon, characterized by the formation and cyclical production of long liquid slugs and fast gas blowdown. Severe slugging may appear for low gas and liquid flow rates when a section with downward inclination angle (pipeline) is followed by another section with an upward inclination (riser). This configuration is common in off-shore petroleum production systems. Main issues related to severe slugging are (Wordsworth *et al.*, 1998): a) High average back pressure at well head, causing tremendous production losses, b) High instantaneous flow rates, causing instabilities in liquid control system of the separators and eventually shutdown, and c) Reservoir flow oscillations.

For steady state and low flow rates, the flow pattern in the pipeline may be stratified, while it may be intermittent in the riser, as shown in Fig. 1(a).

A cycle of severe slugging can be described as taking place according to the following stages (Taitel, 1986). Once the system destabilizes and gas passage is blocked at the bottom of the riser, liquid continues to flow in and gas already in the riser continues to flow out, being possible that liquid level in the riser falls below the top level at the separator. As a consequence, the riser column becomes heavier and pressure at the bottom of the riser increases, compressing the gas in the pipeline and creating a liquid accumulation region. This stage is known as slug formation (Fig. 1(b)).

In a condition in which the liquid level reaches the top while the gas passage is kept blocked at the bottom, pressure reaches a maximum and there is only liquid flowing at the riser, resulting the slug production stage (Fig. 1(c)).

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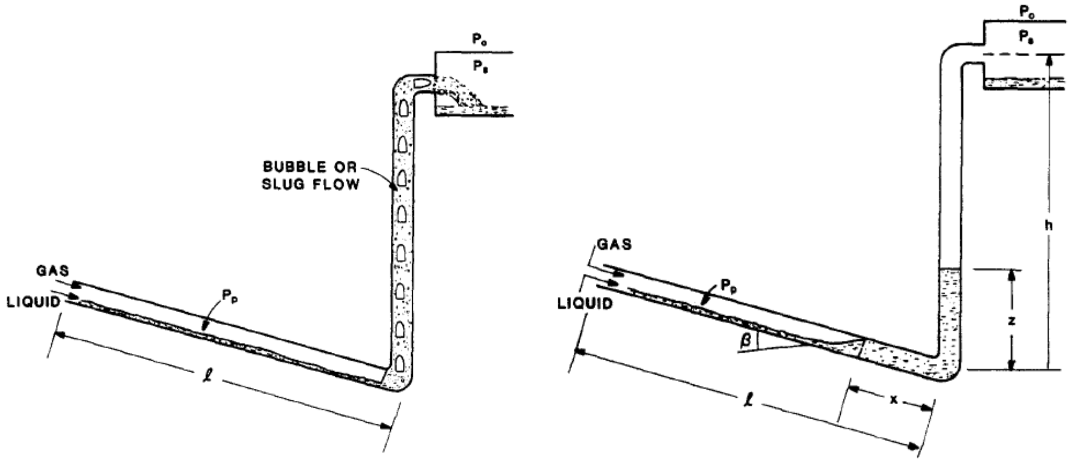
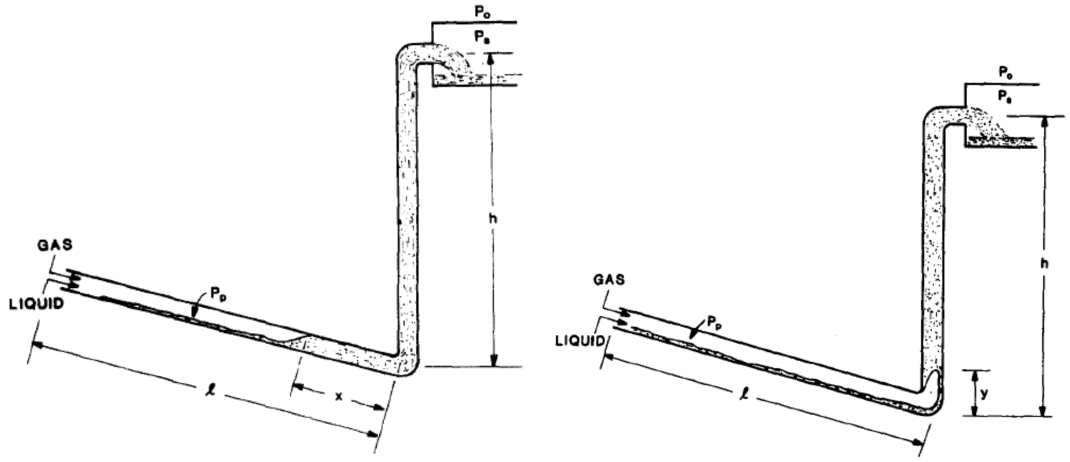


