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Modeling and simulation of severe slugging with mass transfer effects

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A B S T R A C T

A mathematical model and numerical simulations are presented to investigate the dynamics of gas, oil and water flow in a pipeline-riser system. The pipeline is modeled as a lumped parameter system and considers two switchable states: one in which the gas is able to penetrate into the riser and another in which there is a liquid accumulation front, preventing the gas from penetrating the riser. The riser model considers a distributed parameter system, in which movable nodes are used to evaluate local conditions along the subsystem. Mass transfer effects are modeled by using a black oil approximation. The model predicts the liquid penetration length 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. The method of characteristics is used to simplify the differentiation of the resulting hyperbolic system of equations. The equations are discretized and integrated using an implicit method with a predictor–corrector scheme for the treatment of the nonlinearities. Simulations corresponding to severe slugging conditions are presented and compared to results obtained with OLGA computer code, showing a very good agreement. A description of the types of severe slugging for the three-phase flow of gas, oil and water in a pipeline-riser system with mass transfer effects are presented, as well as a stability map.

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.

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 offshore petroleum production systems. The flow destabilization results from two main competing mechanisms: pressure drop across the riser (mainly influenced by the volume fraction distribution) and pipeline compressibility. 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. Due to these issues, predicting and avoiding the occurrence of severe slugging during the project of the exploratory facilities became an indispensable activity in order to ensure continued production at desired levels for project profitability (Lorimer and Ellison, 2000).

Some models were proposed for studying severe slugging in a pipeline-riser system considering isothermal air–water flow. Schmidt et al. (1980), Fabre et al. (1990), Taitel et al. (1990), Sarica and Shoham (1991) and Baliño et al. (2010) are some of the authors that researched the behavior of this biphasic flow and proposed different methods to determine the system stability. A recent monograph by Mokhatab (2010) reviews different issues related to severe slugging for air–water systems.

Using air and water as flowing fluids, it is possible to investigate basic mechanisms of the flow behavior; however, there are many limitations when trying to extrapolate these results to petroleum production systems. Pipeline lengths and riser heights in petroleum production systems are much larger (order of kilometers long) than the values for air–water experimental facilities. The high pressure ratios between the bottom and top of the riser give rise to important expansion effects in the gas phase, invalidating models based on the assumption of a mean void fraction.

Petroleum is a multicomponent system in which both liquid and gas phases coexist at operating conditions (McCain, 1990). Mass transfer between the phases is dependent on pressure and

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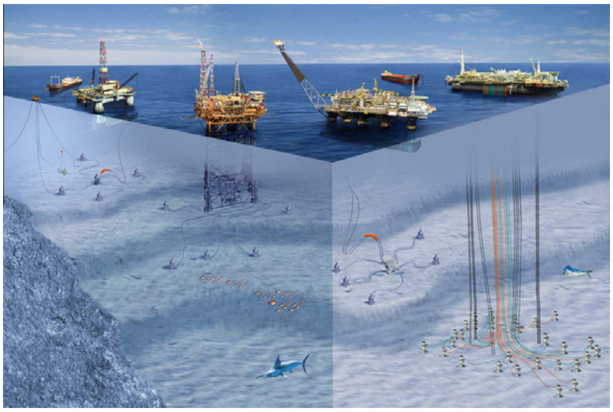

Fig. 1. Typical offshore petroleum production systems (source: Petrobras).

temperature through the pressure, volume and temperature (PVT) data. With the high pressure variations in the riser, mass transfer effects cannot be ignored. Besides, the fluid coming from the reservoir has a water content, so three phases can coexist in the general case.

Transients in petroleum production systems can be simulated using commercial codes. For instance, OLGA (OLGA, 2011) is a computer program developed to simulate oil, water and gas flow in wells, pipelines and receiving facilities. The program solves separate continuity equations for the gas, liquid bulk and liquid droplets, two momentum equations, one for the continuous liquid phase and one for the combination of gas and possible liquid droplets and one mixture energy equation, considering that both phases are at same temperature. The equations are solved using the finite volume method and a semi-implicit time integration. Although commercial codes can be used for getting results in pipeline networks, it is desirable to develop simpler models capable of capturing the basic physics involved in the phenomenon.

