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Review of Slug Detection, Modeling and Control Techniques for Offshore Oil & Gas Production Processes [⋆]

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Abstract: The current offshore oil & gas multi-phase production and transportation installations have big challenges related with the slugging flow: An unstable multi-phase flow regime where the flow rates, pressures and temperatures oscillate in the considered processes. Slug can be caused by different operating conditions and installation structures. The most severe slugs are often induced in long vertical risers or production wells, where liquid blocks gas at the riser/well base and correspondingly it causes the pressure to accumulate and hence originates the oscillating performance. There are many severe consequences to the production processes because of the slugging flow. This paper reviews some observed latest status and key challenges about slug detection, dynamical modeling and elimination of slugging flows. Mathematical modeling of slug has been used to investigate the slug mechanism and anti-slug control. Most of available models are based on mass-balance formulations, which often require sufficient data for reliable parameter tuning/identification. Slug elimination and control have been investigated for many years and there exist many solutions to eliminate the slug, but some of these methods can simultaneously reduce the oil & gas production, which is a very big concern as the production rate is the key evaluation parameter for offshore production. We conclude that the slugging flow is a well-defined phenomenon, even though this subject has been extensively investigated in the past decades, the cost-effective and optimal slug modeling and control are still open topics with many related challenges.

Keywords: Slugging flow, multi-phase, detection, modeling, anti-slug control, Offshore, oil & gas

1. INTRODUCTION

Slug is a common flow pattern in multiple-phase flow system, such as in the oil & gas upstream production process. The gas and liquid (water and oil) may not be evenly distributed throughout the production wells, transport pipelines and risers due to specific configuration and operating condition, such that the liquid and gas travel as a plugged train with a large plug of one phase medium followed by the other phase medium plug through the pipeline. As shown in Figure 1, these large plugs are often referred to as *slugs* (Schmidt et al. (1980); Taitel and Dukler (1976)). This type of irregular flows can result in very poor oil and water separation, reduced production capability, extra fatigue loads to installations and facilities, shortening device life-times, accelerating component corrosion, and even emergent shut-off of production (Aamo et al. (2004); Eikrem (2006); Hassanein and Fairhurst (1998); Havre and Dalsmo (2001); Di-Meglio et al. (2012a); Storkaas (2005); Taitel et al. (1990); Tengesdal et al. (2002)).

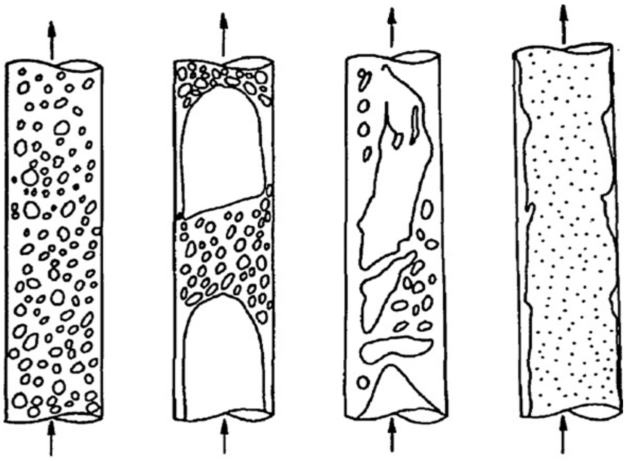

Fig. 1. Typical flow patterns in a vertical pipeline (from left to right): Bubble flow, slug flow, churn flow, and annual flow (Taitel et al. (1980))

Subject to specific operating condition and system configuration, the slugging flow can occur at many different geometric locations within the offshore upstream production process. As shown in Figure 2, a slugging flow could appear in the gas-lifting production wells due to a casing-heading mechanism (Eikrem (2006); Hu (2004)), a terrain slugging could occur in transportation pipelines due to

