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Research on slug flow model of subsea tieback production network for control

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Abstract

Subsea tie-back network production faces many challenges. In order to better simulate the flow conditions of the tie-back network and further provide a suitable simulation method for the subsea slug flow, we propose a new slug flow state model, which is suitable for controlling the slug flow using the top valve. The model uses ODE equations to describe the system, and the simulation results are compared with the typical multiphase flow transient simulation software OLGA. The comparison between the new model and the OLGA model shows that the stability margin is 0~5%. When the top valve opening is 4%, the final stable value of the two models is basically the same. When the top valve opening is 12%, the two models both show that the system is unstable, and the pressure oscillation period of the two is basically the same. The new model can meet the needs of system description, and it has a faster calculation speed, and is more suitable for on-site real-time control.

Keywords

Oil and gas production; Throttle control; ODE model; subsea tie-back; Slug control.

1. Introduction

The underwater production system (SPS) combined with the floating oil storage unit (FPSO) is currently the commonly used offshore oil and gas development mode. The general development mode of the new well in the later period is that the crude oil produced by the underwater Christmas tree or the wellhead is returned to the development platform through the pipeline [1]. Its short construction period makes it widely used in offshore oil and gas development. In the actual development process, oil and gas transportation is the engineering difficulty. Slugs are often a serious problem during transportation [2]. For the control of severe slug flow, researchers have proposed solutions based on top throttle control, gas lift, and slug trapping [3, 4]. Due to the particularity of offshore oil and gas development, the main scheme currently adopted is mainly slug control based on the top throttle valve [5]. However, the slug description model used for the loopback network is relatively scarce.

Since the 1970s, Taitel [6], Xiao J [7] and others began to study the characteristics of slugs based on experiments, mainly analyzing the length and frequency of slugs. After that, researchers began to propose some transient models describing slugs, and these models gradually developed into commercial software for multi-stream simulation, such as OLGA [8]. At this time, the model mostly constructed numerical simulations based on the conservation of momentum and other equations. But it is often too complicated to be used for slug control.

Since this century, researchers have begun to study simplified models for control, and Balio et al. [9] proposed models for pipeline risers. This model is mainly used for theoretical research, and there is still a gap in its calculation speed in practical applications. In recent years, researchers hope to obtain a relatively simple and fast calculation method for slug flow. Researchers began to propose the use of mass conservation to derive the pipeline flow state, and Jahanshahi et al. [10, 11] proposed a pipeline flow model. Based on the model, it has

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successively conducted controllability analysis and control research. Studies have proved that it is feasible to use submarine pipeline pressure to control the riser system [12, 13]. Zhou Hongliang [14] proposed simplified pipeline equation to simulate pipeline flow and verified it, which further promoted the application of ODE equation in slug control. Compared with the earlier model, the newly proposed model has extensive control significance.

The above-mentioned research is limited to a section of pipeline, without considering the mutual influence of the transmission network. In this study, the flow characteristics of the loopback network will be derived. The entire tie-back pipeline is divided into four parts: well-manifold-subsea pipeline-riser, a reasonable simplified model, a feasible calculation method for slug flow state, and verification of the method

2. Tie-back network model

The form of the tie-back network varies according to the actual working conditions. This article will take the two wells and tie-back to the offshore platform as an example to derive the flow state simulation model of the tie-back network. To highlight the research focus of this article, other components in the well and the development process are ignored, Only model the flow process in the system. Specifically, the system can be simplified as shown in Figure 1. The system consists of two wells and a long pipeline, ignoring the pipeline distance between the Christmas tree and the manifold. The long pipeline includes a section of down-dipping pipeline to simulate the influence of pipeline topography on flow conditions.