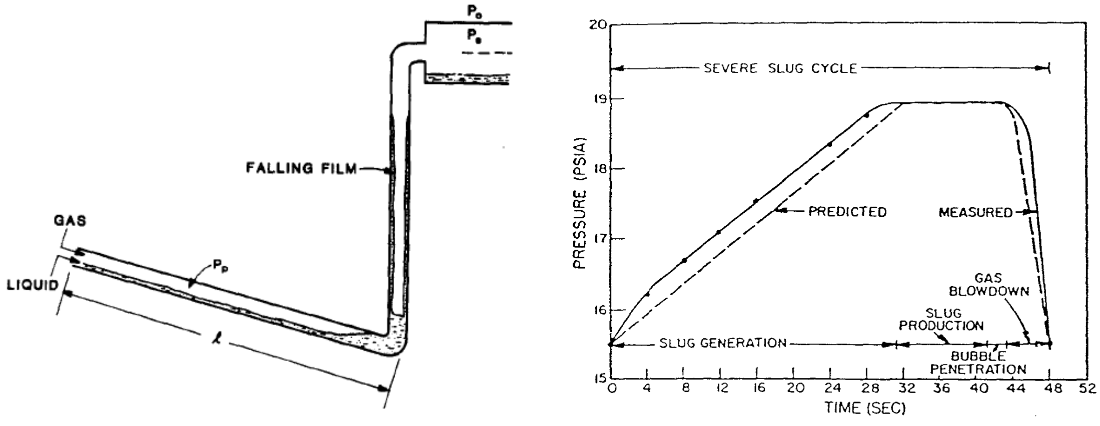
(a) Steady state.

(b) Slug formation.



(c) Slug production.

(d) Gas blowout.



(e) Gas blowdown.

(f) Pressure history.

Figure 1. Stages for severe slugging (from Taitel, 1986; Schmidt, 1977).

Since gas keeps flowing in the pipeline, the liquid accumulation front is pushed back until it reaches the bottom of the riser, starting the blowout stage (Fig. 1(d)).

As the gas phase penetrates into the riser the column becomes lighter, decreasing the pressure and then rising the gas flow. When gas reaches the top of the riser, gas passage is free through the stratified flow pattern in the pipeline and the intermitent/annular flow pattern in the riser, causing a violent expulsion and a rapid decompression that brings the process to slug formation again. This stage is known as gas blowdown (Fig. 1(e)).

Figure 1(f) shows the different stages in the pressure history at the bottom of the riser corresponding to an experiment under laboratory conditions (Schmidt, 1977).

Most of the models for severe slugging were developed for vertical risers. In (Sarica and Soham, 1991) a one-dimensional, gravity-dominant model was presented, with a distributed parameter formulation for the riser. Considering continuity equations for the liquid and gas without phase change, a mixture momentum equation and isothermal evolution, the model was capable of handling discontinuities such as liquid accumulation in the piping and liquid level in the riser. The resulting equations were solved using the method of characteristics. A comparison of simulations with different experimental data showed reasonable agreement, although the model suffered from non-convergence below the stability line.

The objective of this work is to develop a model of severe slugging valid for risers of variable inclination and to simulate experiments made for a catenary riser using air and water as flowing fluids (Wordsworth *et al.*, 1998). Through the identification of conditions in which the steady state solution keeps unchanged with time, it is possible to build the system stability map. Complete results of this study were presented in (Baliño, 2006).