In this work, a mathematical model and numerical simulations are presented to investigate the dynamics of gas, oil and water flow in a pipeline-riser system. In this model continuity equation for gas, oil and water phases are taken into account. Oil and water phases are considered to have the same velocity and are homogenized. Mass transfer between the oil and gas phases is calculated using the black oil approximation. The properties of fluids are calculated by analytical correlations based on experimental results and field data. As in previous models for air–water systems, it is considered an isothermal flow.

Some considerations must be made related to the isothermal approximation for modeling pipeline-riser systems with mass transfer effects. Besides the problem of unstable flow regions, the design and operating guidelines for subsea oil systems are based in the principle of keeping temperature sufficiently high in order to avoid hydrates, waxes and asphaltenes formation. As a consequence, temperature drop across the pipeline/riser system must be reduced with the proper insulation in order to keep temperature above critical values. A typical temperature of the flow leaving the well is approximately 70 °C, while a typical temperature drop is approximately 40 °C.

As stated before, it is accepted that severe slugging is a phenomenon controlled basically by hydrostatic pressure drop in the riser and compressibility of the pipeline, being other physical effects (friction and inertia forces, for example) of minor importance; thus, temperature dependence of the friction term (mainly through oil viscosity) is expected not to be significant. Concerning the gas expansion effect (important in the hydrostatic pressure drop), it depends on the absolute temperature; as fractional changes on the absolute temperature are small, we expect a small influence. Finally, temperature also influences moderately gas solubility and oil formation volume factor (see Section 2.3.5). As a consequence, a calculation based on the mean temperature is a good estimation for severe slugging studies.

Thermal effects can be taken into account in the model by adding the energy equation for the two phases flowing together. It can be shown that this additional equation does not increase the number of characteristic values of the resulting system of equations (see Section 2.4).

Unlike temperature, pressure changes dramatically in subsea oil systems, specially in ultra-deep waters, where pressure may range from 20 to 300 bar. As pressure influence all thermodynamic properties, these high pressure ratios give rise to important expansion and mass transfer effects.

The pipeline is modeled as a lumped parameter system and considers two switchable states, one in which the gas is able to penetrate into the riser, and another in which there is a liquid accumulation front, preventing the gas from penetrating the riser. An additional algebraic equation considering a linear momentum balance for a stationary smooth stratified flow regime is used to relate the flows and the void fraction.

The riser model considers a distributed parameter system, in which movable nodes are used to evaluate local conditions along the subsystem. A simplified momentum equation without inertia terms is considered for the mixture. A drift-flux model, evaluated for the local conditions in the riser, is used as a closure law. Different riser geometries (constant angle or catenary) can be introduced. The method of characteristics is used to simplify the differentiation of the resulting hyperbolic system of equations. The equations are discretized and integrated using an implicit method with a predictor–corrector scheme for the treatment of the nonlinearities.

The model predicts the liquid penetration length 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. As a consequence, this work can be regarded as an extension of the one developed in Baliño et al. (2010), including three-phase flow and mass transfer effects.

2. Riser model

The riser model considers a one-dimensional three-phase isothermal flow. Continuity equation for gas, oil and water phases and a simplified momentum equation without inertia terms for the phases flowing together are the governing equations. Oil and water phases are considered to have the same velocity and are homogenized. Slip between the liquid and gas phases is taken into account by using a drift flux model. Mass transfer between the oil and gas phases is calculated using the black oil approximation. The liquid and gas phases are assumed to be compressible and the gas behaves as a real gas. Solubility of gas and vaporization are neglected for water. The state variables of the riser model are the void fraction α, oil volume fraction α_o, pressure P and total superficial velocity j.

2.1. Riser geometry

The riser geometry is characterized by a function expressing the coordinates of the points belonging to the riser; from this, it is possible to determine the local position along the riser and the local inclination angle. For a catenary riser, geometry is characterized by the coordinates X_r and Z_r, corresponding to the abscissa and the height of the top of the riser (see Fig. 2). It is assumed that the inclination angle at the bottom is zero.