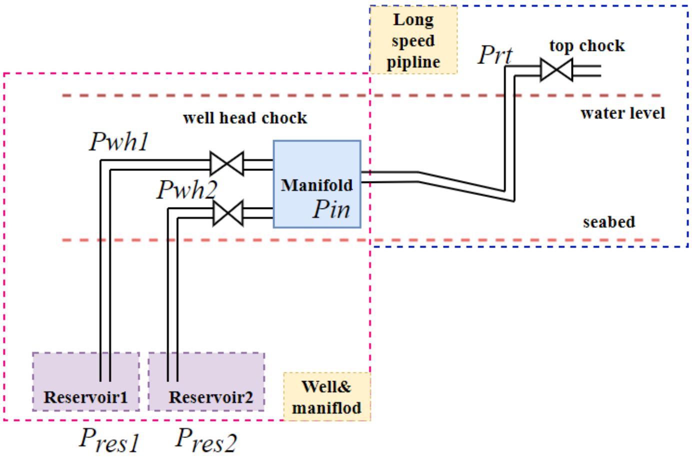

Fig. 1 Simplified model for two well tie-back network

For control, the complex phase transition in the slug process is not the focus of this study. This article will use the method of mass conservation to establish the corresponding state estimation equation. In the model building process, the gas is assumed to be an incompressible ideal gas, and the phase transition between gas and liquid is ignored.

2.1. Dynamic system description

In this study, the following eight state equations are established according to the conservation of mass;

$$\dot{m}_{gw1} = w_{g,wb1} - w_{g,wh1} \tag{1}$$

$$\dot{m}_{lw1} = w_{l,wb1} - w_{l,wh1} \tag{2}$$

$$\dot{m}_{gw2} = w_{g,wb2} - w_{g,wh2} \tag{3}$$

$$\dot{m}_{lw2} = w_{l,wb2} - w_{l,wh2} \tag{4}$$

$$\dot{m}_{G1} = w_{G,in} - w_{G,lp} \tag{5}$$

$$\dot{m}_{L1} = w_{L,in} - w_{L,lp} \tag{6}$$

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$$\dot{m}_{G2}=w_{G,lp}-w_{G,out} \tag{7}$$

$$\dot{m}_{L2}=w_{L,lp}-w_{L,out} \tag{8}$$

Among them, m_{G1} is the gas quality of the submarine pipeline, m_{L1} is the liquid quality of the submarine pipeline, m_{G2} is the gas quality in the riser, m_{L2} is the liquid quality in the riser; m_{gw1}, m_{gw2} are the pipeline gas quality of well 1 and well 2, mlw1 and m_{lw2} are wells respectively 1 and Well 2 Liquid quality in the pipeline。

The whole system state can be described by variable x:

$$x=[m_{gw1},m_{lw1},m_{gw2},m_{lw2},m_{G1},m_{L1},m_{G2},m_{L2}] \tag{9}$$

2.2. Well and collection system

Since the object of this article is the simulation of the dynamic flow between the wellhead and the manifold, there is no need to consider the complex interaction in the well. This article will simplify the model according to the actual situation. In the process of model building, it is assumed that the gas is not compressible. The model retains the following key parts:

1) Reservoir flow;

2) Flow in the well;

3) Valve flow;

4) Pipeline collection after the throttle valve;

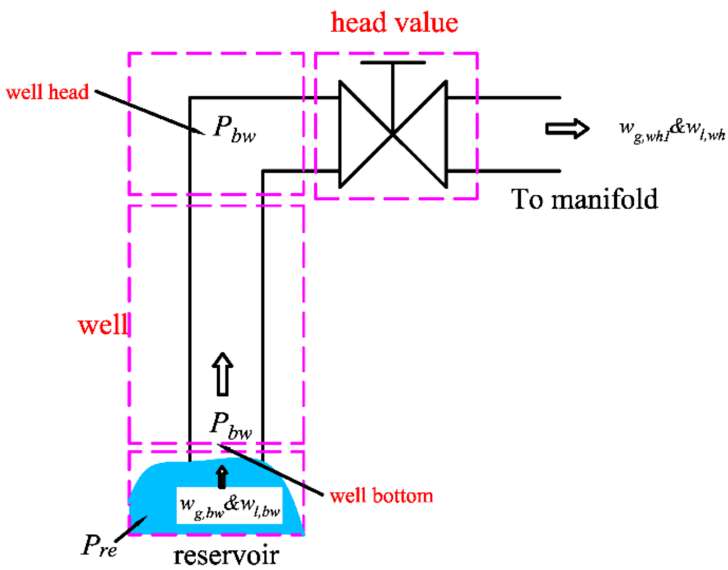

Fig. 2 Simplified model for well and manifold

Let's derive with well 1 below.

