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Numerical study on mitigating severe slugging in pipeline/riser system with wavy pipe

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A B S T R A C T

The gas/liquid two-phase flow in pipeline/wavy-pipe/riser systems was investigated numerically with CFD. A CFD model of the pipeline/wavy-pipe/riser system was obtained by adding a wavy pipe to the model of the pipeline/riser system verified by the experimental data previously. The effects of the geometrical parameters and location of the wavy pipe on its performance of slug mitigation and flow characteristics in pipeline/wavy-pipe/riser systems were examined through the CFD models. With the increase of the amplitude or length of the wavy pipe, the slug in the pipeline/riser system becomes shorter. The optimum location of the wavy pipe in the pipeline exists for a pipeline/riser system and a wavy pipe at given operating conditions. The CFD modelling provides a feasible and flexible way to investigate the effectiveness of the wavy pipes on mitigating severe slugging in pipeline/riser systems.

1. Introduction

Severe slugging in pipeline/riser systems is one of the flow assurance concerns in offshore oil and gas production (Bai and Bai, 2005; Brown, 2002; Guo et al., 2005; Su, 2003). At the late stage of the field life when the reservoir pressure is low and the production is reduced, severe slugging usually forms in the pipeline/riser system due to the low gas and liquid flowrates. Severe slugging is a cyclic process consisting of four stages (Schmidt et al., 1985; Taitel, 1986): liquid buildup stage, slug production stage, gas penetration stage and gas-blowdown/liquid-fallback stage. Severe slugging can result in various problems to the whole production system. The problems exhibit great challenges to the steady operation of the production, mechanical integrity of the structure and efficient management of the reservoir. Therefore, severe slugging mitigation is a highly desirable undertaking.

The major methods for mitigating severe slugging can be grouped into two categories: active and passive slug mitigation, based on whether the 'external interference' is needed or not in the operation. The external interference is essential to the implementation of the active methods but the function of the passive methods can be achieved without any external interference. The passive methods usually take the form of design changes to the facility itself such as sizing of slug catcher, gas lifting by rerouting the gas in the pipeline to the riser (Sarica and Tengesdal, 2000) and flow regime modification by a flow conditioner in the pipeline (Almeida and Gonçalves, 1999; Makogon et al., 2011). They do not need extra investment on the external resources, such as operators, compressors, measurement instruments and actuators. Furthermore, they can work in conjunction with the active methods, easing the challenges of severe slugging induced problems to the active methods. A novel flow conditioner, wavy pipe, was proposed to be installed in the pipeline for modifying the stratified flow so as to change the flow behaviour in the whole pipeline/riser system (Xing et al., 2013a). It was demonstrated experimentally that both of the operating region and severity of severe slugging can be reduced by applying wavy pipes. Most interestingly the wavy pipe performs better with its outlet located upstream of the riser base than just at the riser base (Xing et al., 2013b). A new question was then proposed that 'how the geometrical parameters and location of the wavy pipe affect the flow characteristics in the pipeline/riser system and the performance of severe slugging mitigation?'. The objective of the present study is to address the above question by carrying out a numerical study on the gas–liquid two-phase flow in pipeline/wavy-pipe/riser systems.

One-dimensional (1-D) modelling approach has been adopted by many researchers to investigate the transient flow characteristics in pipeline/riser systems (Taitel et al., 1990; Sarica and Shoham, 1991; Baliño et al., 2010; Nemoto and Baliño, 2012; Malekzadeh et al., 2012a). To employ the above 1-D models for

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simulating multiphase flows in pipeline/riser systems with severe slugging mitigation methods applied, necessary modifications need to be made to the original models. Jansen et al. (1996) modified the 1-D transient model developed by Taitel et al. (1990) to include the effects of choking and gas lifting. A 1-D prediction model for the bypass gas-lifting configuration was developed by Tengesdal et al. (2003) through modifying the model proposed by Sarica and Shoham (1991) to investigate the feasibility of this novel approach. Some researchers have used a commercial code, OLGA, to simulate multiphase flows in pipeline/riser systems and investigate the performance of severe slugging mitigation methods (Malekzadeh et al., 2012a,b; Makogon et al., 2011). Essentially OLGA is a transient, 1-D, modified two-fluid model (SPT Group, 2006). Makogon et al. (2011) developed an OLGA model to show the effectiveness for mitigating severe slugging by adding undulation units in the pipeline. Compared with CFD models the 1-D models are more time efficient especially when OLGA is used, because most severe slugging mitigation methods can be added into the pipeline/riser model as 'components' provided by OLGA. However, it needs to be emphasized that one-dimensional flows have been assumed in both pipeline and riser, thus no information of the phase distribution and the interface between gas/liquid two phases can be obtained from the 1-D models. It is of key importance to identify the deformable interface for understanding the dynamic interactions between the gas/liquid two phases and the pipe bounding them with the coupling effects of the upstream pipeline and downstream riser. At the stage of developing new severe slugging method based on wavy pipe in the present work, the distribution of the gas/liquid two phases provides key information for understanding how the geometrical parameters and location of the wavy pipe affect the flow characteristics in the pipeline/riser system. CFD modelling plays an important role in the study of multiphase flow characteristics, because the details of the flow field in the two-dimensional (2-D) and three-dimensional (3-D) spaces can be presented (Taha and Cui, 2006; Zheng et al., 2007; Wang and Sun, 2010). A 3-D CFD model of a pipeline/riser system involves unacceptable amount of numerical computation due to the large scale of the system. Alternatively, 2-D model was adopted for simulating the gas–liquid two-phase flows in a pipeline/riser system by Xing and Yeung (2010). It has been demonstrated that the proposed 2-D model is able to predict the flow regimes and flow regime transitions correctly compared with the experimental data. Moreover, the 2-D model allowed a detailed description of the slug movement in the pipeline/riser system by tracking the gas/liquid interface. Therefore, in the present work a 2-D CFD model of the pipeline/wavy-pipe/riser system has been developed by adding a wavy pipe to the model of the pipeline/riser system.