Concerning stability analysis for severe slugging, the models that lead to stability criteria (Bøe, 1981; Taitel, 1986) have important simplifications and are not suitable for simulation. On the other hand, commercial computer codes can take into account all effects but they do not incorporate stability analysis. An important motivation for this study is the application of the linear stability theory to the model developed, in order to determine the stability map more efficiently from the point of view of computing cost compared to simulations. Preliminary results were presented in (Burr and Baliño, 2007; Burr and Baliño, 2007a).

2. MODEL

The model considers one-dimensional flow in both pipeline and riser subsystems. In the pipeline it is assumed a stratified flow pattern, while in the riser it is neglected inertia, resulting the NPW (no pressure wave) model (Masella *et al.*, 1998). In this way, severe slugging is controlled mainly by gravity in the riser and compressibility in the pipeline. The model is capable of handling discontinuities in the flow, such as liquid accumulation in the pipeline, liquid level in the riser and void fraction waves.

2.1 Pipeline

The pipeline, shown in Fig. 2(a), can be in a condition of liquid accumulation ($x > 0$) or continuous gas penetration ($x = 0$). It is considered the existence of a buffer vessel with volume υ_e in order to simulate an equivalent pipeline length $L_e = \dfrac{\upsilon_e}{A}$. Considering an ideal gas in isothermal condition and neglecting variations in void fraction at the pipeline α_p, the state equations can be obtained by applying continuity equations for the liquid and gas phases. For $x > 0$ it results:

$$j_{g\,b} = 0 \tag{1}$$

$$\frac{dx}{dt} = \frac{\dfrac{Q_{l\,0}}{A} - j_{l\,b}}{\alpha_p} \tag{2}$$

$$\frac{dP_g}{dt} = \frac{-P_g\left(j_{l\,b} - \dfrac{Q_{l\,0}}{A}\right) + \dfrac{R_g\,T_g}{A}\,\dot{m}_{g\,0}}{(L - x)\,\alpha_p + L_e} \tag{3}$$

$$P_b = P_g + \rho_l\,g\,x\,\sin\beta \tag{4}$$

For $x = 0$ it results:

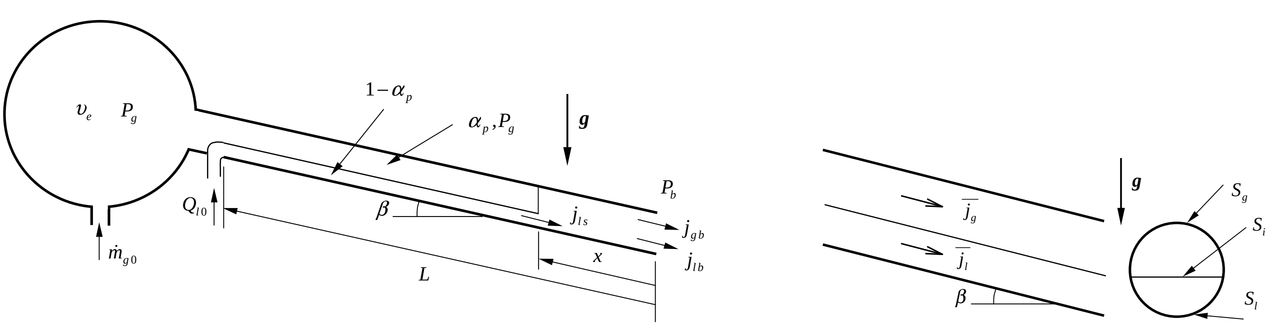
$$j_{l\,b} = \frac{Q_{l\,0}}{A} \tag{5}$$

$$\frac{dP_g}{dt} = \frac{-P_g\,j_{g\,b} + \dfrac{R_g\,T_g}{A}\,\dot{m}_{g\,0}}{L\,\alpha_p + L_e} \tag{6}$$

The void fraction at the pipeline is determined from the following algebraic relationship, derived from the momentum balance in stratified flow (Taitel, 1976) (see Fig. 2(b)):

$$\tau_{w\,g}\,\frac{S_g}{\alpha_p} - \tau_{w\,l}\,\frac{S_l}{1-\alpha_p} + \tau_i\,S_i\left(\frac{1}{1-\alpha_p} + \frac{1}{\alpha_p}\right) + (\rho_l - \rho_g)\,A\,g\,\sin\beta = 0 \tag{7}$$

In Eq. (7) the wetted and interfacial perimeters are determined considering a stratified geometry, while the shear stresses are related to the velocities of the phases through suitable friction factors.



