Experimental and Numerical Study on Gas-Liquid Flow in Hilly-Terrain Pipeline-Riser Systems

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In offshore oil and gas transport, gas-liquid mixed transport is a basic flow phenomenon. In general, pipeline undulations are caused by seabed topography; therefore, it is of great significance to study the mechanisms underlying gas and liquid flows in hilly-terrain pipeline-riser systems. This study established a hilly-terrain pipeline-riser experimental system in an indoor laboratory. The flow pattern and its flow mechanism were studied via experimental observation and pressure detection. Experimental results showed that the gas-liquid flow pattern in the hilly-terrain pipeline-riser system can be divided into four types: severe slugging, dual-peak slug, oscillation flow, and stable flow, where dual-peak slug flow is a special flow pattern in this pipeline system. Hilly-terrain units obstruct the downstream gas transport, weaken the gas-liquid eruption in the riser, and increase the cycle of severe slugging. In this paper, gas is regarded as power in the flow of gas and liquid, and the accumulation of liquid in low-lying areas is regarded as an obstacle. Then, the moment of gas-liquid blowout is studied as main research object, and the mechanism of flow pattern transformation is described in detail. This study investigated the accuracy of the OLGA 7.0 simulation results for the gas-liquid two-phase flow in the hilly-terrain pipeline-riser. The results show that OLGA 7.0 achieves a more accurate calculation of severe slugging and stable flow and can predict both the pressure trend and change characteristics. However, the simulation accuracies for dual-peak slug flow and oscillation flow are poor, and the sensitivity to gas changes is insufficient.

1. Introduction

In offshore oil and gas transport, pipeline-riser systems are used to transport products from different wells to offshore platforms. In these pipelines, gas-liquid flow forms the basic flow phenomenon. Therefore, studying the two-phase flow characteristics and underlying laws in the pipeline-riser system forms the basis to ensure the safe and efficient operation of offshore oil and gas production systems [1–3].

Severe slugging is one of the most dangerous flow patterns in such a riser system [4]. Yocum [5] first reported the phenomenon of severe slugging in 1973. Schmidt et al. [6–8], Fabre et al. [9], and Pots et al. [10] studied the occurrence mechanism of severe slugging and established the relevant occurrence criterion. Taitel [11] identified unstable gas-liquid flow in the pipeline as the cause of severe slugging. In response to low gas-liquid velocity, the slug head reaches the top of the riser before the gas enters the riser at the slug growth stage. This is a necessary condition for the occurrence of severe slugging. Based on this, the criterion of stable flow is proposed, which was revised by Wang et al. [1] and Ma et al. [12].

The flow pattern of gas-liquid flow not only depends on the physical properties, flow rates, and other flow parameters [13], but is also affected by the geometry and position of the pipeline. The flow pattern of gas-liquid flow in pipeline-riser systems has been studied before. Schmidt [6] conducted experimental research to compare the differences between
severe slugging and hydraulic slug flow. Severe slugging was divided into severe slugging of type I and severe slugging of type II according to whether liquid slug is formed in the downward pipe. In addition, if formed in the horizon-riser pipeline system, severe slugging is called severe slugging of type III. This classification method proposed by Schmidt [6] is relatively vague and does not contain specific descriptions of flow processes and characteristics. New classification criteria and flow characteristics of severe slugging flow were proposed by Ma et al. [12] through experimental observation.

Severe slugging occurs only at low gas-liquid flow. Many scholars have studied gas-liquid flow patterns within a wide gas-liquid flow range. According to the flow characteristics of gas-liquid flow, Mokhatab and Towler [14] classified the flow patterns in the pipeline-riser system into stable flow and unsteady flow. Wang et al. [1] identified irregular severe slugging in experiments. When irregular severe slugging occurs, both gas and liquid flow stably for most of the time, but are occasionally subjected to strong fluctuations of pressure and outlet velocity. However, this flow pattern does not commonly occur in experiments. In an experimental study, Malekzadeh et al. [15] found unstable oscillation flow, in addition to the three types of severe slugging (SS I, SS II, and SS III) and steady flow. Unstable oscillation flow is characterized by oscillating liquid holdup in the pipe and continuous flow of gas and liquid from the downward pipe into the riser; the pressure fluctuation is much less than in severe slugging. Malekzadeh et al. [16] have also carried out experimental studies in a horizon-riser pipeline system and observed a total of four flow patterns: stable flow, severe slugging of type III, unstable oscillation flow, and dual-frequency severe slugging flow. Dual-frequency severe slugging was reported for the first time, and the authors focus on its research.

The flow pattern in the pipeline-riser system was initially divided into unstable flow and stable flow and then further subdivided into various flow patterns. The basis of this division has gradually become more precise and clearer, and the formation mechanism of gas-liquid flow, especially for severe slugging, was gradually deepened. However, because of the influence of the topographic structure of the seabed, it is difficult to avoid ups and downs of the gathering and transportation pipeline. Combined with the video captured in the experiment, the flow state and characteristic parameters of the gas-liquid flow in the pipe can be obtained by using these pressure data.