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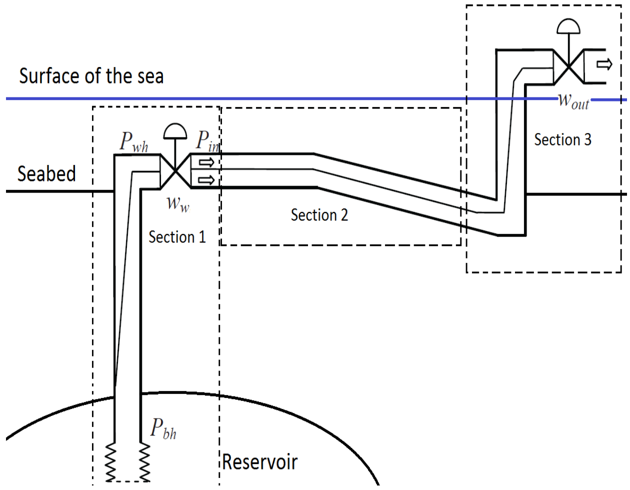

Fig. 2. A schematic illustration of a well-pipeline-riser system in the upstream offshore oil & gas production

the seafloor elevations (Jansen (1990); Ogazi (2011)), and a severe slug could appear at the riser part due to the significant gravity influence (Jahanshahi et al. (2013b); Di-Meglio et al. (2012a)). Some slugging flow could be simply induced due to some intermittent system/operational performances, such as pigging, start-up, blow-down, or changes of production references etc. (Sivertsen et al. (2010)).

This paper intends to give a brief review of the latest status and key techniques about slug detection, dynamical modeling and slug elimination for offshore oil & gas production processes. The rest of the paper is organized as: Section 2 focuses on discussion of different slug detection criteria; Section 3 introduces several typical slug dynamic models for the purpose of supporting anti-slug control design and analysis; Section 4 illustrates different slug elimination methods which are classified into passive and active approaches; Finally, we conclude the paper in Section 5 with the opinion that even though the slugging flow is a well defined concept and this subject has been extensively studied in several decades, the cost-effective and optimal slug modeling and control are still open topics with many related challenges.

2. SLUG DETECTION

The occurrence of slug can be determined according to relevant flow dynamic theory by checking the system configuration, parameters and operating conditions (Hamathy (1960); Taitel and Dukler (1976)).

2.1 Flow Pattern Map

As the slug is defined as a steady-state flow pattern, some flow pattern map as shown in Figure 3 can be experimentally obtained for all possible operating conditions (Taitel et al. (1980); Taitel (1986)). These flow patterns in Figure 3 correlate with superficial velocities of both liquid and gas phases. If there are more operational and manipulated variables/parameters, this type of flow map needs to be extended to cover all possible operating ranges. Correspondingly, the required experimental work and resource consumption could be extremely high and time-consuming.

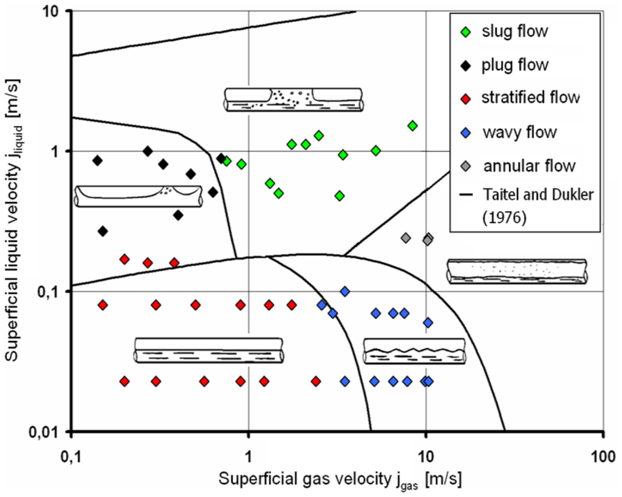

Fig. 3. A illustration of different flow patterns in a flow map (Taitel (1986))