2. Wavy pipe and experimental campaign

2.1. Wavy pipe

A wavy pipe is a pipe section constructed by connecting standard piping bends in series in one plane. The minimum unit of a wavy pipe is a piping bend, which can be described using three geometrical parameters, i.e. the internal diameter of the tube (d), the bend radius (R) and the bend angle (α) as shown in Fig. 1a. Different geometries can be created by joining several bends together in different manners. A wave-shaped pipe, wavy pipe, can be made by twisting each connection between two bends by 180°. As illustrated in Fig. 1b the wavy pipe can be described by three geometrical parameters: amplitude (A) which is the maximum distance between the bend centreline and the centreline of wavy pipe; pitch (P) which is the distance between the adjacent two peaks or dips; length (L) which is the distance between the central points of the two ends of wavy pipe.

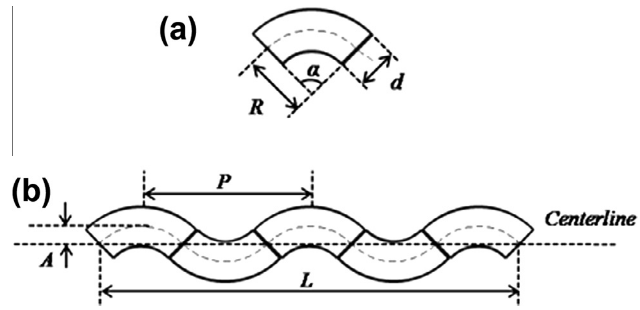

Fig. 1. Piping bend and wavy pipe (a) piping bend and (b) wavy pipe of 5 bends.

2.2. Experimental campaign

The experimental tests of wavy pipes on mitigating severe slugging were conducted on the three-phase test facility at Cranfield University (The schematic of the test facility is included in Electronic Annex.). The 4″ pipeline/riser system consists of a 55 m long pipeline with 2° downwardly inclined and a catenary-shaped riser with a vertical height of 10.5 m. The riser discharges the fluids into a vertical two-phase separator (1.2 m high and 0.5 m in diameter) where the fluids are separated into liquid and gas for metering purpose. The gas and liquid return to a three-phase separator. The pressure in the three-phase separator is controlled through the gas outlet valve. After separation in the three-phase separator the air is exhausted into atmosphere while the water enters its coalescer, where the liquid is cleaned before returning to the storage tank.

The superficial liquid (water) velocity (U_{SL}) ranged from 0.1 m/s to 1.0 m/s and superficial air velocity (U_{SG0}) at standard conditions (101325 Pa, 20 °C) was from 0.3 m/s to 3.0 m/s. The pressure in the three-phase separator was controlled as 1 barg in each test run. It needs to be mentioned that the superficial air velocity at the standard conditions (U_{SG0}) rather than at the local conditions of the pipeline/riser system have been used. Because U_{SG0} is not affected by the fluctuating pressure and is consistent with the constant mass flowrate at the inlet of the pipeline/riser system.

The flow regimes in the pipeline/riser systems have been classified into four categories (Xing et al., 2013b): severe slugging, transitional severe slugging, oscillation flow and continuous flow. They appear in sequence with the increase of the gas flowrate at a constant liquid flowrate. All of the severe slugging, transitional severe slugging and oscillation flow regimes exhibit cyclic flow behaviour. The slug of severe slugging is longer than the riser, while transitional severe slugging is characterised by the absence of the slug production stage of severe slugging and the slug length equal to the riser. For the oscillation flow more than one aerated slugs coexist in the riser separated by gas packets. No liquid slugs can be observed in the riser in the continuous flow.

3. CFD model development

The commercial codes, Gambit (Release 2.3) and Fluent (Release 6.3, 2006), were used to build the geometry/mesh and conduct the numerical computation of the CFD models, respectively. The solved equations of the CFD model are included in Electronic Annex.