2.2.1. Reservoir to the bottom of the well

Liquid flow from the reservoir into the well:

$$w_{l,wb1}=PI(P_{res1}-P_{wb1}) \tag{10}$$

Gas flow:

$$w_{g,\ wb1}=\mathrm{GLR1}\times w_{l,wb1} \tag{11}$$

Where PI is the bottom hole production coefficient; GLR1 is the gas-liquid mass ratio of the reservoir.

2.2.2. Flow in the well

The inflow from the reservoir can be expressed as:

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$$\begin{aligned} w_{l,wb1} &= w_{o,wb1} + w_{w,wb1} \\ w_{g,wb1} &= \frac{m_{gw1}}{m_{gw1} + m_{lw1}} w_{c,wb1} \\ w_{l,wb1} &= \frac{m_{lw1}}{m_{gw1} + m_{lw1}} w_{c,wb1} \end{aligned} \tag{12}$$

m_{gw1}， m_{lw2} is the cumulative mass in the well, which is gas and liquid in the well。

Pressure conduction：

$$P_{bh1} = P_{wh1} + \bar{\rho}_{m,w1} g L_{w1} + \Delta P_{fw1} \tag{13}$$

Volume average density

$$\bar{\rho}_{m,w1} = \frac{m_{gw1} + m_{lw1}}{V_w} \tag{14}$$

$$\Delta P_{fw} = \frac{\bar{\alpha}_{l,w} \lambda_{w1} \bar{\rho}_l \bar{U}_{sl,w}^2 L_{w1}}{2D_{w1}} \tag{15}$$

The liquid volume fraction can be calculated by the following formula：

$$\bar{\alpha}_{l,w1} = \frac{m_{l,w1}}{V_{w1} \rho_{l1}} \tag{16}$$

2.2.3. Value

For wellhead throttling, a simple but widely used valve equation is used. However, it should be pointed out that there are many potential problems that are not taken into account in this valve model-for example: the cooling of the throttle, the critical flow and the turbulence of the gas downstream of the valve.

$$w_{c,wh1} = C_{k1} \sqrt{\rho_{m,w1} (P_{wh1} - P_{man})} u_1 \ (P_{wh1} \geq P_{man}) \tag{17}$$

$$P_{wh1} = \frac{RT_{w1}}{M} \frac{m_{gw1}}{L_t A_t - \nu_l m_{lw1}} 10^{-5} \tag{18}$$

P_{man} Manifold pressure, in this article is equivalent to the inlet pressure of the long pipeline P_1；υ_l Liquid volume ratio； R Gas constant； T_{W1} Inlet temperature； u_1 Wellhead valve opening

2.2.4. Collection

$$\begin{aligned} w_{g,in} &= \sum_{i=1}^{n} w_{g,wh,i} \\ w_{l,in} &= \sum_{i=1}^{n} w_{l,wh,i} \end{aligned} \tag{19}$$

2.3. Piping system

The long pipeline model can be simplified as the following structure. The pipeline can be simplified as the inlet, the pipe, the submarine pipeline and the outlet.

