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Linear stability analysis for severe slugging in air–water systems considering different mitigation mechanisms

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ABSTRACT

This work presents a numerical study of the effects of mechanisms such as gas injection, choking and different boundary conditions on the stability of the stationary state for two-phase flows in vertical and catenary pipeline–riser systems. Numerical linear stability analysis is performed to a suitable mathematical model for the two-phase flows in a pipeline–riser system. The mathematical model considers the continuity equations for the liquid and gas phases and a simplified momentum equation for the mixture, neglecting inertia (NPW – no pressure wave model). A drift flux correlation, evaluated in local conditions, is utilized as a closure law. Gas injection and a choke valve are added, respectively, at the riser bottom and top. The extended model is applied to air–water pipeline–riser systems reported in the literature. Numerical linear stability analysis results are compared with experimental and numerical results reported in the literature with excellent agreement.

Introduction

Offshore oil production systems may present an intermittent flow regime at some point of their life span. Such intermittent flow regime may vary from a short period oscillatory flow with constant gas and liquid penetration into the riser to severe slugging, with 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 last regime may have period of hours and causes higher average pressures and instantaneous flow rates and reservoir oscillations. These operational conditions may lead to oil production shutdown.

In the case of severe slugging, mitigation devices have to be employed to keep oil production. There are four basic methods presented in the literature to reduce or to suppress severe slugging: pressure increase at the separator, flow restriction in the riser (choke valve), gas injection and flow restriction in the pipeline (venturi).

The main reason why back pressure increase has a stabilization effect is that the pressure increase compress the gas phase and makes the system less compressible. As reservoir and separator pressures are the boundary conditions in petroleum production systems and this pressure difference is the driving force for the flow, the main disadvantage of this technique is a reduction in production.

In normal petroleum production system operation the choke valve controls the flow, allowing a production compatible with the reservoir characteristics. In severe slugging, it is acknowledged that choking can stabilize the flow by increasing the back pressure, which is a function of the fluid flow rate (Schmidt, 1977; Taitel, 1986). In addition to the system pressure increase, any increase in flow rate at the top of the riser gives rise to an increase in frictional pressure drop across the valve, causing an additional stabilization effect. Again, closure of a choke valve causes a decrease in production. Manipulation of the choke valve is usually the system control action to stabilize different flow regimes and prevent slugging (Storkaas and Skogestad, 2007). The stabilization requires very careful choking to ensure minimum back pressure.

Gas injection is a process used to artificially lift fluids from wells where there is insufficient reservoir pressure. By injecting gas, it is possible to aerate the liquid column and to reduce the pressure gradient. Due to this effect, it is acknowledged that gas injection can stabilize the flow in severe slugging, although relatively large gas flow rates are necessary (Jansen et al., 1996). Besides, the pumping operational cost of gas injection can be very significant.

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In Tengesdal et al. (2002) and Tengesdal et al. (2003) a technique called self-lifting was investigated. The principle of this technique is to transfer the pipeline gas to the riser at a point above the riser-base; in this way, the pressure difference between the pipeline and the riser injection point is the driving force for gas lifting, without the necessity of external power for gas injection. The transfer process will reduce both the hydrostatic head in the riser and the pressure in the pipeline, consequently lessening or eliminating the severe slugging by maintaining the two-phase flow steady state in the riser.

In Almeida and Gonçalves (1999) a method was presented for severe slugging elimination based on a venturi device internally placed in the flow line near the junction with the riser. The venturi accelerates the fluids, eliminating the stratified flow pattern near the riser inlet in the blowdown stage. The absence of stratified flow in this region hinders the liquid accumulation at the bottom of the riser and consequently ceases the severe intermittence. The method was verified in a small scale experimental facility and a comparison was made with choking at the riser head.

Most of the studies for severe slugging in air–water systems were developed for vertical risers and assume one-dimensional and isothermal flow and a mixture momentum equation in which only the gravitational term is important (Taitel et al., 1990; Sarica and Shoham, 1991). A recent monograph by Mokhatab (2010) reviews different issues related to severe slugging for air–water systems.

In Baliño et al. (2010) a model for severe slugging valid for risers with variable inclination was presented. The model was used to simulate numerically the air–water multiphase flow in a catenary riser for the experimental conditions reported in Wordsworth et al. (1998). This model was extended for oil–gas–water systems (Nemoto and Baliño, 2012) and for air–water systems including inertial effects and mitigation devices (Baliño, 2012).