The top of the riser is connected to a vertical gravity separator. After the gas-liquid mixture enters the separator, because of the influence of gravity, the gas is discharged into the atmosphere through the upper outlet valve of the separator, and the liquid phase accumulates in the lower part of the separator. The liquid then enters the return pipeline through the bottom outlet pipe, from where it finally flows into the water tank. A magnetic reversal liquid level meter is mounted on the separator to monitor the liquid level in the separator, and a pressure gauge is mounted on top of the separator to measure pressure in the separator. In addition, the oil outlet pipe is equipped with an emergency exhaust valve to prevent safety accidents in the separator caused by

2. Experimental Apparatus and Methodology

The experimental system of this study consists of four parts: gas-liquid supply, test loop, gas-liquid separation, and measurement and shooting part, as shown in Figure 1. The media used in the experiment are water and air. To ensure an adequate liquid supply, water was first stored in a tank and then pressurized via a centrifugal pump, using a precision regulator to regulate the liquid inlet flow. A GA37VSDAP-13 twin screw gas compressor was used to compress the air, and the compressed air was then stored in the gas buffer tank. The maximum pressure can reach up to 1.3 MPa by changing the speed of the inverter driving motor in the compressor and maintain stable pressure in the buffer tank. In the experiment, the pressure of the buffer tank was set to 8 bar, considering factors such as the pressure of the buffer tank and the stable air source. The gas in the buffer tank is regulated by a stop valve and a precision regulator, which provides a steady gas flow for the experimental system.

The horizontal pipe has a length of 69.4 m, and a transparent polymethyl methacrylate pipe of 4 m length was used to facilitate the observation of the flow pattern, while the rest of the pipe consists of stainless steel. The hilly-terrain segment structure is shown in Figure 2; it has an undulating angle of 45° and a height of 1 m, which was installed 58 m away from the entrance. The downward pipe is 11.5 m in length, and the downward angle is 4°. The height of the riser is 6.9 m. To observe the flow condition of the gas-liquid in the pipe, hilly-terrain pipe, downward pipe, and riser pipe consist of transparent polymethyl methacrylate. Pressure data are collected at key points in the test loop: the pressure difference between the bottom of the hilly-terrain pipe and the bottom of the riser and the pressure at the bottom of the riser. Combined with the video captured in the experiment, the flow state and characteristic parameters of the gas-liquid flow in the pipe can be obtained by using these pressure data.

The test loop consists of a horizontal pipe, a hilly-terrain pipe, a downward pipe, and a riser pipe. The pipes (with an inner diameter of 51 mm) are connected by flanges. The horizontal pipe has a length of 69.4 m, and a transparent polymethyl methacrylate pipe of 4 m length was used to facilitate the observation of the flow pattern, while the rest of the pipe consists of stainless steel. The hilly-terrain segment structure is shown in Figure 2; it has an undulating angle of 45° and a height of 1 m, which was installed 58 m away from the entrance. The downward pipe is 11.5 m in length, and the downward angle is 4°. The height of the riser is 6.9 m. To observe the flow condition of the gas-liquid in the pipe, hilly-terrain pipe, downward pipe, and riser pipe consist of transparent polymethyl methacrylate. Pressure data are collected at key points in the test loop: the pressure difference between the bottom of the hilly-terrain pipe and the bottom of the riser and the pressure at the bottom of the riser. Combined with the video captured in the experiment, the flow state and characteristic parameters of the gas-liquid flow in the pipe can be obtained by using these pressure data.

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overpressure. In this experiment, the gas-phase valve was fully open and the pressure in the separator was close to atmospheric pressure.

The following physical quantities were measured in this study: flow rate, temperature, and pressure. Because many times of micro and precise regulation of the gas flow are needed, an EJA115 micro-orifice flowmeter was used to measure the gas flow. To meet specific requirements, three types of orifice plates were used in this study. The orifice plate diameter and flow range were 0.864 mm, 2.527 mm, and 6.350 mm, as well as 1.85–12.9 nL/min, 14.6–105 nL/min, and 89–630 nL/min, respectively. The input voltage of the orifice flowmeter is 12 V; the output current signal ranges within 4–20 mA, and the measurement error level is 0.2. A Keller PR25Y piezoresistive pressure transmitter and ROSEMOUNT 3595 capacitive pressure transmitter were used to measure pressure. The Keller PR25Y piezoresistive pressure transducer, with a frequency limit of 2 kHz, output current of 4–20 mA, and a maximum error of 0.25%, achieved high precision, repeatability, and temperature stability. It is suitable for high-precision, high-speed data acquisition and was installed at the bottom of the riser in the experiment. The Rosemount 3595 capacitor-based pressure transmitter had a frequency response of 22 Hz and an output current signal of 4–20 mA. It was equipped with a microprocessor, LCD screen, and adjustable range for measuring inlet pressure, differential pressure of hilly-terrain, and riser pipes. A RWBPA61 temperature sensor, with an accuracy of 0.5 level and a measurement range of 0–120°C, was used for
temperature measurement. It was calibrated using a standard mercury thermometer.

