EXPERIMENTAL STUDY OF SEVERE SLUGGING IN AN AIR-WATER PIPELINE-RISER SYSTEM

Alan Junji Yamaguchi
Departamento de Engenharia Mecânica, Escola Politécnica, Universidade de São Paulo, Av. Prof. Mello Moraes, 2231, CEP 05508-900, Cidade Universitária, São Paulo, SP, Brazil
alanjy@usp.br

Jorge Luis Baliño
Departamento de Engenharia Mecânica, Escola Politécnica, Universidade de São Paulo, Av. Prof. Mello Moraes, 2231, CEP 05508-900, Cidade Universitária, São Paulo, SP, Brazil
jlbalino@usp.br

Abstract. Severe slugging is a cyclic phenomenon that occurs in pipeline-riser systems, causing losses in the petroleum production. A hilly terrain and low flow rates of fluids are the two main conditions for its appearance. An air-water rig was built at University of São Paulo in order to study multiphase flows. Experiments in a pipeline and vertical riser were made. A method of controlling the gas flow rate was implemented, based on choking in orifice plates. Severe slugging data was produced in order to build flow regime maps and validate already existing numerical models.

Keywords: Severe slugging, pipeline-riser system, stability, air-water flow

1. INTRODUCTION

The production of petroleum is advancing even more towards ultra-deepwater in regions in the West Africa and Brazil. Pipeline-riser systems are necessary to transport the fluids from the reservoir to the platform. The configuration of a pipeline inclined downwards followed by a vertical riser is common in offshore production. This is one of the conditions that may cause the appearance of severe slugging. This cyclic phenomenon occurs with low flow rates of gas and liquid, where the liquid accumulates at the bottom of the riser, blocking the passage of gas and causing production losses and problems related to the separator control system, because of the high instantaneous flow rates.

Under certain conditions the steady operating state may not exist and a severe slugging cycle may occur. For low flows, the flow pattern at the pipeline is stratified. When the system destabilizes the liquid accumulates at the bottom of the riser and the pressure at this point increases; this stage of severe slugging is known as slug formation (Fig. 1a).

After the liquid level reaches the top of the riser, pressure at the bottom of the riser reaches a maximum (Fig. 1b) and only liquid flows out, characterizing the slug production stage.

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

The pressure at the bottom of the riser decreases because the column becomes lighter with the presence of gas. The gas flow increases and when the 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 the slug formation (blowdown stage, Fig. 1d).

Wordsworth et al. (1998) presented the results of a work carried out by the company CALTEC on behalf of the company Petrobras. Its main objective was to study experimentally the influence of pressure on the multiphase flow behavior in a catenary pipeline-riser system and on the initiation and characteristics of the severe slugging. Air and water were used and the pressure ranging was from 1 to 15 barg. This experimental data is used to test existing computer tools and to support the development of new modeling techniques.

Taitel et al. (1990) studied the severe slugging experimentally in order to develop a prediction model of the behavior in the stable region of a pipeline-riser system. It was shown that the Bøe criterion (Bøe, 1981) does not predict accurately the stable region.

Baliño et al. (2010) proposed a numerical model for severe slugging for air-water flow in risers with variable inclination and applied it successfully to simulate the experimental conditions reported in Wordsworth et al. (1998). Stability and flow regime maps were numerically build as well. In Baliño (2012, 2014) the model was extended by taking into account inertial effects and the influence of severe slugging mitigation devices (gas injection and choking).

According to Tin and Sarshar (1993) a classification of severe slugging was made based on the observed regime flow: Severe Slugging 1 (SS1), Severe Slugging 2 (SS2), Severe Slugging 3 (SS3) and Oscillation (OSC).

Severe Slugging 1 is characterized by the severe liquid slug length being greater to or equal to one riser height and maximum pipeline pressure is equal to the hydrostatic head of the riser.
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(a) Slug formation.  
(b) Slug production stage.  
(c) Gas blowout.  
(d) Gas blowdown.  

Figure 1: Stages for severe slugging (Taitel, 1986).

In the Severe Slugging 2 the severe liquid length is less than one riser height with intermittent bubble penetration through the slug production phase and the liquid does not recede back up the pipeline during the gas blowdown stage.

For Severe Slugging 3 the flow in the riser visually resembles normal slug flow with pressure, slug lengths and frequencies revealing cyclic variations of smaller periods and amplitudes when compared to SS1.

Oscillation has cyclic pressure fluctuations without the spontaneous vigorous blowdown.

The Multiphase Flow Multipurpose Laboratory at University of São Paulo was built within the frame of a project financed by Petrobras (Baliño, 2009) with the purpose of providing experimental data related to multiphase flow phenomena. An air-water pipeline connected to a vertical rig was built, where severe slugging is one of the main topics of study.