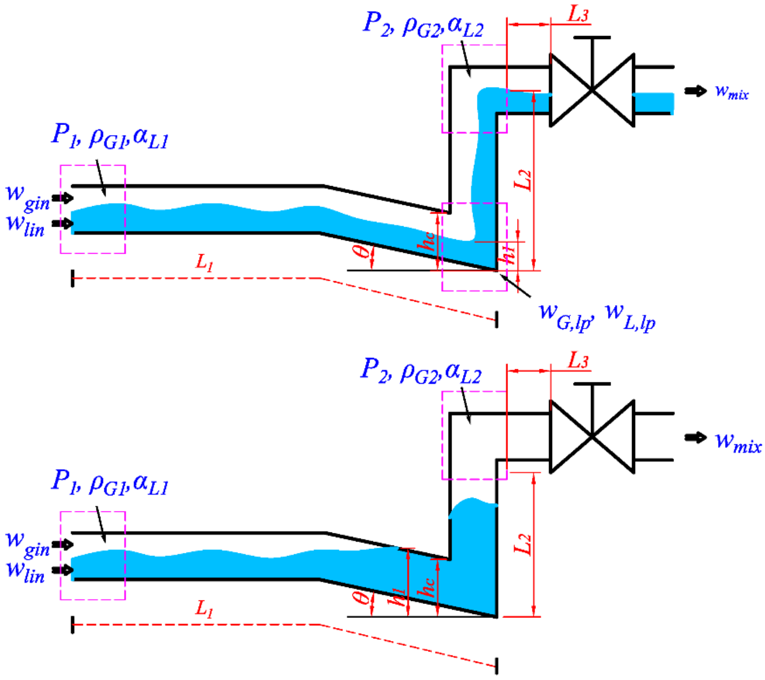

Fig. 3 Simplified model for subsea pipeline and riser pipeline

2.3.1. Entrance boundary condition

The inlet boundary flow rate of the long-distance pipeline often changes. According to the mass fraction and density of the liquid flowing into the two phases, the mass volume fraction of the liquid in the pipeline can be obtained;

$$\alpha_L = \frac{\alpha_{Lm}/\rho_L}{\alpha_{Lm}/\rho_L + (1-\alpha_{Lm})/\rho_G} \tag{20}$$

The average liquid mass fraction in the pipeline section can be estimated by the inlet flow rate, and the average liquid volume fraction in the pipeline can be obtained by combining the above formula:

$$\bar{\alpha}_{L1} \cong \frac{\bar{\rho}_{G1} w_{L,in}}{\bar{\rho}_{G1} w_{L,in} + \rho_L w_{G,in}} \tag{21}$$

2.3.2. Export boundary conditions

After the long pipeline reaches the offshore platform, its external boundary pressure is constant (separator pressure). In this paper, the constant pressure condition and the throttle valve model are used as the boundary conditions of the pipeline outlet, namely:

$$w_{mix,\text{out}} = C_{k3} f(z) \sqrt{\rho_t (P_2 - P_0)} \tag{22}$$

Liquid mass fraction of outlet throttle:

$$w_{G,\text{out}} = (1-\alpha_{Lm,t}) w_{\text{mix,out}} \tag{23}$$

$$\alpha_{Lm,t} = \frac{\alpha_{L,t}\rho_L}{\alpha_{L,t}\rho_L + (1-\alpha_{L,t})\rho_{G2}} \tag{24}$$

Density of the two-phase mixture at the top of the riser:

$$\rho_t = \alpha_{L,t}\rho_L + (1-\alpha_{L,t})\rho_{G2} \tag{25}$$

In the above formula, $\alpha_{L,t}$ is the liquid volume fraction at the top of the riser. In the vertical direction, gravity will dominate the pressure and liquid volume fraction changes in the two-phase flow pipeline. For a steady flow, the pressure and liquid volume fraction changes are approximately linear. It can be assumed that the pressure gradient along the riser is constant. The liquid volume fraction maintains an approximately constant gradient along the riser.