(a) Definition of variables.

(b) Stratified flow.

Figure 2. Subsystem pipeline.

2.2 Riser

At the riser (see Fig. 3) they are considered continuity equations for the phases and mixture momentum equation with an ideal and isothermal gas, resulting:

$$-\frac{\partial \alpha_r}{\partial t} + \frac{\partial j_l}{\partial s} = 0 \tag{8}$$

$$\frac{\partial}{\partial t}(P\,\alpha_r) + \frac{\partial}{\partial s}(P\,j_g) = 0 \tag{9}$$

$$\frac{\partial P}{\partial s} = -\rho_m\,g\,\sin\theta - \frac{4\,\tau_w}{D} \tag{10}$$

The shear stress at the wall was calculated using a homogeneous two-phase model. The different velocities for the phases (slip) are determined by using a drift flux correlation:

$$u_g = \frac{j_g}{\alpha_r} = C_d\,j + U_d \tag{11}$$

$$j_l = j - j_g = u_l\,(1-\alpha_r) = (1-\alpha_r\,C_d)\,j - \alpha_r\,U_d \tag{12}$$

where the parameters C_d and U_d depend on the local geometric and flow conditions (Bendiksen, 1984). Equations (8) and (9) can be transformed in ordinary differential equations along characteristic lines corresponding to the gas velocity:

$$\frac{D_g P}{Dt} = -\frac{P}{\alpha_r}\frac{\partial j}{\partial s} \tag{13}$$

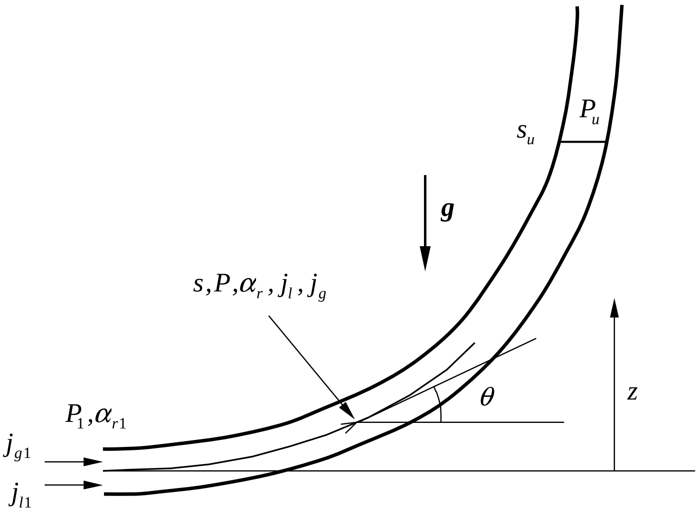


Figure 3. Definition of variables at the riser.

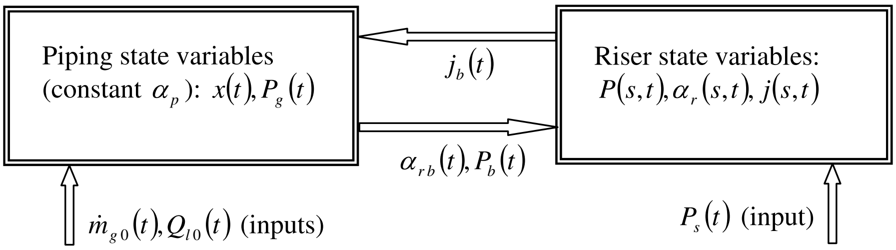


Figure 4. Coupling between subsystems.