2.2 Bøe Criterion

Slug flow can be estimated by using some simple criteria than an empirical flow map subject to some specific constraints. Such as, Taitel and Dukler (1976) gave a criterion for stratified flow in horizontal pipelines, and this criterion has been adopted in oil & gas industry in combination with the studies from Schmidt et al. (1980), which proved that the occurrence of stratified flow in a horizontal pipeline is a pre-condition for severe slug. Later on, an extension of this criterion is presented in Bøe (1981) for a pipeline-riser system, and it is now referred to as *Bøe Criterion* and it is described as:

$$U_L^S \geq \left[\frac{P_p}{\rho_L g(1-\epsilon_L)Lsin(\alpha)}\right] U_G^S, \qquad (1)$$

where U_L^S is the (pipeline) injected superficial velocity of liquid, U_G^S is the (pipeline) injected superficial velocity of gas, α is the inclination angle of the riser, ϵ_L is the ratio between the liquid and the combined gas and liquid in the riser, and P_p is the pressure at the riser base (bottom of the riser). The interpretation of this criterion is based on the observation (Schmidt et al. (1980)) that: *The rate of gas pressure accumulation at the riser base must be greater than that at the pipeline section, in order to have a severe slug to be formed in the riser.* However, the Bøe Criterion is based on the assumptions of constant inlet flow rates, a pressure balance over the riser as well as the gas mass balance in the pipeline.

As Bøe criterion assumes that if the liquid column is stable, a constant steady state should exist. However, some exceptions have been discovered in Taitel et al. (1990) with a fact that a tendency of a cyclic process still can exist even when the liquid column is stable. This work concluded that the Bøe criterion is good at differing from steady to cyclic flow with a few exceptions, especially with the cases of high liquid flow rates, where a predicted severe slugging region with Bøe Criterion can actually be stable. Jansen et al. (1996) further noticed that the Bøe Criterion is only valid when no slug elimination methods are applied.

2.3 Taitel Criterion

An alternative slug criterion is proposed by Taitel et al. (1990), which was an extension of the result from Taitel (1986). This *Taitel Criterion* sets up the correlation of the gas holdup pressure at the riser base and the riser (topside) back-pressure as:

$$\frac{P_s}{P_0} > \frac{\frac{\epsilon l + L}{\epsilon'} - h}{\frac{P_0}{\rho_L g \Phi}}, \tag{2}$$

where P_s is the back-pressure that the riser needs to overcome in order to generate the production flow, and it is often correlated with the downstream separator pressure located on the separation platform. P_0 is the atmospheric pressure, ρ_L is the (combined oil and water) liquid density, ϵ is the ratio of volume of the liquid over the volume of combined liquid and gas, ϵ' is the void fraction for a Taylor bubble that penetrates into the riser. A Taylor bubble (also called gas slug) is the large asymmetric bullet-shaped bubble within a gas-liquid multi-phase flow. The Taylor bubble can occupy almost the entire cross-section of the pipeline and has a length of several times of the pipeline diameter (Liao and Zhao (2003)). l is the pipeline length before the riser, h is the height of the riser, L is the length before the liquid and gas is being combined into two phase, g is the gravitational acceleration, and Φ is an index of local liquid holdup in the riser, and it can be calculated by $\Phi = 1 - \frac{u_{GS}}{u_t}$, where u_t is the Taylor bubble velocity, and u_{GS} is the gas superficial velocity. In Taitel et al. (1990) ϵ' is assumed to be a constant (0.9) in any vertical flow, and ϵ has only one value based on the separator pressure.