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2.3.3. Pipeline model

In the pipeline, the gas and liquid are often unevenly distributed. In this case, the quality of the liquid in the pipeline is, and the lowest point of the pipeline liquid level at the bottom of the riser can be defined as: $\bar{h}_1 = K_h h_c \bar{\alpha}_{L1}$。 If the quality of the liquid in the pipe increases, the liquid level at the bottom of the riser will also chang.

$$h_1 = K_h h_c \bar{\alpha}_{L1} + \left(\frac{m_{L1} - \rho_L V_1 \bar{\alpha}_{L1}}{\pi r_1^2 (1 - \bar{\alpha}_{L1}) \rho_L}\right) \sin(\theta) \tag{26}$$

Pipe inlet pressure:

$$P_1 = \frac{m_{G1} R T_1}{(V_1 - m_{L1}/\rho_l) M_G} \tag{27}$$

For the pressure loss caused by friction in the pipeline, this article only considers the friction of the liquid, which is:

$$\Delta P_{fp} = \frac{\bar{\alpha}_{L1} \lambda_p \rho_L \bar{U}_{sl,in}^2 L_1}{4 r_1} \tag{28}$$

2.3.4. riser model

According to the ideal gas equation, the pressure at the top of the riser can be expressed as :

$$P_2 = \frac{m_{G1} R T_2}{(V_1 - m_{L2}/\rho_2) M_G} \tag{29}$$

Pressure loss in riser:

$$\Delta P_{fr} = \frac{m_{L2}(m_{G2} + m_{L2}) \lambda_r \bar{U}_m^2 (L_2 + L_3)}{4 V_2^2 \rho_l r_2} \tag{30}$$

2.3.5. Gas flow model at the bottom of the riser

As shown in Figure 4, when the height of the liquid at the bottom of the riser exceeds the critical level (h1>hc), a slug will occur at the bottom of the riser, and the gas flow rate at this time is 0, that is:

$$w_{G,lp} = 0, \quad h_1 \geq h_c \tag{31}$$

$$w_{G,lp} = K_G A_G \sqrt{\rho_{G1} \Delta P_G}, \quad h_1 < h_c \tag{32}$$

Pressure conduction

$$\Delta P_G = P_1 - \Delta P_{fp} - P_2 - \bar{\rho}_m g L_2 - \Delta P_{fr} \tag{33}$$

2.3.6. Liquid flow model at the bottom of the riser

The liquid at the bottom of the riser and the gas at the bottom of the riser are described by a similar equation, and the flow equation is:

$$w_{L,lp} = K_L A_L \sqrt{\rho_L \Delta P_L} \tag{34}$$

Among them:

$$\Delta P_L = P_1 - \Delta P_{fp} + \rho_L g h_1 - P_2 - \bar{\rho}_m g L_2 - \Delta P_{fr} \tag{35}$$

$$A_G \cong \pi r_1^2 \left(\frac{h_c - h_1}{h_c}\right)^2, \quad h_1 < h_c \tag{36}$$

$$A_L = \pi r_1^2 - A_G \tag{37}$$

3. OLGA model

The dynamic two-fluid model has been widely used in the simulation of two-phase flow systems. At present, this method has been developed into a variety of commercial software, among which Schlumberger provides multi-phase flow dynamic simulation software which is widely used [8].

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OLGA does not simulate the entire process of slug formation, but its complex two-fluid model takes into account the effects of backflow and droplets [14], and its simulation of slug flow is relatively accurate. This article will use OLGA to verify the model proposed in this article. The structure of OLGA is as follows:

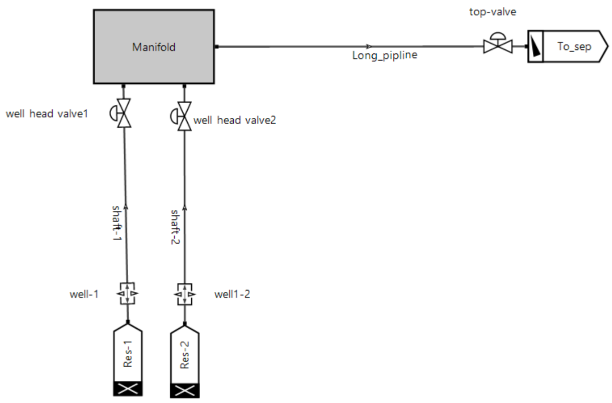

Fig. 4 OLGA model for subsea tie-back

In actual use, OLGA only needs to point out the boundary conditions, and its higher calculation accuracy has a higher degree of recognition in the industry. In this model, it is assumed that the reservoir pressure is stable, and the fluid in the pipeline is established using the black oil model provided by the OLGA component Mutiflash.