$$\frac{D_g \alpha_r}{Dt} = \frac{\partial j}{\partial s} - \alpha_r \frac{\partial}{\partial s}\left(C_d\, j + U_d\right) \tag{14}$$

where:

$$\frac{D_g}{Dt} = \frac{\partial}{\partial t} + u_g \frac{\partial}{\partial s} \tag{15}$$

2.3 Coupling between pipeline and riser

Figure 4 shows the state variables and the coupling between the subsystems. State variables for the pipeline are the gas pressure and position of the liquid accumulation front, while for the riser they are the local pressure, void fraction and total superficial velocity. The pipeline imposes pressure and void fraction at the bottom of the riser, while the riser imposes the total superficial velocity to the pipeline; these variables are the boundary conditions for the corresponding subsystems. Additional boundary conditions are the liquid volumetric flow rate and the gas mass flow rate at the pipeline, as well as the separation pressure at the top of the riser.

3. DISCRETIZATION

Equations (13) and (14) where discretized and integrated along the characteristic direction with the gas velocity (points 1 and 2 in Fig. 5), while Eq. (10) was integrated between points $2L$ and 2. An implicit scheme was used, with a predictor-corrector method for treatment of the nonlinearities. Two computer programs were developed for calculating the steady state and the transients.

4. SIMULATIONS

4.1 Catenary geometry

The catenary geometry is characterized with the coordinates X and Z corresponding to the top of the riser, assuming that the inclination angle at the bottom is zero. Local height of a point belonging to the catenary can be written as:

$$z = a\left[\cosh\left(\frac{x}{a}\right) - 1\right] \tag{16}$$

where the dimensional constant a is obtained as the solution of the following equation:

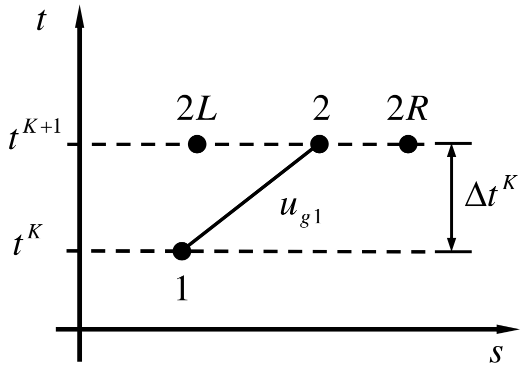


Figure 5. Propagation of the characteristics.

$$Z = a \left[\cosh \left(\frac{X}{a} \right) - 1 \right] \tag{17}$$

The local position s along the catenary and top position s_t result:

$$s = a \sinh \left(\frac{x}{a} \right) \tag{18}$$

$$s_t = a \sinh \left(\frac{X}{a} \right) \tag{19}$$

The local inclination angle θ results:

$$\theta = \arg\tan \left[\sinh \left(\frac{x}{a} \right) \right] \tag{20}$$

Knowing the position s, the abscissa x can be calculated from (18):

$$x = a \operatorname{arg\,sinh} \left(\frac{s}{a} \right) \tag{21}$$

4.2 Simulation parameters

Necessary parameters were defined in order to simulate the experimental data corresponding to (Wordsworth *et al.*, 1998), using air and water at $T_g = 298\ K$, $\mu_l = 1.\ 10^{-3}\, kg/m/s$, $\mu_g = 1.8\ 10^{-5}\, kg/m/s$, $\rho_l = 1.\ 10^{3}\, kg/m^3$, $R_g = 287\ m^2/s^2/K$. Pipeline parameters: $L = 57.4\, m$, $L_e = 0\, m$, $D = 5.25018\ 10^{-2}\ m$, $\epsilon = 4.6\ 10^{-5}\ m$, $\beta = 2\,^o$. Parameters for catenary riser: $D = 5.25018\ 10^{-2}\ m$, $\epsilon = 4.6\ 10^{-5}\ m$, $Z = 9.886\, m$, $X = 6.435\, m$, resulting from (19) $s_t = 12.5463\, m$.