2.4 Jansen Criterion

An extension of Taitel Criterion was carried out in Jansen et al. (1996), considering that the gas from the artificial lifting is the only gas flowing through the riser. However, this criterion assumed a constant steady-state gas injection into the riser base. The *Jansen Criterion* can be expressed in the following:

$$\frac{P_s}{P_0} > \frac{\frac{\epsilon_{GR} L}{\epsilon'_G} - h_R}{\frac{P_0}{\epsilon_{GR} g \rho_L}}, \tag{3}$$

where $\epsilon_{GR} = 1 - \frac{U^S_{GR}}{U_{Bubble}}$ and $U_{Bubble} = C_0 U_s + U_D$. U_{Bubble} is the Taylor bubble's superficial velocity, U^S_{GR} is the superficial velocity of gas in the riser, and U_s is the combined superficial velocity of gas and liquid. Here C_0 is the drift parameter, and U_D is the bubble drift velocity. This study concluded that for complete Taylor bubbles these two parameter values are constant: $C_0 = 1.2$ and $U_D = 0.35$; For complete bubble flow these values are $C_0 = 1.0$ and U_D (Hamathy (1960)). Figure 4 shows the flow map comparison of the Bøe Criterion and the Jansen criterion. These experiments were committed with no slug elimination methods applied and only constant liquid and gas injection rates.

2.5 Other Criteria

Even though the Jansen Criterion is still widely used, other criteria have also been proposed and used for specific pipeline/riser constructions, such as Montgomery (2002) developed a criterion for S-shaped risers. Tchambak (2004) presented a prediction criterion which also focused on S-shaped risers, but with three different gas injection locations: the gas injection at the pipeline inlet, the downstream, and the upstream of the riser base.

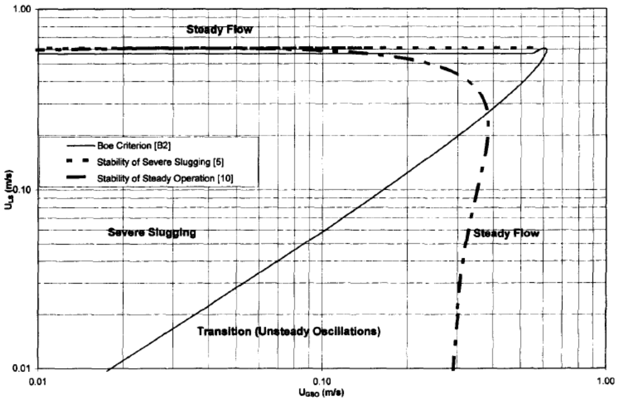

Fig. 4. Flow map comparison of Bøe Criterion and other criteria (Jansen et al. (1996))

2.6 Slug Detection Methods

All the above mentioned slug criteria can provide some guidelines for real-life applications, such as providing parameter limitations for physical system/process design, committing condition monitoring for operations, as well as supporting anti-slug control design and analysis (Yang et al. (2013, 2014)). Of course, the applicability of any criterion depends on (i) whether the corresponding criterion's assumptions are fully valid; (ii) the evaluation variable/parameters are available or measurable. We observed that almost all slug criteria require either the pressure information at the riser base, which unfortunately is not available (no installed transmitters at all) in most real-life offshore constructions, or the liquid and gas injection information as well as very detailed physical construction description. An alternative approach for slug detection is to purely use measured data and conduct some signal processing analysis on it. For instance, the riser topside pressure and its changing rate are employed in our previous work (Pedersen et al. (2014a)) to detect whether a severe slug is happening or not based on a lab facility developed by Jepsen et al. (2013), so that a supervisor will decide switches between an anti-slug controller and a production controller.

In practice, the alignment of these theoretical oriented criteria with real-time data analysis can lead to more reliable and accurate slug detection. Besides that, where in the considered system/process to install what type of transmitter(s) to collect slug-relevant signals, as well as how to efficiently and reliably process the obtained data, turn to be also very important issues as well. Sometimes, some model-based estimation approaches may also need to be coordinated in order to retrieve unavailable key slug-relevant parameters (Helgesen (2010),Sivertsen and Skogestad (2005)).

3. SLUG MODELING

Modeling multi-phase flow dynamics in a process is always a challenging and active topic. Hereby we do not focus on sophisticated CFD-based modeling approaches, with respect to fact that we are interested in reviewing some dynamic models which can be potentially employed for the purpose of anti-slugging control design and analysis.