4. Simulation verification

This paper uses ode15s provided by matlab as a solution tool to solve the established model.

At the same time, the same conditions were used to establish the OLGA model. The system structure is similar to the simplified structure of the tie-back network. The initial parameters of the well are as follows:

Tab. 1 Model initial parameter

parameter	value
P_{res1}	32MPa
P_{res2}	33MPa
PI_1	2.7e-6kg/(s·Pa)
PI2	2.7e-6kg/(s·Pa)
P_{sep}	5 MPa
L_{well1}	3000m
L_{well2}	3000m
GLR_1	0.042
GLR_2	0.045
D_{w1}	0.12m
D_{w2}	0.12m
wc_1&wc_2	0.17
ρ_{l1}&ρ_{l2}	832.2kg/m^3
C_{k1}	3.3×10^{-3}
C_{k2}	3.3×10^{-3}
C_{k3}	1.16×10^{-3}
Mg	18gr

μ	$1.426\times10^{-4}Pa\cdot s$
k_1	0.6
k_2	0.6

The long-distance pipeline submarine pipeline has a length of 5000m and a pipe diameter of 0.12m, including a 2000m horizontal pipeline and a 3000m down-dip pipeline. The riser has a length of 300m and a pipe diameter of 0.1m. There is a 100m horizontal pipeline on the upper part of the riser. The elevation map is shown below:

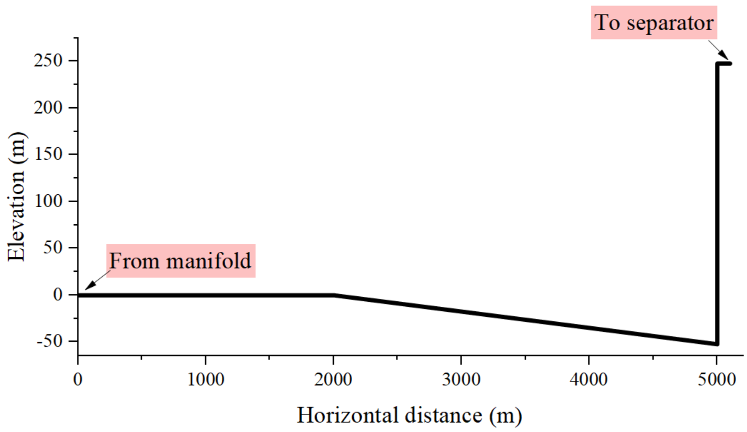

Fig. 5 Elevation of long pipline

For a slug model controlled by a top valve, the most critical need is to match the stability margin (critical valve opening), open-loop oscillation frequency and oscillation range [10]. The details of the slug are not the focus of this model.。

4.1. Model stability margin and extreme value

When the system slugs, the outlet pressure of the manifold, the pressure at the top of the riser, and the outlet flow will show an oscillating trend. In order to compare the effects of different models, record the maximum and minimum values of the inlet pressure of the manifold inlet, the pressure at the top of the riser, and the outlet flow after the two models have stabilized at an interval of 1% of the opening degree. The upper line represents the maximum value during the shock, and the lower line represents the minimum value during the shock.