4.3 Results

Discretizing the riser with $N = 51$ nodes, simulation results are shown for the following boundary conditions: $P_s = 2\, bar$, $Q_{l\,0} = 1.2984\ 10^{-3}\, m^3/s$ and $\dot{m}_{g\,0} = 1.0\ 10^{-4}\, kg/s$. After executing the program for steady state, the following results were obtained for variables at representative locations: $P_b = P_g = 2.96610\ 10^5\, Pa$, $\alpha_p = 0.51315$, $\alpha_{r\,b} = 0.012915$, $j_b = 6.13319\ 10^{-1}\, m/s$, $j_{g\,b} = 1.33191\ 10^{-2}\ m/s$, $j_{l\,b} = 6.0000\ 10^{-1}\ m/s$, $x = 0\, m$, $s_u = s_t = 12.5463\ m$, $\alpha_{r\,u} = 0.018361$, $j_u = 6.19752\ 10^{-1}\, m/s$, $j_{g\,u} = 1.97528\ 10^{-2}\ m/s$, $j_{l\,u} = 6.0000\ 10^{-1}\ m/s$.

Setting the steady state solution as initial condition for the transient program, it was observed that the system destabilizes and reaches a limit cycle. A simulation time of $500\, s$ was chosen, in order to let the system reach the limit cycle. The following figures show the limit cycles corresponding to different variables: pressure at the bottom of the riser (Fig. 6(a)), gas pressure at the pipeline (Fig. 6(b)), void fraction (Fig. 6(c)), total superficial velocity (Fig. 6(d)), gas superficial velocity (Fig. 6(e)) and liquid superficial velocity (Fig. 6(f)) at the bottom of the riser, position of liquid accumulation front (Fig. 6(g)) and position of liquid level at the riser (Fig. 6(h)).

The different stages described in Section 1. are observed in this transient. In this case, the liquid level at the riser remains at the top. This transient characterizes a severe slugging type I (Wordsworth *et al.*, 1998).

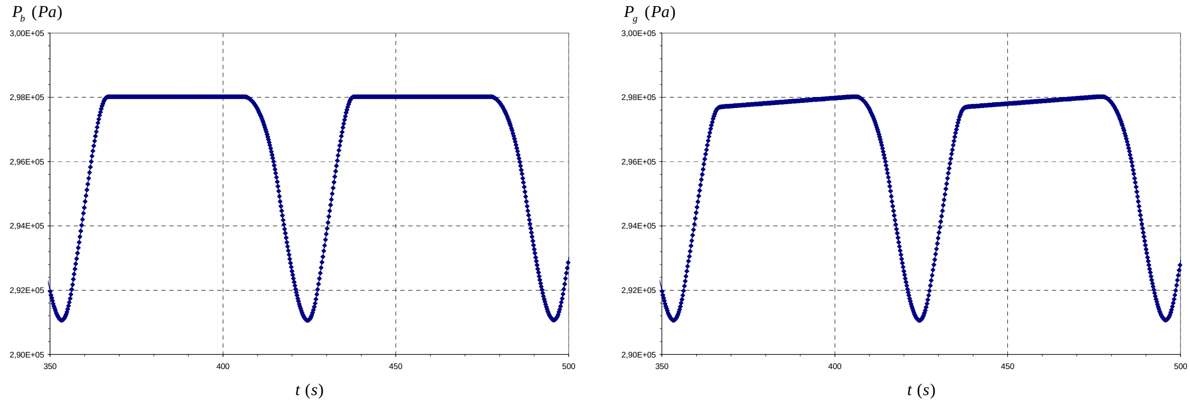
5. STABILITY MAP

Figure 7 shows the stability map corresponding to the separator pressure $P_s = 2\, bar$. The numeric stability curve was obtained by keeping constant a value of liquid or gas flow rate and varying the other in fixed increments until passing from one condition (stable or unstable) to another; when this happens, the procedure is repeated with half the increment until achieving convergence (percentage error less than 5 %). In the same figure the experimental data from (Wordsworth *et al.*, 1998) corresponding to $P_s = 2\, bar$ are shown. An excellent agreement is observed in the prediction of the stability region for the different reported types of severe slugging.