3.1 Early-Stage models

Taitel et al. (1980) is one of the early studies to describe the transition relationships among flow patterns for two-phase gas and liquid flows in vertical pipelines. The achieved models mainly focus however, on the steady-state flows. A similar study was observed in Viggiani et al. (1988). Sarica and Shoham (1991) presented a dynamic model for pipeline-riser systems based on a 1-D gravity-dominant flow in both the pipeline and riser. The experimental verification showed that this model can satisfyingly predict pipeline pressure transients, liquid accumulation, slug length, and cycle time for all flow conditions tested. The detailed physical size and dimensions of the considered system are required using this model, and it is also noticed that the pipeline inclination angle is a very sensitive parameter. This model was compared to a model developed by Jansen (1990). It is concluded that this model developed in Sarica and Shoham (1991) can successfully predict severe slug outside the Bøe (1981) region. However, when non-slugging flow occurs, this model does not converge to the same validated model from Jansen (1990).

3.2 Mass-Balance Models

Storkaas et al. (2003) presented an ODE model for severe slugging in a pipeline-riser based on mass balance equations with 3 states:

$$\begin{aligned} \dot{m}_L &= w_{L,in} - w_{L,out} \\ \dot{m}_{G1} &= w_{G,in} - w_{G1} \\ \dot{m}_{G2} &= w_{G1} - w_{G,out} \end{aligned} \tag{4}$$

along with an algebraic model of the choke valve locating at the topside of the riser. The developed model was compared with OLGA simulation and tested at a scaled medium-sized testing facility. Both results showed good consistencies of the models and data. Several slug elimination controllers were designed based on this model (Sivertsen and Skogestad (2005),Storkaas (2005)).

An improved model of (Storkaas et al. (2003)) with 4 states for a pipeline-riser facility is proposed in Jahanshahi and Skogestad (2011). The considered system is divided into two subsystems: one describing the horizontal pipeline, and the other one describing the vertical riser. Each subsystem are modeled with two mass equations (gas and liquid). Similar 3-state or 4-state models can also be found in Eikrem (2006, 2008); Kaasa and V. Alstad (2008); Di-Meglio et al. (2009); Silva and Nydal (2010).

It has been noticed that no matter which model formulation people intend to use, there are always a number of (model) tuning parameters need to be handled. For example, Kaasa and V. Alstad (2008) with 7, and Di-Meglio et al. (2009) with 5, both Eikrem (2008) and Silva and Nydal (2010) with 3. This indicates that it can be hard or time-consuming to make a relevant model fit to the real data. Some tradeoff between model precision and complexity needs to be managed. It is also noticed that a 6-state model is proposed in Jahanshahi (2013) for considering a well-pipeline-riser system. This model however requests the average mass ratio of gas and liquid to the well from reservoir known, and this can be an open issue since this information is hardly available in reality. We noticed that the model developed and used in Di-Meglio et al. (2009, 2012b) is based on a virtual valve model locating at the bottom of the riser, thereby this model does not depend much on the physical appearance as the model proposed by Jahanshahi and Skogestad (2011) does. Consequently the Di-Meglio model can be easily adapted to handle both pipeline-riser and (gas-lifting) well facilities. Our previous Biltoft et al. (2013) used Di-Meglio model and described the model tuning and Pedersen et al. (2014a) designed a hybrid switching controller on top of the tuned model.

3.3 PDE-Based Models

For other types of relevant models, we would mention that Sinègre et al. (2006) developed a PDE model to predict slugs in gas-lifting wells where the stability analysis was performed through small gain theorem. Di-Meglio et al. (2011) proposed a low-dimensional PDE model which comprises the gas mass fraction, the pressure, and gas velocity as states. Compared with numerical simulations the model proves to be accurate according to oscillation frequencies and shapes. Another PDE model was developed by Nemoto and Baliño (2012), which is based on two switchable states: One indicates the status where the gas is able to penetrate into the riser (steady flow), and the other state in which there is a liquid accumulation preventing the gas from penetrating into the riser (severe slugging). The model considers the liquid penetration length and the liquid height in the riser, thus the model can distinguish different sizes of slugs.

