Chemical Engineering Science 161 (2017) 1–13

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Influence of pipeline modeling in stability analysis for severe slugging

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HIGHLIGHTS

- We study stability of a dynamic model for severe slugging in air-water systems.
- We study three different pipeline models.
- We build stability maps and stratified-intermittent transition boundary.
- We analyze the behavior based on the basic assumptions for the stability criteria.

ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form 31 October 2016
Accepted 1 December 2016
Available online 2 December 2016

Keywords:
Severe slugging
Pipeline-riser system
Air-water flow
Linear stability theory
Petroleum production technology

ABSTRACT

In this paper a numerical linear stability analysis is performed to a mathematical model for the two-phase flow in a pipeline-riser system. Most of dynamic models and stability criteria are based on a simplified lumped parameter pipeline, where it is assumed that the void fraction variations can be neglected. As a pipeline with a constant void fraction is not able to describe the flow pattern transition or void fraction propagation waves, the choice of pipeline model influences the stability map. Three different models for the pipeline are considered: (a) A lumped parameter model with constant void fraction; (b) A lumped parameter model with time dependent void fraction; (c) A distributed parameter model, with void fraction dependent on time and position.

The results show that the constant void fraction model overestimates the unstable region, pushing the near horizontal branch of the stability boundary beyond the stratified-intermittent transition boundary for high buffer lengths and invalidating the model assumptions. The distributed parameter model is capable of describing void fraction waves along the pipeline under the restriction of a stratified flow pattern, with an additional stabilizing effect, being less sensitive to high buffer lengths and not crossing the stratified-intermittent transition in the nearly horizontal branch. The lumped parameter model with variable void fraction behaves close to the distributed model, but predicting bigger unstable regions.

The behavior of the different pipeline models is explained based on the basic assumptions that led to many semi-empirical stability criteria. It is concluded that a distributed parameter model is recommended, with a void fraction correlation that includes the transition from stratified to intermittent flow pattern taken into account in the problem statement.

1. Introduction

In offshore petroleum production systems, the fluids that leave the well are often transported to platforms by means of flexible pipes. The pipes are composed of a pipeline (or flowline), which conducts the fluids over the seabed topography, and a riser, which elevates the fluids to the separator vessel located at the platform, as shown in Fig. 1. Usually, the transported fluids are composed of gas, oil and water, but due to the severe conditions of pressure and temperature, it is possible the formation of emulsions, hydrates and wax. These features make the modeling of the multiphase flow dynamics a complex task (Nemoto and Baliño, 2012).

Severe slugging may appear in offshore oil production systems 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 phenomenon, characterized by the formation and cyclical production of long liquid slugs and fast gas blowdown, may have a period of hours, causing higher average pressures, instantaneous flow rates and oscillations at the reservoir. These operational conditions may lead to the oil production

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http://dx.doi.org/10.1016/j.ces.2016.12.004
0009-2509/