Thermal effects are important in subsea oil systems for well transients and are taken into account in simulations by including the thermal energy equation in the analysis, as done in commercial codes. Nevertheless, as discussed in Nemoto and Baliño (2012), isothermal flow is a reasonable assumption for severe slugging because temperature variations are much smaller than pressure variations in operating conditions; consequently thermal effects have a secondary influence in offshore petroleum systems. For the air–water experiments reported in the literature, on the other hand, temperature variations are negligible.

Although a pipeline–riser is designed to operate in steady state flow regime, it is possible that this condition does not exist. The stability of a pipeline–riser system depends on the set of parameters defining the operational state. It is common to represent the stability in a map with liquid and gas reference superficial velocities in the axes, leaving the rest of the parameters fixed; then the stability curve is defined as the relationship between the superficial velocities at the stability boundary.

Many stability criteria were developed based on simplified models for vertical risers (Bøe, 1981; Taitel, 1986; Pots et al., 1987; Jansen et al., 1996).

In Bøe (1981) a stability criterion was derived based on the existence of a stratified flow pattern in the pipeline and a pressure balance at the bottom of the riser, in a condition in which the riser is partially full of liquid only (slug formation stage in a severe slugging type 1 (SS1)). The condition is stated by equalizing the pressure rate in the riser due to the addition of liquid at the bottom and the pressure rate in the pipeline due to the addition of gas. Notice that there are milder severe slugging scenarios such as SS3 (in which there is continuous gas penetration at the bottom of the riser), in which the slug formation stage does not exist.

In Taitel (1986) stability criteria were derived based on the net pressure difference between the riser and the pipeline following the perturbation of a gas pocket penetrating in the riser at the stationary state, considering two boundary conditions: (a) constant separator pressure and (b) choke valve. Although non-dimensional parameters were obtained with trends in agreement with experimental data, the criteria ignored the flow rate of liquid and gas in the perturbation process. Besides, the non-dimensional parameters depend on variables that are not controlled, such as the void fraction at the pipeline, the mean void fraction at the riser and the void fraction in the gas cap penetrating the liquid column.

In Pots et al. (1987) a stability criterion is stated, based on a parameter defined as the ratio between the rate of gas pressure buildup in the pipeline and the rate of hydrostatic pressure buildup in the riser, after the gas flow passage from the pipeline to the riser is blocked. If the hydrostatic pressure buildup (due to the slug growth in the riser) exceeds the gas pressure buildup in the pipeline (due to the gas that continuously get in the system), the riser becomes filled with liquid before the gas pressure can drive the liquid slug out of the line. This condition implies that severe slugging type 1 will occur.

In Jansen et al. (1996) the stability criterion presented in Taitel (1986) was extended by assuming a constant gas injection rate at the bottom of the riser. A comparison was made with experimental data for a vertical riser considering a choke valve and gas injection.

Although the stability criteria cited above 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.

The stability curve for any pipeline–riser system can be obtained numerically if a model and a computer simulation program are available. The stationary solution for a given point in the system parameter space is given as initial condition for the numerical simulation; if the numerical solution plus an infinitesimal perturbation (the truncation error in space discretization is enough as a perturbation) converges to the initial condition with time, the stationary solution is stable and it is the system steady state. If the numerical solution goes away with time, the stationary state is unstable, there is no steady state and an intermittent solution develops with time. By changing the point and repeating this process, the stability map can be built. For unstable flow, the analysis of the limit cycle leads to the determination of the flow regime map, showing the regions corresponding to the different types of intermittency.

In Baliño et al. (2010), stability and flow regime maps for the multiphase flow in a catenary pipeline–riser system were numerically built. This procedure is laborious and computationally costly, specially for configurations in the parameter space close to the stability boundary, where the time rate of decay or growth of the numerical solution is very small, resulting in very long simulation periods.

As a more efficient alternative to time domain simulations, the linear stability analysis is a powerful technique to identify the stable and unstable regions. To perform the linear stability analysis of a dynamic system we need a model characterized by a set of governing equations. The stationary state is then obtained by setting the time derivatives to zero. Once the stationary state is obtained, the state variables are written as their stationary state value plus a perturbation and are substituted into the governing equations, which gives the perturbation governing equations. Next, these equations are linearized. The linear perturbation governing equations determine how 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.

In Zakarian (2000), the linear stability analysis was applied for two-phase flows in pipeline–riser systems. The two-phase flow