6. CONCLUSIONS

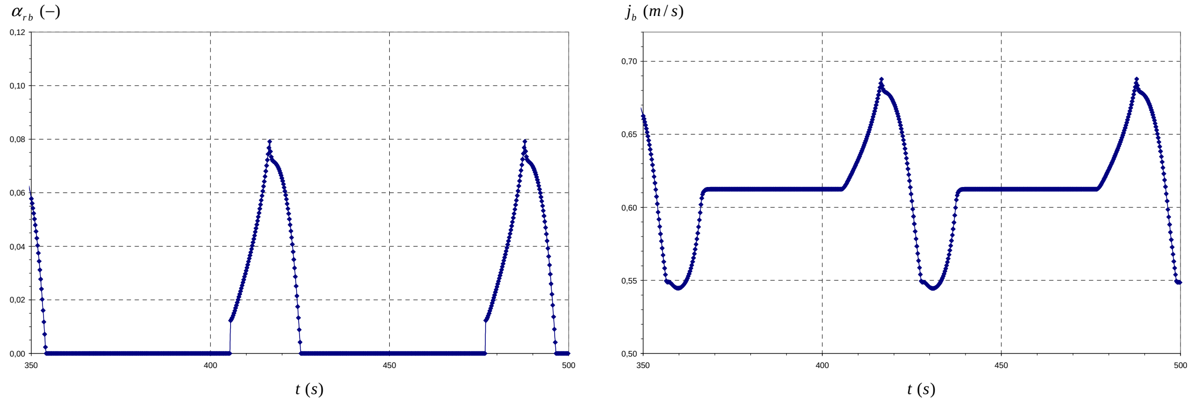
A dynamic model for severe slugging, applicable to risers with locally variable inclination angles, was developed. This model allows to identify the different types of severe slugging reported in literature, through the tracking of the liquid level in the riser and the liquid accumulation length at the pipeline.

It is important to notice that the model does not have adjusted parameters from severe slugging experimental data. The model was used to simulate the data from (Wordsworth *et al.*, 1998) for a catenary riser with $P_s = 2\, bar$. The results show severe slugging cycles lower than the experimental ones (differences of approximately $30\,\%$) and excellent prediction of the stability curve. The reasons for the differences in the cycles are being investigated and may be attributed



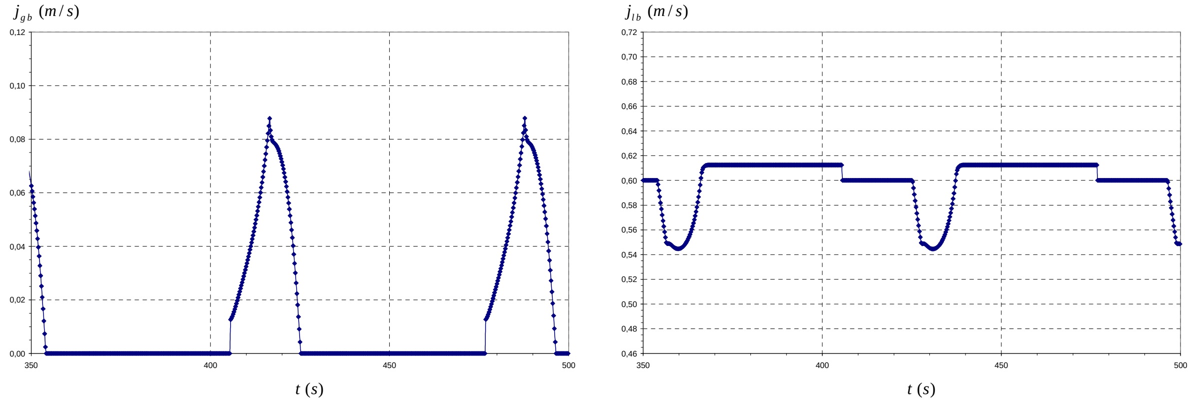
(a) Pressure at the bottom of the riser.