The objective of this paper is to show new experimental data for air-water flow in a pipeline-riser system. The gas flow rate is controlled by a methodology based on choking in orifice plates. These new results will be used to validate existing numerical and stability models.

2. EXPERIMENTAL APPARATUS

2.1 Experimental facility

The experimental system (see Fig. 2) consisted of a 7-m-long pipeline connected to a 6.5-m-height riser. The tube diameter of the pipeline-riser system is 2 in and it is made of acrylic to visualize the flow. The pipeline inclination may vary from -2 to +10 degrees from the horizontal. From the top of the riser follows a steel tube to separator. The air is vented to the atmosphere while the water is returned to a 1000-l-capacity accumulation tank.

The water coming from the accumulation tank feeds the pipeline through a centrifugal pump (W22 from Weq) controlled by a variable-frequency driver. Air flows from a compressor (Aircenter SX3 from Kaefer) through a 1/2 inch steel tube to the pipeline. This connection contains an orifice plate used to control the gas mass flow. There is also a gas
connection at the bottom of the riser with the purpose of studying gas injection as severe slugging suppression mechanism.

Instrumentation is completed with pressure (manometric and differential) and temperature transducers at the most important points of the circuit: separator and gas injection at the pipeline and at the bottom of the riser. Water flow rate $Q_{l0}$ is measured with an electromagnetic flow meter (Sitrans MAG 5000 from Siemens), while a Coriolis flow meter (Sitrans MAG 6000 from Siemens) is used to measure the gas mass flow rate $\dot{m}_{g0}$. The fluids flow rates are used to obtain the superficial velocities at the reference condition, necessary for the stability and flow regime maps, as:

$$j_{g0} = \frac{R_g T_0 \dot{m}_{g0}}{P_0 A}$$  \hspace{1cm} (1)

$$j_{l0} = \frac{Q_{l0}}{A}$$  \hspace{1cm} (2)

where $A$ is the flow passage area and $R_g = 287 \text{ J/kg/K}$ is the air gas constant. The reference condition is defined for pressure $P_0 = 1.013 \text{ bar}$ and temperature $T_0 = 293 \text{ K}$.

A programmable logic controller is used to control most of the main instruments of the circuit. The hardware used is the FAM3 from Yokogawa. Data acquisition is obtained by the use of two programs by Yokogawa: WideField and Fast Tools. A more detailed description of the experimental facility can be seen in Yamaguchi (2013).

### 2.2 Gas injection control

In the experimental facility of Wordsworth et al. (1998), gas flow was measured by using orifice plates working in the subsonic flow regime. When analyzing the experimental data of Wordsworth et al. (1998), it was realized that the gas...
flow was relatively constant when the flow was stable, but showed considerable fluctuations in severe slugging conditions, due to the coupling of the pressures located upstream and downstream the orifice plate. As a constant mass flow rate boundary condition is desirable for a comparison of experimental data with simulation models (for superficial velocities below 1 m/s), a device based on a choked flow was developed.

![Figure 4: Schematic for the sizing of plates with very small orifices.](image)

Usually sonic nozzles are used as a reference for mass flows, but small-diameter nozzles are very expensive. As an alternative, plates with very small holes were considered. Very small holes (diameters ranging from 20 µm) can be made with the laser micro drilling technique.

The following theory was developed for the sizing of plates with very small orifices (see Fig. 4). Pressure $P_1$ and temperature $T_1$ are known, and air is treated as an ideal gas. Three regions are considered:

- From 1 to the orifice inlet $e$ the flow is considered to be isentropic (region A).
- From the orifice inlet $e$ to the orifice outlet $s$ (orifice plate) (region B), the orifice can be regarded as a short capillary tube, where a Fanno flow with choked condition at $s$ is achieved.
- From $s$ to 2 (region C), an adiabatic jet flow in a sudden area expansion is considered.

From the definition of the Mach number:

$$Ma = \frac{v}{a} = \frac{v}{(\gamma RT)^{\frac{1}{2}}} = \frac{m}{\rho A (\gamma RT)^{\frac{1}{2}}}$$  \hspace{1cm} (3)

where $v$ and $m$ are respectively the gas velocity and the mass flow rate, $\gamma$ the adiabatic coefficient, $R$ the gas constant, $T$ the temperature and $A$ the flow passage area. As the pressure of an ideal gas is $P = \rho RT$, then the Mach number can be calculated as:

$$Ma = \left(\frac{R}{\gamma}\right)^{\frac{1}{2}} m \frac{T_e}{A \bar{T}}$$  \hspace{1cm} (4)