3.4 Challenges with Slug Models

The main issue of slug modeling is that most models are based on mass-balance principle, thus the liquids and gasses injected into the system have to be known, which is often not the case in reality. For this reason several studies have focused on developing observers to estimate flow rates. For instance, Grimstad and Foss (2014) developed an adaptive extension to the observer developed by Aamo et al. (2004) which estimates the well flow rate and downhole pressure from topside measurements on gas-lift wells. However, this adaptive observer only works with a slowly varying reservoir pressure. Mansoori et al. (2014) studied different transients of the bottom-hole pressure in the well using system identification techniques to estimate a reservoir model. Another issue arises as the well-pipeline-riser models heavily depend on the initial conditions of the masses of all phases in the pipelines, which also can be hard to estimate (Jepsen et al. (2013); Pedersen et al. (2014b)).

Not all wells/risers are limited by few measurements. Some new ones have more transmitters and actuators integrated, and they are commonly referred to as "Smart wells/risers" or "Intelligent wells/risers" (Johal and Cousins (1999)). Within these smart wells, the downhole transmitters can monitor the well and reservoir conditions, and some of them even equipped with control valves to control the inflow of fluids from the reservoir to the well. Johal and Cousins (1999) patented an intelligent riser for deep-water oil & gas fields where gas-lifting, slug catching, and measurements are combined into one big riser system. These Smart wells are also being used to improve the performance of artificial reservoir flooding, generally water-flooding (van Essen et al. (2006, 2009); Zandvliet et al. (2006)). As the industry now is considering more advanced model-based control methods to the water-flooding technique, some focus has been put into the integration of reservoir modeling and slug modeling (Doren et al. (2011)).

4. SLUG CONTROL

Due to it negative influences, the slug flow, especially a severe slug, is not expected in any normal operation. Thereby slug elimination, or we call *slug control* in the following, need to be carefully dealt. In the following, from the control engineering point of view, we classify most methods/approaches into two categories:

- *Passive approaches*: The slug elimination is conducted by some proper and dedicated system/process design, instead of using feedback control strategy; and
- *Active approaches*: The slug elimination is realized by some automatic feedback control strategy based on a given system/process.

In some cases, some feedback control strategy is applied along with some dedicated change in the system/process. To avoid confusion, we put them into the active approach category.

4.1 Passive Slug Control

Elimination of severe riser slug by creating a change in the process has been investigated for a long time. Early studies, such as Yocum (1973), identified several different solutions for process changes, which still are being used in practice today to handle the slug. These solutions can be categorized into three groups:

(1) Reducing the incoming line diameter near the riser to establish a stable flow regime;
(2) Using dual multiple risers, instead of a single riser;
(3) Using fluid remix device, which purposely mixes fluids at the riser base to avoid liquid accumulation, hence to prevent a stratified flow to progress into a severe slugging.

These three kinds of solutions form the fundamental basis for all passive slug control methods explained in the following.

Flow conditioners A flow conditioner is referred to a specific device that is installed in the pipeline with the objective to affect the original flow regime. A typical example of this is a *Wavy Pipe* developed by Xing et al. (2013) at Cranfield University (UK). A 7-bend Wavy Pipe is illustrated in Figure 5 and it is placed close to the riser base. The basic idea here is to artificially introduce a number of small slugs through the wavy pipe, so that a severe riser slug can be avoided due to the fact that the movement of the gas in the pipeline to the riser base is accelerated compared with the liquid accumulation. Another type of flow conditioner using a helix-shaped pipeline is reported in Adedigba (2007) and it is illustrated in Figure 5 as well.