LabVIEW software was used to collect experimental data. The data acquisition system includes a PCI-6255 high-speed A/D acquisition card, a SCB-68 junction box, a DC-stabilized power supply, and a PC. NI PCI-6255 is a high-speed M-series multifunctional DAQ board card that can maintain high precision even at high sampling rate. The acquisition card has a 16-bit 80-way analog channel and a 40-way differential channel. An SCB-68 signal input/output junction box is attached to the acquisition card and connected to a self-made circuit board. A 250Ω resistance is welded on the circuit board to convert the 4–20 mA current signal output by the instrument into a 1–5 V voltage signal, which is then transmitted to a DAQ board card through the junction box, thus realizing data acquisition and transmission. In addition, in the experiment, three high-resolution GoPro cameras were used to shoot three areas (indicated with the red dotted line in Figure 1). The GoPro cameras enabled adjustment of the field of vision and frame number according to user requirements and recorded the flow state of gas-liquid in the pipeline.

3. Flow Patterns in Hilly-Terrain Pipeline-Riser Systems

Based on previous simulation and exploratory experiments, orthogonal superficial gas and liquid velocity was designed in this study to conduct further tests of working conditions. The superficial gas velocity range was 0.227–12.218 m/s, and the superficial liquid velocity range was 0.024–0.610 m/s. LabVIEW was used to collect pressure data, and the GoPro camera was turned on to shoot the transparent section of the horizontal pipe, the hilly-terrain section, and the downward pipe-riser section. In this study, the flow pattern of gas-liquid two-phase flow was divided according to the fluctuation characteristics of the pressure at the bottom of the riser and experimental observations. According to the fluctuation range of the bottom pressure of the riser, the flow pattern was classified into four types: severe slugging, dual-peak slug, oscillating flow, and stable flow. Each flow type was further divided according to different characteristics. Severe slugging was classified as severe slugging of type I, severe slugging of type II, and severe slugging of type III. Oscillating flow was classified as low-frequency oscillation and high-frequency oscillation. Stable flow was classified as irregular and regular stable flows. Compared with other studies, the present study applies a more detailed and comprehensive classification of flow patterns, which is more conducive to deepening the understanding of gas-liquid flow characteristics in pipeline-riser systems.

3.1. Severe Slugging. Ma [12] divided severe slugging into severe slugging of types I–III. However, Ma regarded the flow pattern between severe slugging and stable flow as a transition flow pattern, which is too rough to be further divided. In a hilly-terrain pipeline-riser system, severe slugging exists only when the riser is filled with liquid during the gas-liquid flow. In other words, when severe slugging occurs, the maximum pressure at the bottom of the riser is equal to the static pressure when the riser is full of liquid (68 kPa in this experimental system), and the impact and damage to the pipeline system are most “severe.”

3.1.1. Severe Slugging of Type I (SS I). SS I is typical severe slugging, complete with four cycles: slug growth, slug production, gas-liquid blowout, and liquid fallback. However, because of the hilly-terrain pipe before the downward pipe, the gas-liquid flow state of SS I changes at different stages. The curves of pressure at the bottom of the riser ($P_r$) and the pressure difference between the bottom of the hilly-terrain pipe and the bottom of the riser ($\Delta P_{hr}$) are shown in Figure 3. The flow process diagram is shown in Figure 4.

Liquid fallback is assumed as initial stage, and the gas-liquid flow process within a cycle is described as follows.

Liquid fallback (Figure 4(a)): because of the influence of gravity, the liquid in the riser falls back to the bottom of the riser, which leads to an increase in $P_r$. The slug tail is then pushed upstream by the pressure difference, and the height of the slug in the riser decreases, which results in a decrease of $P_r$. With the inflow of gas into the downward pipe, the slug tail stops to move backward, the liquid and liquid film in the riser fall back continuously, and $P_r$ continues to increase until the maximum static pressure value (resulting from the height of the falling liquid) is reached. At the initial stage of liquid fallback, the liquid in the hilly-terrain pipe is still carried downstream by the gas, the height of liquid slug between the bottom of the riser and the bottom of hilly-terrain pipe decreases, and thus, $\Delta P_{hr}$ decreases. With more fluid in the riser falling back and the decreasing gas energy, the fluid in the horizontal pipe accumulates toward the bottom of the hilly-terrain pipe, and thus, $\Delta P_{hr}$ increases.

Gas discharging (Figure 4(b)): falling liquid accumulates at the bottom of the riser and the bottom of the hilly-terrain pipe, respectively, both of which enclose the gas space $V_{hr}$. The liquid continuously flows into the downward pipe and the riser pipe, the head and tail of the riser slug increase, and $P_r$ continues to increase. The gas space $V_{hr}$ is continuously compressed and its volume decreases; therefore, the pressure increases continuously. The gas-liquid interface is then pushed forward until the gas in $V_{hr}$ enters the riser and is released through the riser slug. At this time, bubble flow happens in the riser, as shown in Figure 4(b). After gas discharge from $V_{hr}$, the pressure decreases, part of the riser slug flows back into the downward pipe, and thus, $P_r$ decreases. When the gas in $P_r$ cannot pass through the riser slug, the gas discharging stage ends.