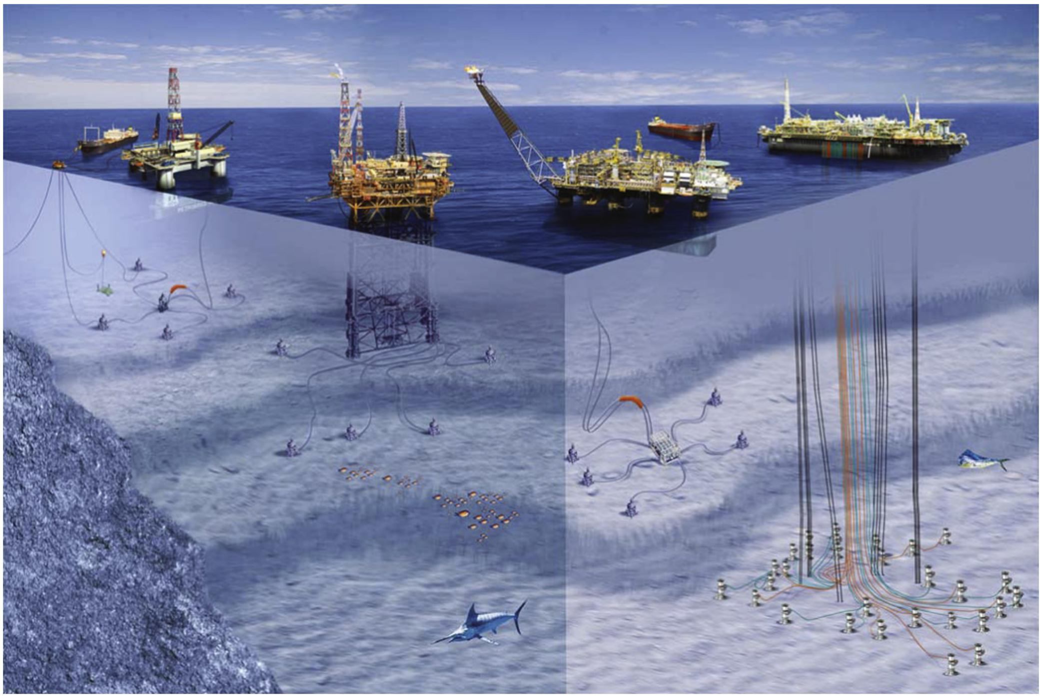

Fig. 1. Typical offshore petroleum production systems. *Source*: Petrobras.

shutdown. The steps leading to the process of severe slugging formation can be seen in Taitel (1986) and a monograph describing basic characteristics of severe slugging in air-water systems can be seen in Mokhatab (2010).

Many severe slugging studies in air-water systems were made, specially for vertical riser with one-dimensional and isothermal flow and a mixture momentum equation in which only the gravitational term is relevant (Taitel et al., 1990; Sarica and Shoham, 1991). In all these models, inertial effects and propagation of pressure waves were neglected, resulting in the no-pressure-wave (NPW) approximation (Masella et al., 1998). As a result of this approximation, pressure changes are felt instantaneously at any point in the riser. Besides, a stratified flow pattern was assumed at the pipeline and variations of void fraction were neglected. The void fraction at the pipeline was obtained from a momentum balance in the gas and liquid phases assuming a stationary state, resulting in an algebraic relation between the representative variables (Taitel and Dukler, 1976). In Baliño et al. (2010) a model including a friction term and a riser variable inclination was presented, while in Baliño (2012, 2014) the model was improved by taking into account pressure drop and variable void fraction in the pipeline, inertial effects using the rigid water-hammer approximation and severe slugging mitigation devices.

Many stability criteria were developed based on simplified models for vertical risers (Bøe, 1981; Taitel, 1986; Pots et al., 1987; Jansen et al., 1996). Although these stability criteria are useful for a first estimation of the unstable region (they are even used in commercial steady-state computer codes), a common drawback is that they were not derived from complete dynamic system models, but from ad hoc conditions in which many physical effects were disregarded; consequently, their applicability is quite limited.

As a numerically cost-efficient alternative to temporal simulations, the linear stability theory is a powerful technique to identify the stable and unstable regions. To perform the linear stability analysis of a dynamic system, a model characterized by a set of governing equations is needed. Then, the stationary state is obtained by setting to zero the time derivatives. The governing equations are linearized with respect to the stationary solution. These linearized equations determine how infinitesimal perturbations of the stationary solution evolve with time. The growth rate of the perturbations is given by the real part of the eigenvalues of the spectrum associated with the linearized equations. If all eigenvalues have negative real part, then the stationary solution is stable, but if at least one eigenvalue has positive real part, the stationary solution is unstable.

In Zakarian (2000), the linear stability theory was applied for a pipeline-riser system with a vertical riser using the NPW model without friction and considering only two nodes. For a vertical riser, an equation for the flow instability evolution was presented. The stability maps obtained showed a good qualitative agreement with the experimental results reported in the literature.

In Azevedo et al. (2015), a linear stability analysis was made for the model developed in Baliño et al. (2010), considering an arbitrary discretization and including severe slugging mitigation devices such as increase in separation pressure, choke valve at the top of the riser and gas injection at the bottom of the riser. Results were compared with experimental and numerical results reported in the literature with excellent agreement. The results also showed a better agreement when compared to experimental results and to the stability curves obtained through numerical time simulations when the nodalization is increased from the simplest two-node description made in Zakarian (2000).

The stability criteria and most of the models presented above (with the exception of the one in Baliño (2012, 2014)) are based on a simplified lumped parameter pipeline connected to the bottom of the riser. At the pipeline it is assumed that the void fraction variations can be neglected.

For relatively short pipeline lengths or short equivalent buffer lengths, simulation results show that the model with constant pipeline void fraction works fine and void fraction fluctuations are low. As the pipeline or equivalent buffer length increases, simulation and stability analysis show that the unstable region increases, reaching higher gas and liquid superficial velocities.