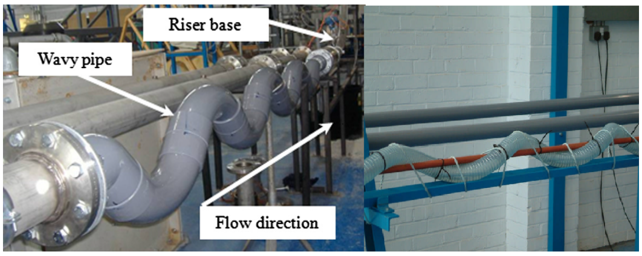

Fig. 5. Two different flow conditioners: Wavy Pipe (left) and Helix Pipe (right) developed at Cranfield University (Xing et al. (2013); Adedigba (2007))

A venturi-shaped device is patented by Almeida and Gonçalves (1999) as one type of flow conditioner, which consists of a convergent nozzle section followed by a divergent diffuser section. This device is supposed to be located as part of the horizontal pipeline near to the riser base. Venturi-shaped devices can give a pressure drop causing a mixing effect and converting the stratified flow to a non-stratified flow temporarily. A similar functional flow conditioner can be found in Makogan (2007). It should be noticed that the flow conditioner approach is similar as the permanent choking approach proposed by Jansen et al. (1996), thereby they both may have a payoff with a reduced production rate (Ogazi et al. (2009); Pedersen et al. (2014a)).

Slug Catchers Using a slug catcher after the riser or topside of well is the most commonly used passive slug elimination approach in the actual production systems. The slug catchers can be classified as *vessel-type, finger-type and parking-loop* according to their different configurations. However, it should be aware that this type of approach is very effective but with a big price (McGuiness and Cooke (1993)).

Other Alternatives Hassanein and Fairhurst (1998) presented a method to avoid slug formation by attenuating the non-homogeneous liquid and gas into one homogeneous fluid. The idea was to reduce the surface tension of the fluid by injecting a surfactant which could change the fluid into foam, hence making the fluid homogeneous. However, this approach will definitely increase the difficulty of separation at the downstream separation process, thereby ultimately affect the product quality and capability. A self-gas lifting approach is proposed in Sarica and Tengesdal (2000). The basic idea is to reduce the static head (weight of liquid) in the riser by an extra pipeline to pass the gas directly into the riser (bypassing the riser base). Tengesdal et al. (2002) investigated the possibility of compressing gas in the pipeline and then separating it from liquid at the upstream of the riser base.

4.2 Active Slug Control

Active slug elimination approach involves some automatic feedback control mechanism, which manipulates some actuators, which installed in the process system, subject to some sensor feedback signals. These signals can be from pressure, temperature and/or flow transmitters, depending on which specific system is studied. The selections of actuators and sensors can be guided by some fundamental system property analysis, e.g., following the *input-output controllability analysis* (Jahanshahi et al. (2012); Skogestad and Postlethwaite (2005)).

Choke Valve Control Choking some controllable valve(s) in a considered process is the most investigated active slug elimination approach. The anti-slug control using the (riser) topside choke valve has been studied for many years, and typical work can be found in Havre and Dalsmo (2001); Di-Meglio et al. (2012a); Storkaas and Skogestad (2008); Jahanshahi et al. (2012). Ogazi (2011) also considered the control valve located at the separator gas outlet as an alternative anti-slug control actuator. Eikrem et al. (2004); Jahanshahi et al. (2013a); Scibilia et al. (2008) focused on the estimation of the seabed/downhole pressure from a topside pressure transmitter for the purpose of regulating the topside choke valve. Ogazi et al. (2009) also investigated the possibility of using large valve openings to maximize the oil production rate while also eliminating the slug. Enricone Stasiak et al. (2012) also developed a topside control design for minimized either the flow or pressure oscillations while keeping the choke valve opening higher than the opening which characterizes the beginning of the limit cycle. Pedersen et al. (2014a) developed a self-learning controller which consists of a supervisor and two baseline PID controllers, in order to automatically find out the best (choke valve's) operating position with the maximal production rate subject to no-slug. Sinègre and Petit (2006) proved that the density-wave instability in gas-lifted wells, which is different from the casing-heading phenomenon (Sinègre et al. (2005)), can also be controlled by manipulating the choke valve only based on the well head pressure measurement. Most of practical anti-slug control structures are PID types, thereby how to effectively tune these controllers have been focused, such as Godhavn et al. (2005) proposed three PI tuning methods for eliminating slug. Jahanshahi et al. (2014) developed a new IMC-PIDF controller as an extension to the tuning methods proposed by Godhavn et al. (2005).