Slug growth (Figure 4(c)): after the gas in $V_{hr}$ is discharged, the slug in the riser and the downward pipe continues to grow. The gas in $V_{hr}$ is enclosed in the downward pipe, and the hilly-terrain slug is connected to the riser slug, as shown in Figure 4(c). Gas continuously accumulates in the gas space $V_s$ of the horizontal pipe, upstream of the hilly-terrain pipe, and therefore, the pressure $V_s$ increases, but the speed of this increase is always less than that of the pressure at the bottom of the hilly-terrain pipe;
consequently, the gas cannot pass through the hilly-terrain slug. During this process, the riser slug grows continuously; therefore, \( P_r \) increases, while the height of the slug between the bottom of the riser and the bottom of the hilly-terrain pipe changes little; therefore, \( \Delta P_{hr} \) remained basically unchanged.

Slug production (Figures 4(d) and 4(e)): after the head of the riser slug reaches the top of the riser, the riser slug flows into the terminal treatment equipment. Because of the inflow of inlet gas, the volume \( V_h \) continuously increases, thus pushing the tail of the hilly-terrain slug forward (as shown in Figure 4(d)). When the tail of the slug reaches the bottom of the hilly-terrain pipe, the gas in \( V_h \) penetrates the slug and then enters the downward pipe, thus resulting in a decrease of \( \Delta P_{hr} \) and an increase of \( V_{hr} \) and forward movement of the tail of the slug. The pressure of \( V_h \) gradually decreases, until the gas cannot penetrate the slug. Liquid in hilly-terrain pipe and horizontal pipe flowed backward and then accumulated in the hilly-terrain pipe, thus resulting in the tail of the slug moving back and \( \Delta P_{hr} \) increasing. The inlet gas accumulates again in \( V_h \), and the process is repeated until the tail of the riser slug enters the riser; then, the slug production stage

Figure 4: Schematic diagram of the gas-liquid flow cycle for severe slugging of type I. (a) Liquid fallback. (b) Gas discharging. (c) Slug growth. (d) Slug production (gas does not penetrate the slug). (e) Slug production (gas has penetrated the slug). (f) Gas-liquid blowout.

Figure 3: Pressures of \( P_r \) and \( \Delta P_{hr} \) for severe slugging of type I.
ends. At this stage, the riser slug height remains unchanged; therefore, \( P_r \) basically remains constant. Because of the passage of gas and liquid backflow, \( \Delta P_{hr} \) shows periodic fluctuation during the later period.

Gas-liquid blowout (Figure 4(f)): the gas in \( V_{hr} \) enters the riser, and the length of the slug shortens, which results in a decrease of \( P_r \) and then, the gas expands and the flow accelerates. The \( P_r \) reduction caused by the shorter slug is mutually promoted with the gas expansion, which causes the gas to push the slug toward accelerating the flow out of the riser. The rapid outflow of the slug results in a sharp decrease in \( P_r \), and the upstream pressure of the hilly-terrain pipe basically remains unchanged at this moment. Driven by the large pressure difference, the liquid in the hilly-terrain pipe erupts, which accelerates the flow to the rear pipe. Part of this fluid enters the downward pipe and the other part returns to the hilly-terrain pipe, where it accumulates and forms the riser slug and the hilly-terrain slug, respectively. The stage ends when the gas pressure in the riser is insufficient to allow liquid outflow.

3.1.2. Severe Slugging of Type II (SS II). Based on SS I, when the speed of the inlet gas increases, the gas-liquid flow pattern transitions to SS II; the resulting \( P_r \) and \( \Delta P_{hr} \) curves are shown in Figure 5. SS II still shows obvious periodicity. However, because of the influence of the hilly-terrain pipe, in this study, the highest \( P_r \) value of SS II is still the highest pressure caused by the riser height of the liquid slug, which differs from the SS II in other pipe systems. In essence, there is no difference in flow characteristics and process between SS II and SS I. Consequently, only the differences that exist between both are described in the following.

In the gas-liquid blowout stage, SS II erupts more violently than SS I, and more liquid in the riser pipe flows into the separator; therefore, the liquid slug generated during the SS II liquid fallback stage is shorter. A comparison of Figures 3 and 5 shows that the maximum pressure at the bottom of the riser during the SS I liquid fallback stage is higher than that of SS II.

SS II also has a gas discharging stage, but it has less fallback liquid; therefore, the slug generated in the riser is shorter, and the gas space \( V_{hr} \) is more easily penetrated through the riser slug after being compressed. In addition, because of the larger inlet gas velocity and the faster gas accumulation velocity in \( V_{hr} \), the time for the gas discharging stage of the SS II is shorter than that of SS I.

When the head of the riser slug grows to the top of the riser, the gas in \( V_h \) enters the riser and triggers a gas-liquid blowout. Therefore, there is no slug production stage in SS II, which is the main difference from SS I.

3.1.3. Severe Slugging of Type III (SS III). Based on SS I, increasing the inlet liquid volume, the gas-liquid flow changes to SS III, and the \( P_r \) and \( \Delta P_{hr} \) curves change as shown in Figure 6. The following details the differences between SS III and SS I.

Because of the high inlet liquid velocity, the amount of liquid in the pipeline, and the relatively low gas velocity, which results in less liquid backflow during the gas-liquid blowout stage, the liquid slugs generated in the riser and the hilly-terrain pipe are longer. Figure 7 shows that after the liquid fallback stage, \( P_r \) reaches about 45 kPa, which is much larger compared with SS I. The falling liquid will also seal the gas space \( V_{hr} \) in the downward pipe; however, because of the high hydrostatic pressure generated at the bottom of the riser after liquid fallback, the pressure of \( V_{hr} \) is insufficient to overcome the obstruction of the liquid slug; therefore, there is no longer a gas discharging stage. The above two points indicate the main differences between SS III and SS I.