(b) Gas pressure at the pipeline.



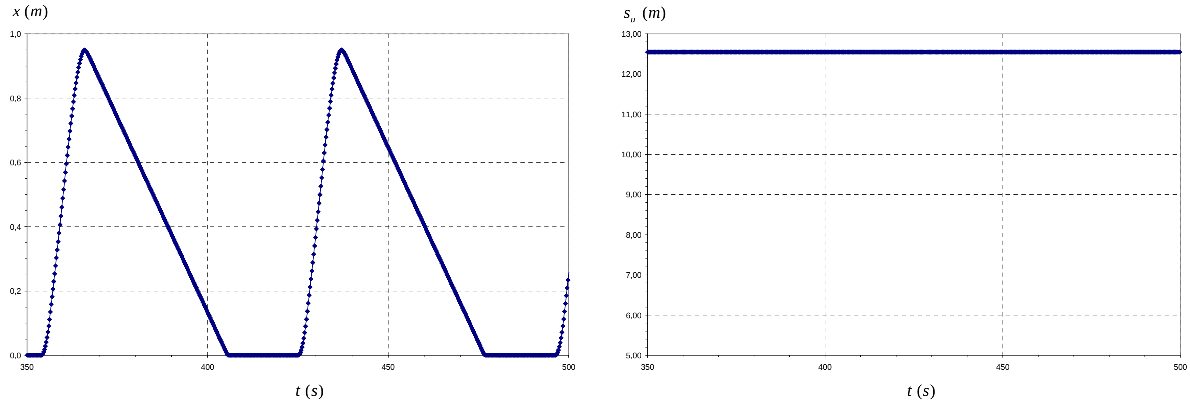
(c) Void fraction at the bottom of the riser.

(d) Total superficial velocity at the bottom of the riser.



(e) Gas superficial velocity at the bottom of the riser.

(f) Liquid superficial velocity at the bottom of the riser.



(g) Position of liquid accumulation front at the pipeline.

(h) Position of liquid level at the riser.

Figure 6. Limit cycles for $Q_{l\,0} = 1.2984\ 10^{-3}\ m^3/s$ and $\dot{m}_{g\,0} = 1.0\ 10^{-4}\ kg/s$.

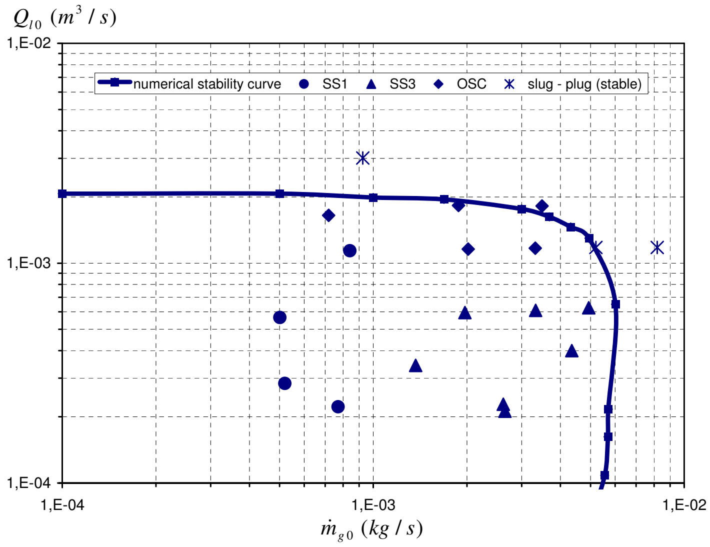


Figure 7. Stability map for $P_s = 2\,bar$.

to the drift correlation, valid for plug and slug flow, used in the model. The correlation works fine close to the steady state, with an excellent prediction of stability, but in the blowdown stage the flow pattern may be churn or annular, resulting an overestimation of the gas velocity. Another reason may be the simple homogeneous model used for the friction term in the riser. This is a work in progress.

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