Gas-Lifting Control It has been proved that using artificial gas-lifting is also an effective approach in elimination severe slugs (Asheim (1988); Plucenio et al. (2012)), through a huge amount of gas might be needed to generate an actual effect on the flow pattern. Hu (2004) mentioned two methods to obtain stable flow in the production well, i.e., using the gas-lifting approach and using the water-flooding to increase reservoir pressure. Krima et al. (2012) developed several PI controller design strategies for the gas-lifting focusing on mitigating hydrodynamic slug in OLGA simulations. It is concluded that a good control design for the topside control choke valve can reduce the required amount of injection gas, and thus a combined MIMO control design for gas lifting and topside choke valve can be a more optimal solution.

MIMO Slug Control The two most available actuators are the topside choke valve and the external gas lifting. They have the possibility of being combined in a MIMO or MISO control system problem. For the well case, Pagano et al. (2008) developed a model-free PI-controller where the injection valve of the gas-lifting is controlled to stabilize the gas flow injected into the production tube, meanwhile the topside choke valve is used to stabilize the topside pressure. Abardeh (2013) investigated anti-slug control in S-shaped risers, where a robust control solution was proposed using the topside choke valve and artificial gas-lifting. Jahanshahi et al. (2013b) used feedback linearization to design a nonlinear model-based control for a pipeline-riser system using both the riser-base pressure and the topside pressure. Nevertheless, the stability of the concerned system needs to be guaranteed (Asheim (1988)).

Slug Compression A slug compression system is reported in Kovalev (2003). This solution is a combination of process change and active feedback control of choke valves. A topside mini-separator is installed to separate the liquid from the gas upstream the first stage separator. Between the two separators there are two choke valves: One for the gas pipeline and one for the liquid pipeline. This way the liquid injection into the first stage separator is controlled to stabilize the height of the liquid, while the gas injection is used to compensate for the possible slugging. This is an advantage as the gas pipe is much easier to control when no liquid is in. This slug suppression system was implemented and experimentally verified that this solution can successfully eliminate all types of slug and improve the production rate of both oil and gas as well. However, the investment for extra equipment as well as the corresponding extra maintenance will lead to the increase of costs for running production.

5. CONCLUSIONS

This paper examines the historical and current status and some key techniques related with the slugging flow in offshore oil & gas production processes, specially focusing on the riser-induced slug occurring in production wells or pipeline-riser installations.

For detection and modeling of the slug flow, if all operating conditions and physical structure and parameters of considered well-pipeline-riser systems are known or measurable, the corresponding slug criteria or dynamic models can provide precise slug detection and prediction. However in many practical cases, these detail information is very limited.

Some key slug elimination approaches have been analyzed and they are classified into passive and active slug control categories. The two most popular active slug control approaches are feedback control of a riser/well topside choke valve and feedback control of artificial gas-lifting in a riser/well. Two main objectives of slug control are (i) eliminating the (severe) slugging flow; meanwhile (ii) optimizing the production rates. Model-free (developed) controllers have proven to be effective as well as they are data driven and hence only depending on relevant measurements. However, besides requiring *ad hoc* parameter tunings, the model-free developed solutions often face to the time-delay challenge due to the fact that the slug has to occur before any feedback controller can react, while the model-based control solution can enjoy the big advantage of slug prediction.

Through different slugging mechanisms, modeling approaches and anti-slug control have been extensively investigated over several decades by both academic and industrial societies, these topics are still quite open with many related challenges.

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