During the gas-liquid blowout stage, the energy of gas accumulation is relatively insufficient, and the severity of SS III gas-liquid eruption is weaker than that of SS I. Therefore, the pressure at the bottom of the riser after this stage is comparatively higher (25 kPa).
In this study, a special flow pattern was discovered: dual-peak slug (DPS). DPS has obvious periodicity, and the $P_r$ fluctuation curves have two different peaks (as shown in Figure 7). A clear difference exists between these two peaks: the larger peak value reaches the highest hydrostatic pressure value when the riser is fully filled with liquid, which reached 68 kPa; the smaller peak is between 30 and 55 kPa (the working condition as shown in Figure 7 is between 45 and 55 kPa).

When DPS flow occurs, slug growth and gas-liquid eruption occur successively in the pipeline system, and there is no slug production stage. Two different peaks appear alternately in the $P_r$ fluctuation curve, indicating that the riser slug height is different at the beginning of the gas-liquid blowout stage; moreover, the gas-liquid eruption intensity of the two adjacent cycles is also different. According to the severity of the eruption, the two adjacent cycles were named “large eruption” and “small eruption.” The DPS flow can be considered as a flow pattern in which gas-liquid “large eruption” and “small eruption” alternation. The process will be analyzed in detail in the following.

When dual-peak slug occurs, the superficial gas velocity is larger; therefore, when the hilly-terrain slug erupts, it continually triggers the riser slug eruption. The “big eruption” cycle of gas-liquid eruption is more intense and thus causes the gas to drive out most of the liquid from the pipeline system. Therefore, the slug generated in the liquid fallback stage is shorter, and the hydrostatic pressure generated at the bottom of the hilly-terrain pipe is smaller. Under constant gas-liquid input, in the next cycle, the slug tail in the hilly-terrain pipe can flow through the bottom relatively quickly, which in turn causes gas-liquid eruptions in the hilly-terrain pipe and the riser pipe. Because the gas-liquid eruption happens earlier and the maximum height of the riser slug is smaller, the pressure peak at the bottom of the riser in this cycle is smaller. Because of insufficient gas accumulation and low energy, the gas-liquid eruption is lighter, which is called a “small eruption.” In this “small eruption” cycle, the slug generated in the liquid fallback stage is longer, which causes a large hydrostatic pressure at the bottom of the hilly-terrain pipe; consequently, the next cycle takes longer to push the slug tail in the hilly-terrain pipe through the bottom. Eventually, a long slug is generated in the riser, and the pressure fluctuation at the bottom of the riser produces a large peak, which causes a “large eruption.” Therefore, because of the influence of the hilly-terrain pipe, the “large eruption” cycle alternates with the “small eruption” cycle.

3.3. Oscillation Flow. The variation curves of $P_r$ and $\Delta P_{hr}$ of the oscillation flow are shown in Figure 8. The main feature of these curves is the irregularity of $P_r$ fluctuation. The fluctuation amplitude exceeds the static pressure of the water column at 1/5 of the riser height (14 kPa in this experiment). The gas-liquid eruption and the slug growth in the riser alternate continuously. The severity of the gas-liquid eruption and the maximum length of the riser slug are random. The frequency of $P_r$ fluctuations differs greatly. By performing a FFT conversion on the $P_r$ signal, it can be divided into low-frequency oscillation flow (<0.1 Hz) and high-frequency oscillation flow (>0.1 Hz) according to the differences of the main frequency.

3.3.1. Low-Frequency Oscillation. The low-frequency oscillation (LFO) evolves from DPS, and the $P_r$ fluctuation ranges between 5 and 50 kPa, as shown in Figure 8(a). Similar to the DPS, high and low peaks alternate on the $P_r$ fluctuation curve for LFO; however, the riser gas-liquid eruption frequency is higher, and the fluctuation amplitude is lower. The reason is that the larger the inlet gas velocity is, the faster the gas in $V_h$ pushes the slug forward, and the gas is faster conveyed through the hilly-terrain pipe down the downward pipe and therefore causes more frequent slug growth and gas-liquid eruption.

3.3.2. High-Frequency Oscillation. High-frequency oscillation (HFO) occurs at a large inlet superficial liquid velocity (>0.28 m/s in this study). The fluctuation of $P_r$ basically ranges within 15–40 kPa. Compared with LFO, the fluctuation amplitude of $P_r$ under the HFO flow pattern is relatively low, but the fluctuation frequency is high. This is mainly caused by the high inlet fluid velocity. Under the same gas-liquid ratio conditions as in LFO, the HFO inlet gas-liquid velocity is higher, and the gas accumulation velocity in $V_h$ and liquid slug growth velocity in the riser are faster; therefore, the gas-liquid eruption frequency is higher, resulting in high-frequency $P_r$ fluctuations.

