Journal of Computational Science xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Journal of Computational Science

journal homepage: www.elsevier.com/locate/jocs

Modeling and simulation of severe slugging in air-water systems including inertial effects

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A R T I C L E I N F O

Article history:
Received 31 January 2013
Received in revised form 29 July 2013
Accepted 25 August 2013
Available online xxx

Keywords:
Severe slugging
Pipeline-riser system
Air-water flow
Stability
Lumped and distributed parameter systems
Switched systems
Petroleum production technology

A B S T R A C T

A mathematical model and numerical simulations corresponding to severe slugging in air-water pipeline-riser systems are presented. The mathematical model considers continuity equations for liquid and gas phases, with a simplified momentum equation for the mixture. A drift-flux model, evaluated for the local conditions in the riser, is used as a closure law. In many models appearing in the literature, propagation of pressure waves is neglected both in the pipeline and in the riser. Besides, variations of void fraction in the stratified flow in the pipeline are also neglected and the void fraction obtained from the stationary state is used in the simulations. This paper shows an improvement in a model previously published by the author, including inertial effects. In the riser, inertial terms are taken into account by using the rigid water-hammer approximation. In the pipeline, the local acceleration of the water and gas phases are included in the momentum equations for stratified flow, allowing to calculate the instantaneous values of pressure drop and void fraction. The developed model predicts the location of the liquid accumulation front in the pipeline and the liquid level in the riser, so it is possible to determine which type of severe slugging occurs in the system. A comparison is made with experimental results published in literature including a choke valve and gas injection at the bottom of the riser, showing very good results for slugging cycle and stability maps. Simulations were also made assessing the effect of different strategies to mitigate severe slugging, such as choking, gas injection and increase in separation pressure, showing correct trends.

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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: (a) High average back pressure at well head, causing tremendous production losses, (b) High instantaneous flow rates, causing instabilities in the 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 [1]. 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 the 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)).

As 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 in the riser. This is the slug production stage (Fig. 1(c)).

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 intermittent/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)).

Fig. 1(f) shows the different stages in the pressure history at the bottom of the riser corresponding to an experiment under laboratory conditions [2].

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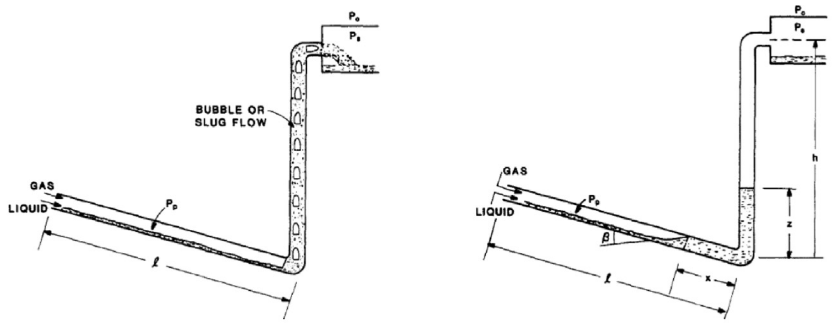
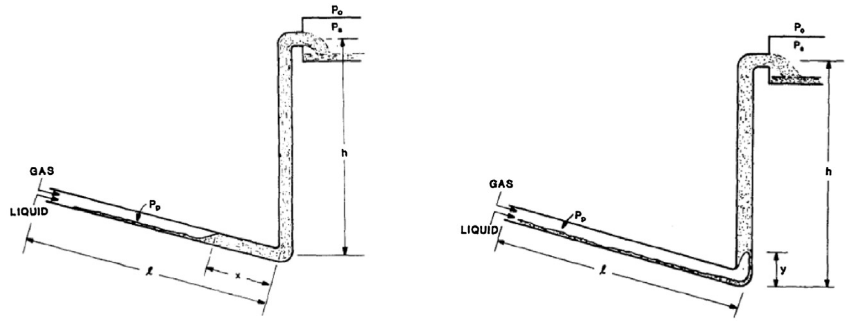
http://dx.doi.org/10.1016/j.jocs.2013.08.006

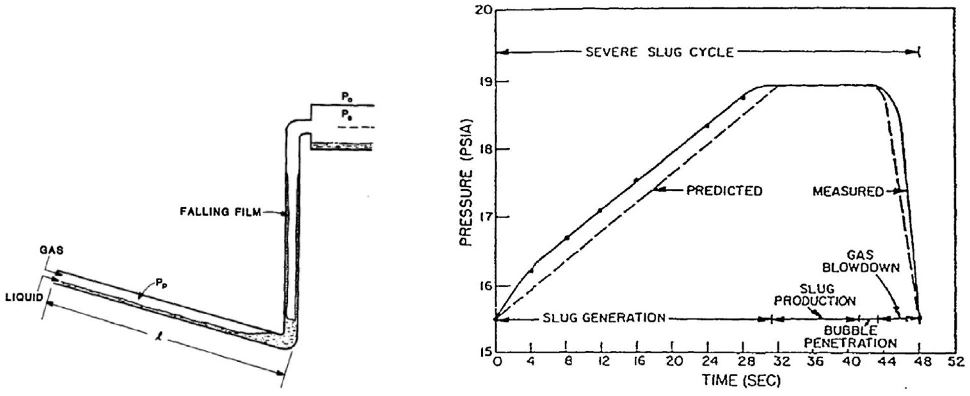
Please cite this article in press as: J.L. Baliño, Modeling and simulation of severe slugging in air-water systems including inertial effects, J. Comput. Sci. (2013), http://dx.doi.org/10.1016/j.jocs.2013.08.006



(a) Steady state. (b) Slug formation.



(c) Slug production. (d) Gas blowout.



(e) Gas blowdown. (f) Pressure history.

Fig. 1. Stages for severe slugging (from [1,2]).

A classification of severe slugging can be made, according to the observed flow regime, as follows:

- Severe Slugging 1 (SS1): the liquid slug length is greater to or equal to one riser length and maximum pipeline pressure is equal to the hydrostatic head of the riser (neglecting other pressure drop terms).
- Severe Slugging 2 (SS2): the liquid length is less than one riser length, with intermittent gas penetration at the bottom of the riser.
- Severe Slugging 3 (SS3): there is continuous gas penetration at the bottom of the riser; visually, the flow in the riser resembles normal slug flow, but pressure, slug lengths and frequencies reveal cyclic variations of smaller periods and amplitudes compared to SS1.
- Oscillation (OSC): there are cyclic pressure fluctuations without the spontaneous vigorous blowdown.

Most of the models for severe slugging were developed for vertical risers and assume one-dimensional, isothermal flow and a mixture momentum equation in which only the gravitational term is important.

In [3] a model was presented considering constant mean values for the gas density and void fraction in the riser, allowing to calculate time variations of pipeline pressure, position of the accumulation region, flow rate into the riser and mean holdup. It was found that as the operation point moves closer to the stability line the numerical procedure did not converge, giving gas mass flows going to infinite as the spatial discretization was decreased. Experimental data were obtained from a facility for different buffer volumes (simulating equivalent pipeline lengths) and a comparison was made with the simulation results, showing good agreement except for the blowout/blowdown stage. Setting apart the non-convergence problems, lumped parameter models seem to work fine for short risers, where the local variations of variables are small, but are not successful in long risers, typical of offshore systems.

In [4] a model with a distributed parameter formulation for the riser was presented. Considering continuity equations for the liquid and gas without phase change and a gravity-dominant mixture momentum equation, the model was capable of handling

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