As shown in Figure 7, the instability critical points of the two models are both at 5%. As the top valve opening increases, the slug phenomenon becomes more serious. The figure shows that the oscillation range of the OLGA model is slightly smaller than the model proposed in this article, and the difference between the two is about 0.2Mpa; the pressure at the top of the riser of the OLGA model is also smaller than the model proposed in this article; the outlet flow of the pipeline is basically the same. It can be found that the model proposed in this article has the same safety margin and similar extreme value compared with OLGA. Compared with the dynamic dual-flow model used by OLGA, the model proposed in this article is simpler and has faster calculation speed. More suitable for real-time control of slug flow of top valves.

4.2. Oscillation frequency

Under the conditions mentioned above, the slug oscillation frequency of the top valve at different openings is compared. Figures 8 to 11 show the simulation results of the valve opening of 4% and the valve opening of 12%. Among them, 4% of the top valve opening is a typical stable working area, and 12% is an unstable working area. The drawing data are all real-time data of the simulation model. Because the calculation method of OLGA is slightly different from that of the ODE model mentioned in this article, there is a certain gap between its initial value. This article only needs to consider its slug oscillation frequency and critical oscillation extreme value.

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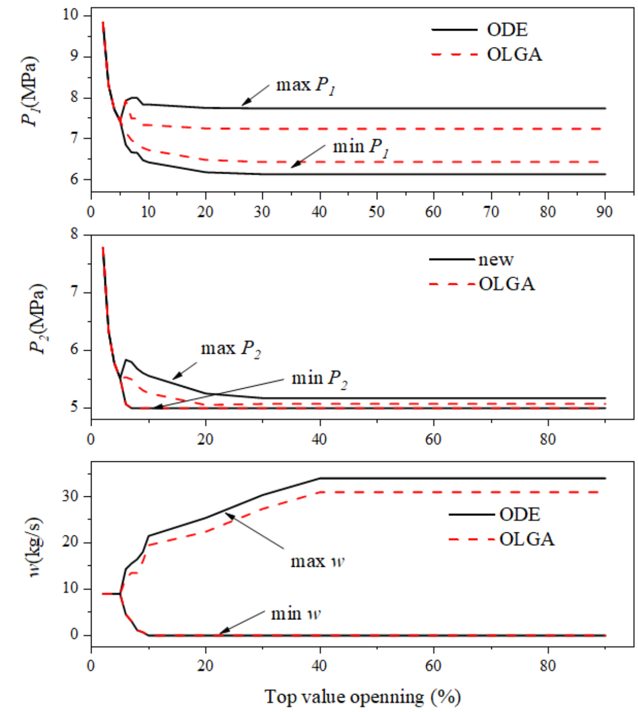

Fig. 6 Bifurcation diagram for different model

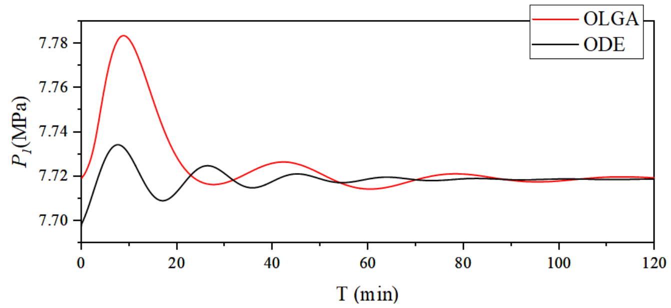

Fig. 7 Manifold outlet pressure variation（top-value 9%)

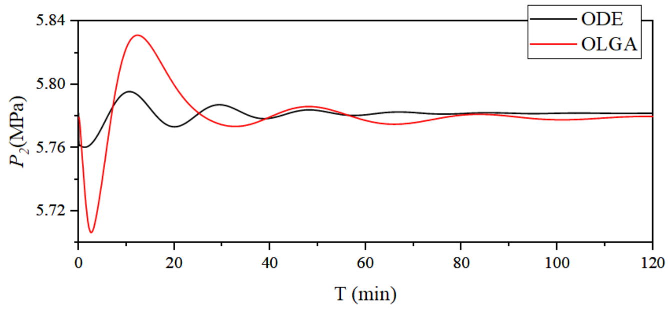

Fig. 8 Manifold outlet pressure variation（top-value 4%)

Figures 8 and 9 reflect that the two models finally stabilized at the same stable pressure within the stable working range of the model, where the pressure at the manifold outlet was stabilized at 7.72MPa, and the pressure at the top of the riser was stabilized at 5.77MPa. In comparison, the two have the same working characteristics.