3.4. Stable Flow. The variation curves of $P_r$ and $\Delta P_{hr}$ under stable flow are shown in Figure 9. The characteristic of this stable flow is that the fluctuation amplitude of $P_r$ is less than 1/5 of the static pressure caused by the water column at riser height (14 kPa in this study); moreover, the gas-liquid flow in
the riser follows a hydraulic slug flow pattern. Stable flow evolves from oscillation flow. If a liquid fallback and a gas-liquid eruption are regarded as a flow cycle, because of the influence of the hilly-terrain pipe, with increasing inlet gas velocity, not all cycles of $P_r$ fluctuations decrease synchronously. According to the different characteristics of $P_r$ fluctuations, the stable flow can be divided into irregular-stable flow and regular-stable flow.

3.4.1. Irregular-Stable Flow. After several stable flow periods (where the $P_r$ fluctuation amplitude is less than 14 kPa), a “large eruption” occurs; i.e., a higher $P_r$ fluctuation amplitude occurs. This type of flow is called irregular-stable flow (IST). The $P_r$ fluctuation curve is shown in Figure 9(a). The reason for this change in amplitude is that after multiple stable flow cycles, the gas in $V_h$ is not replenished sufficiently, and the pressure drops, which results in an increase of the amount of liquid falling in the hilly-terrain pipe. When the eruption occurred again, the riser liquid slug had grown to a higher height, thus resulting in a larger $P_r$ fluctuation pressure during this period.

3.4.2. Regular-Stable Flow. When the fluctuation range of $P_r$ during all flow periods is less than 14 kPa, it is called regular-stable flow (RST). The gas in the hilly-terrain pipe and riser flows at high speed. Although the liquid appears to briefly fall back, it is carried downstream by the gas and flows. There is no liquid accumulation at the bottom of the hilly-terrain pipe.
pipe and the riser. This flow state causes the least damage to the pipeline system and is the most ideal state for gas-liquid flow in pipeline-riser systems.

4. Results and Discussion

4.1. Frequency Domain and Probability Density Function Characteristics of $P_r$. $P_r$ is an important characteristic parameter when assessing the flow pattern. This study investigated the frequency domain characteristics and probability density function (PDF) characteristics of $P_r$ under different flow patterns. The processing results are shown in Figure 10. The frequency domain characteristics of $P_r$ are obtained by fast Fourier transform (FFT). To arrive at a more widely applicable PDF feature, the pressure in the PDF distribution image has been standardized, and the processing method can be calculated with the following equation:

$$P_r^* = \frac{P_r - \bar{P}}{S_r}.$$  \hspace{1cm} (1)

In the formula,

$$\bar{P} = \frac{1}{N} \sum_{i=1}^{N} P_r,$$  \hspace{1cm} (2)

$$S_r = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (P_r - \bar{P})^2}.$$  

The frequency domain distribution diagram of $P_r$ shows that severe slugging has strong periodicity, and the frequency domain curve of $P_r$ shows a distinct single-peak distribution, especially for SS II. For SS III, because of the large difference in the height of the liquid slug formed in the riser after eruption, the periodicity of the fluctuation curve is slightly weaker; therefore, there is a subprimary frequency. In general, the frequency distribution of severe slugging is narrow, and the main frequency is clear. Under DPS, there are three peaks in the frequency domain curve of $P_r$. The frequency domain characteristics of the oscillating flow differ greatly, mainly because of differences in oscillating frequencies. The frequency domain for LFO is narrowly distributed and has a single-peak characteristic. Its main frequency is less than 0.1 Hz. HFO has a wide frequency domain distribution, the main frequency of which is higher than 0.1 Hz. The frequency distribution of the stable flow is relatively wide, and gas-liquid eruptions happen after a few stable cycles. Therefore, the frequency domain curve of $P_r$ shows a double-peak characteristic, while RST shows a single-peak characteristic with a small main frequency.

Analysis of the PDF distribution characteristics of $P_r$ under different flow patterns indicates that severe slugging has clear single-peak characteristics, especially for SS I and SS III. The peak value is the highest pressure; therefore, the pipeline system is in a high-pressure state most of the time. Since SS II has no liquid production stage, the peak pressure is not the highest value. For DPS, $P_r$ has two peaks, and its PDF distribution also has two peaks; however, the distribution area is wider than that in severe slugging. The fluctuation of the $P_r$ curve for the oscillation flow is relatively large; therefore, the PDF is widely distributed. Compared with LFO, the peak of PDF distribution for HFO is on the right. This is because the HFO flow pattern has a larger inlet flow rate, and the riser contains more liquid during the flow, which results in a higher pressure at the bottom of the riser. The PDF distribution of the stable flow is more in line with a normal distribution, which is the ideal flow pattern.

4.2. Flow Evolution of Gas-Liquid. For a specific pipeline system, when the inlet flow rate changes, the gas-liquid flow conditions change accordingly. This is a gradual process without mutation. There is no obvious boundary between different flow patterns, and therefore, these patterns are artificially classified according to different flow characteristics; therefore, the flow pattern change cannot be viewed from the perspective of splitting. The mechanism of flow pattern transition is discussed in the following by combining experimental phenomena and flow pattern diagrams (as shown in Figure 11).