**2.2.1 Region A**

In region A the flow is considered as isentropic. Using Eq. (4) to calculate the Mach numbers at section 1 and $e$ and eliminating the mass flow, it results:

$$Ma_e = \left(\frac{D}{d}\right)^{\frac{1}{2}} \left(\frac{T_e}{T_1}\right)^{\frac{1}{2}} \left(\frac{P_e}{P_1}\right)^{-1} Ma_1$$  \hspace{1cm} (5)

where $D$ and $d$ are respectively the diameter of the pipe and the orifice. By using the stagnation equations it is possible to obtain the pressure, temperature and density ratios at the orifice inlet as:

$$\frac{P_e}{P_1} = \left[\frac{2 + (\gamma - 1)Ma_1^2}{2 + (\gamma - 1)Ma_e^2}\right]^{\gamma - 1}$$  \hspace{1cm} (6)

$$\frac{T_e}{T_1} = \left[\frac{2 + (\gamma - 1)Ma_1^2}{2 + (\gamma - 1)Ma_e^2}\right]$$  \hspace{1cm} (7)

By substituting Eq. (6) and (7) in Eq. (5) an expression relating these two Mach numbers is obtained:

$$\frac{Ma_e}{2 + (\gamma - 1)Ma_e^2}^{\frac{1}{\gamma - 1}} = \left(\frac{D}{d}\right)^{\frac{1}{2}} \frac{Ma_1}{2 + (\gamma - 1)Ma_1^2}^{\frac{1}{\gamma - 1}}$$  \hspace{1cm} (8)
2.2.2 Region B

In region B (orifice plate between e and s) the orifice can be regarded as a short capillary tube, where a Fanno flow choked at the outlet is assumed. Properties ratios at the outlet can be calculated as:

\[
\frac{T_s}{T_e} = \frac{2 + (\gamma + 1) Ma_e^2}{\gamma - 1}
\]  
\[
\frac{P_s}{P_e} = Ma_e \left[ \frac{2 + (\gamma + 1) Ma_e^2}{\gamma - 1} \right]^{1/2}
\]

Mach number at the inlet can be determined from the Fanno relation:

\[
\bar{f} \frac{L}{d} = 1 - \frac{Ma_e^2}{\gamma Ma_e^2 + \frac{\gamma - 1}{2\gamma} \ln \left( \frac{(\gamma + 1)Ma_e^2}{2 + (\gamma - 1)Ma_e^2} \right)}
\]

where \( \bar{f} \) is the mean Darcy friction factor and \( L \) is the length of the capillary tube (in this case \( L \) is the thickness of the orifice plate, which can be greater than the orifice diameter.

Having \( Ma_e \) from Eq. (11), \( Ma_1 \) and \( \dot{m} \) are determined respectively from Eq. (8) and (4); iterations are needed because of the dependence of the friction factor with the flow rate.

2.2.3 Region C

From e to 2 (region C), an adiabatic jet flow in a sudden area expansion is considered. Mass, momentum (with negligible shear stresses at the wall) and adiabatic energy conservation equations are applied. Properties at section 2 can be obtained by solving the following quadratic equation on the characteristic velocity \( u \) :

\[
\dot{m} \frac{A_2}{2} \left( 1 - \frac{V - u}{2\gamma} \right) u^2 - \left( P_s + \dot{m} V_s \right) u + \dot{m} R \left( T_s + \frac{V_s^2}{2\gamma} \right) = 0
\]

Having solved \( u \), temperature and pressure at section 2 can be obtained as:

\[
T_2 = T_s + \frac{\gamma - 1}{2\gamma} \left( V_s^2 - u^2 \right)
\]

\[
P_2 = \frac{\dot{m} RT_s}{A_2} \left[ \frac{\gamma - 1}{2\gamma R(T_s - T_2) + (\gamma - 1)V_s^2} \right]^{1/2}
\]

Conditions at section 2 are used to verify that the plate is at the choked condition.

Two sets of 20 2-cm-diameter, 2-mm-thick stainless steel plates with orifices ranging from 0.1 to 2 mm were fabricated by the company Lasertools (http://lasertools.com.br/) (see a typical plate in Fig. 5). The sets are intended to be used at the injection points located at the pipeline and at the bottom of the riser. As the diameters are not constant through the plate thickness (there is some conicalness as the laser beam drills the plate) and because the sonic condition is not achieved for the geometric diameter in orifice plates due to vena contracta effects (AFT, 2010), an effective diameter was determined based on a calibration against the Coriolis flow meter for different upstream pressures.

A typical calibration curve is shown in Fig. 6; several experimental runs were made in order to check repeatability. It can be observed a good correlation for the effective diameter, which is slightly less than the geometric one, for upstream pressure corresponding to choked conditions. It was necessary to change the plates whenever the mass flow range was outside the calibration curve.