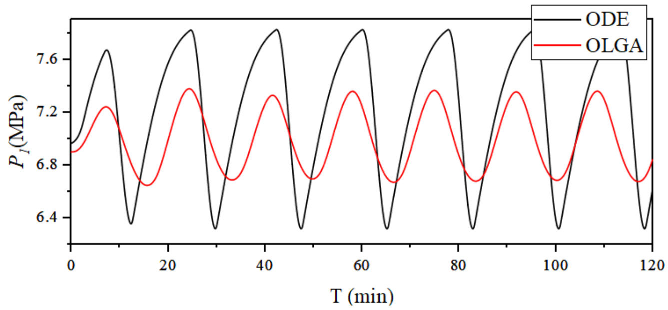

Fig. 9 Pressure variation at top of riser（top-value 12%)

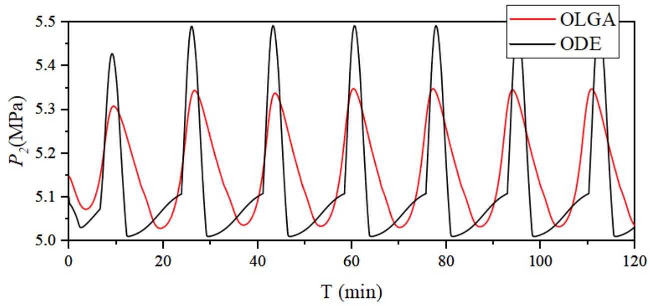

Fig. 10 Pressure variation at top of riser（top-value 9%)

Figure 10 shows that when the valve opening is 12%, the outlet pressure of the OLGA manifold varies from 6.6 MPa to 7.4 MPa, and a pressure oscillation period is about 17 minutes. In comparison, the pressure range of the new model is 6.4MPa~7.8MPa, and its pressure oscillation period is about 17min, which is basically the same as OLGA. As shown in Figure 11, when the top valve opening is 12%, the pressure change period at the top of the OLGA riser is 16.5min, which is basically consistent with the model proposed in this paper. The pressure change range is 5.0MPa~5.35MPa, and the new model change range is 5.01MPa~5.5MPa.

From the above analysis, it can be found that the model proposed in this paper has basically the same stability characteristics as OLGA in the stable working range. In the unstable working range, the pressure oscillation range of the OLGA model is smaller than that of the ODE model, but the period is basically the same. The newly proposed model can be used to describe the state of slug flow.

5. Conclusion and future work

This paper proposes a new model of a new underwater tie-back network, which is used to estimate the flow status of the underwater tie-back network. During the establishment process, the flow pattern in the pipeline was simplified to a certain extent, and the system was divided into five parts: well-manifold-horizontal pipeline-downward inclined pipeline-riser. The valves in the pipeline are replaced by virtual valve formulas. The whole system can be described by eight variables in x. It can be solved by combining its constraint equations. Although the model has been simplified to a certain extent, this simplification is reasonable for system control, which is of great significance for the state estimation and estimation filtering of the tie-back network.

Through comparison with the OLGA model, it is found that the instability points of the simplified model are basically coincident with the OLGA calculation results. The results show that the unstable points of the simplified model and the OLGA model both appear at about 5% of the top valve opening. Although the simplified model cannot reflect the entire process of slug occurrence, the data characteristics embodied by this model are sufficient for control.

For actual production, slug control has high real-time performance. The model proposed in this paper has a faster calculation speed, and its calculation results can better reflect the

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characteristics of slugs. It is proposed for further control performance research in the future. A feasible model. The research in this paper is of great significance in using the top valve to control slug flow in real time.

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