In gas-liquid flow, because of the influence of gravity, liquid accumulates at the bottom of the hilly-terrain pipe and the bottom of the riser, which obstructs the flow. Only when the gas overcomes this barrier, it can be transported downstream. Before the gas breaks through the slug, the slug grows and the gas pressure continues to increase. The way for the gas to break through this obstacle is to penetrate the slug tail and then continuously increase its flow speed because of the expansion force, which triggers an eruption, and liquid fallback after the eruption. It can be considered that most of the flow patterns contain gas-liquid eruptions and liquid fallbacks. The moment of gas-liquid eruption determines the highest pressure in the riser, i.e., the pressure fluctuation range of the riser, and therefore, this is used as the key point of the analysis.

In the hilly-terrain pipeline-riser system, the gas-liquid eruption starting time is determined by the time when the gas enters the bottom of the hilly-terrain pipe and the bottom of the riser. The moment when the gas enters the bottom of the hilly-terrain pipe is determined by the relative magnitude of the upstream gas pressure $P_{tg}$ and the bottom hydrostatic pressure $P_{bh}$. When $P_{tg}$ exceeds $P_{bh}$, the hilly-terrain slug tail is pushed forward; otherwise, it either grows backward or stops. The moment when the gas enters the riser is mainly related to the speed of conveying the gas through the hilly-terrain pipe down the inclined pipe.

With regard to the flow under any working condition, the liquid slug generated after the liquid fallback stage is the obstacle the gas needs to overcome, i.e., this is the starting point of the analysis. Using the inlet superficial liquid velocity $V_{sl} = 0.065$ m/s as an example, when the inlet superficial gas velocity is low ($V_{sg} < 0.245$ m/s), the gas-liquid eruption is lighter and more liquid falls back. Therefore, the obstacle the gas needs to overcome is greater, and $P_{tg}$ is much smaller than $P_{bh}$. The gas accumulation rate in $V_{bh}$ is relatively slow, resulting in a slow increase in $P_{tg}$. At the same time, the liquid is continuously transferred to the riser, and the riser slug grows; therefore, $P_{bh}$ increases relatively quickly. When
the riser is filled with liquid, \( P_d \) no longer changes, while \( P_{tg} \) continues to increase because of gas accumulation. When \( P_{tg} > P_d \), the hilly-terrain slug tail is pushed forward until the gas passes through the bottom of the hilly-terrain pipe. At this time, upstream gas has insufficient energy and cannot cause a gas-liquid eruption in the hilly-terrain pipe. The gas can only be intermittently sent downstream in the form of bubble flow until the riser slug tail is pushed into the riser, thus causing a riser gas-liquid eruption. In this process, there is the slug production stage, which is SS I. When the inlet gas velocity becomes large, the \( P_d \) increasing rate basically remains unchanged, but the \( P_{tg} \) increasing rate increases. When the gas enters the bottom of the hilly-terrain pipe, the speed of delivering the gas downstream is accelerated;
however, it still has the form of bubble flow. Therefore, the
time for the gas to enter the riser is shortened, and the period
of the slug production stage is shortened. When the slug
production period becomes zero, it is SS II.

Unlike the horizontal-downward-riser system, in the
hilly-terrain pipeline-riser system, when the inlet gas ve-
clocity increases, the maximum length of the riser slug will
not gradually shorten, thereby causing gas-liquid erosion in
advance. The reason is that the liquid accumulates at the
bottom of the hilly-terrain pipe, which obstructs gas transpor-
tation. It is therefore necessary for the gas to first
push the slug tail into the bottom of the hilly-terrain pipe.
However, when the pressure \( V_h \) is insufficient to quickly
advance the long liquid slug, the moment of the gas-liquid
eruption in the riser is mainly affected by the length of the
slug produced by the falling liquid in the hilly-terrain pipe.
When the gas-liquid eruption in the riser is violent, there is
little falling liquid, and the gas-liquid erosion is advanced in
the next cycle, but it will be less severe. In the next cycle, a
longer fallback slug will be generated, and the eruption time
will be delayed. Therefore, two peaks can be observed in \( P_r \)
fluctuations, i.e., DPS. Furthermore, as the gas velocity in-
creases, the maximum pressure in the "small eruption" cycle
gradually decreases.

As the inlet gas velocity increases, the obstruction of the
liquid in the hilly-terrain pipe weakens, and the speed of the
downstream gas delivery increases, thus causing gas-liquid
eruption when the slug head grows to the middle of the riser.
However, because of the inconsistent intensity of each
eruption and the different amount of the falling liquid, the
length of the maximum riser slug differs. Therefore, the
pressure at the riser bottom fluctuates with different peaks,
which is LFO. When the inlet gas velocity continues to
increase, the power provided by the gas is higher, thus
resulting in a weaker liquid blocking effect; therefore, the
riser slug length decreases. Consequently, the pressure
fluctuation amplitude decreases gradually, while the fre-
cquency increases, and the gas-liquid flow pattern changes to
stable flow.

**4.3. Influence of Hilly-Terrain Unit.** This study used \( P_r \)
to characterize the effect of the hilly-terrain pipe on the flow.
The hilly-terrain pipe was replaced with a horizontal pipe
with the same inner diameter. Under the same operating
conditions, the fluctuation curves of \( P_r \) in the hilly-terrain
pipeline-riser system and the horizontal-riser system are
shown in Figure 12.