3. METHODOLOGY

The initial experiments were done with the pipeline having +5 degrees of inclination. The water flow rate was kept constant during the experiments. Ranges corresponding to the flow variables were: water flow rate from 0.4 m³/h to 1.6 m³/h, air mass flow rate from 0.221 kg/h to 0.547 kg/h, water superficial velocity from 0.0550 m/s to 0.219 m/s and air superficial velocity from 0.025 m/s to 0.063 m/s The pressure at the separator was kept constant at 0.93 bara.
Figure 5: Typical orifice plate for gas mass flow rate control.

Figure 6: Calibration curve for the plate with measured diameter of \(1.09\, \text{mm}\) and effective diameter of \(0.92\, \text{mm}\).

The main difference between a stable and unstable flow could be verified by analyzing the pressure at the bottom of the riser. For unstable cases a cyclic pressure fluctuation can be observed and a period/frequency can be obtained by applying the Fast Fourier Transform (FFT) or calculating the mean value for at least 10 cycles.

The experimental procedure consisted in keeping a constant value of water or gas flow rate and control the other fluid flow rate in order to reach the desired superficial velocities. A partially closed valve was introduced in the water line in order to create a pressure drop comparable to the severe slugging pressure fluctuations; in this way, water flow fluctuations were minimized. Using the stability curve obtained from the numerical model it was possible to reduce the quantity of necessary experiments to obtain enough data to comparison considering the limitation of minimum of \(0.05\, \text{m/s}\) of water superficial velocity and \(0.025\, \text{m/s}\) of gas superficial velocity.

4. RESULTS AND DISCUSSION

Table 1 shows the experimental cases for separator pressure \((P_s)\) of \(0.931\, \text{bar}a\) and pipeline inclination of +5 degrees. The average temperature at the bottom of the riser was \(25.6^\circ\text{C}\). The unstable region was found for values of water superficial velocities lower than \(0.110\, \text{m/s}\) and gas superficial velocities lower than \(0.413\, \text{m/s}\). From the 31 experimental runs, 10 of them showed pressure oscillations indicating unstable cases. Visual analysis concluded that most of them were SS3 or OSC.

As an example of a stable behavior, Fig. 7 shows the pressure history at the bottom of the riser for case 1 (see Table
Table 1: Experimental results for 5 degree pipeline inclination.

<table>
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<tr>
<th>Case</th>
<th>( T({}^\circ\text{C}) )</th>
<th>( j_{g0} (\text{m/s}) )</th>
<th>( j_{l0} (\text{m/s}) )</th>
<th>( Ps (\text{bara}) )</th>
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1). Small-amplitude, high-frequency pressure fluctuations, characteristic of the intermittent (bubbly, slug) flow pattern can be observed. As an example of an unstable behavior, Fig. 8 shows the pressure history at the bottom of the riser for case 28 (see Table 1), resulting a period of 41.4 s, a mean pressure of approx. \(1.56 \times 10^5 Pa\) and an amplitude of the pressure fluctuations of approx. 4 kPa. Figure 9 shows the pressure limit cycle for the same experimental conditions obtained by numerical simulation using the model of Baliño (2012, 2014); a slightly higher period of 41.4 s, a mean pressure of approx. \(1.52 \times 10^5 Pa\) and an amplitude of the pressure fluctuations of approx. 4.2 kPa were determined from the simulations. There is a good agreement between experimental and simulation data; the difference in mean pressures is partly due to the fact the the pressure tap was located above the lowest point in the riser.

Figure 10 shows the stability map with the experimental data points. In the same figure it is also shown the stability boundary calculated with the linear stability theory developed in Azevedo et al. (2014), based on the model of Baliño et al. (2010), for the same operating conditions. It can be seen that the experimental results show an excellent agreement with the linear stability curve. It was also seen that the period for the unstable cases increased as the superficial velocities diminished, as predicted by the theory.

5. CONCLUSIONS

The first experimental results showed an excellent agreement with dynamic simulations in the time domain and with the stability curve obtained from a numerical model based on linear stability theory for a pipeline-riser system with +5 degrees of inclination. The gas mass flow rate control strategy based on choked flow in a plate with a small orifice proved to be successful. A more detailed study using more sophisticated instrumentation for measuring void fraction and filming, in order to characterize more objectively the flow patterns, is underway.
Figure 7: Pressure history at the bottom of the riser for a stable behavior (case 1, Table 1).

Figure 8: Pressure history at the bottom of the riser for an unstable behavior (case 28, Table 1).

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Figure 9: Simulated pressure limit cycle at the bottom of the riser for an unstable behavior (case 28, Table 1).

Figure 10: Experimental data and stability map.

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7. REFERENCES


8. RESPONSIBILITY NOTICE

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