In Figure 12(a), severe slugging has occurred in both
pipeline systems. However, because of the influence of the
hilly-terrain pipe, the period of severe slugging is clearly
prolonged, and the slug generated during the liquid fallback
stage is longer, which indicates that the gas-liquid erosion is
less severe. Figure 12(b) shows that when a hilly-terrain pipe
is tested, the flow pattern is DPS, while it is oscillation flow
for the horizontal-riser system. Figure 12(c) shows a larger
liquid volume and a smaller pressure fluctuation in the hilly-
terrain pipeline-riser system. In Figure 12(d), these two are
similar.

The influence of hilly-terrain pipe on the gas-liquid flow
can be summarized in the following: For a specific riser
system that contains a hilly-terrain unit, there is a critical gas
velocity for a certain liquid volume. When the gas velocity is
lower than the critical gas velocity, liquid accumulates in the
hilly-terrain pipe, which obstructs the gas, resulting in a
slower gas transport downstream and a less severe eruption.
When the critical gas velocity is exceeded, the gas can
quickly push the liquid, thus making it difficult for the liquid
to accumulate at the bottom of the hilly-terrain pipe. At this
time, the hilly-terrain unit exerts less influence on the flow.
When the inlet liquid velocity is large, part of the falling
liquid accumulates in the hilly-terrain pipe, and therefore,
the growth height of the riser slug is small. Consequently, the
\( P_r \) fluctuation is reduced.

**5. Numerical Simulation**

OLGA is the industry standard tool for transient simulation
of multiphase petroleum production. OLGA is used for
networks of wells, flowlines and pipelines, and process
equipment [18], covering the production system from
bottom hole into the production system [19, 20]. OLGA
comes with a steady-state preprocessor included which is
intended for calculating initial values to the transient sim-
ulations, but which also is useful for traditional steady-state
parameter variations. However, the transient capabilities of
OLGA dramatically increase the range of applicability
compared with steady-state simulators. In the software
OLGA 7.0, the same geometric model as in the laboratory is
established, and the same working conditions are input to
simulate the gas-liquid flow. A comparison of \( P_r \) fluctuation
curves between these two is shown in Figure 13.

The flow patterns shown in Figures 13(a)–13(c) indicate
severe slugging. In general, the amplitude and change trend
Figure 12: Comparison of $P_r$ in pipeline systems with or without hilly-terrain unit. (a) $v_d = 0.039 \text{ m/s}$, $v_{sg} = 0.077 \text{ m/s}$. (b) $v_d = 0.065 \text{ m/s}$, $v_{sg} = 0.371 \text{ m/s}$. (c) $v_d = 0.239 \text{ m/s}$, $v_{sg} = 1.356 \text{ m/s}$. (d) $v_d = 0.064 \text{ m/s}$, $v_{sg} = 0.789 \text{ m/s}$.

Figure 13: Continued.
Figure 13: Comparison of OLGA simulation results and experimental results. (a) $v_d = 0.039$ m/s, $v_{sg} = 0.077$ m/s. (b) $v_d = 0.067$ m/s, $v_{sg} = 0.245$ m/s. (c) $v_d = 0.6095$ m/s, $v_{sg} = 0.146$ m/s. (d) $v_d = 0.188$ m/s, $v_{sg} = 0.369$ m/s. (e) $v_d = 0.352$ m/s, $v_{sg} = 2.154$ m/s. (f) $v_d = 0.104$ m/s, $v_{sg} = 0.843$ m/s. (g) $v_d = 0.105$ m/s, $v_{sg} = 3.113$ m/s. (h) $v_d = 0.106$ m/s, $v_{sg} = 6.184$ m/s.
of $P_t$ between the two are basically the same. The OLGA simulation results are consistent with the characteristics of severe slugging. Specifically, in the OLGA simulation results, severe slugging has poor periodicity, and the calculation of the period length is inaccurate. The prediction results for SS I and SS III flow patterns are too small, while the calculation results for SS II are too large. This indicates that the calculation result of OLGA is not as sensitive to the change of gas velocity as the experiment. In addition, in SS I and SS III flow patterns, the minimum pressure of the simulation is close to zero, indicating that there is a time when the riser slug length is zero. In this experiment, because of the influence of hilly-terrain pipe, the gas-liquid eruption is not severe, and there is always a liquid slug in the riser; therefore, the pressure fluctuation calculated by OLGA is larger.

Figure 13(d) shows the DPS, which is a special flow pattern because of the influence of the hilly-terrain pipe; however, OLGA cannot calculate and identify this pattern. In OLGA, the flow pattern when $v_{SL} = 0.188 \text{ m/s}$ and $v_{SG} = 0.369 \text{ m/s}$ is SS I. OLGA also results in deviations in the calculation of oscillation flow (Figures 13(e) and 13(f)). The pressure fluctuation amplitude and change trend differ from the experimental results. This is also because of the insensitivity of the OLGA calculation results to changes in gas velocity.

The OLGA calculation of stable flow is relatively accurate. In Figure 13(g), the pressure change trend indicates a large eruption after a few cycles of stable flow. The difference is that the period calculated by OLGA is longer and the pressure fluctuation range is larger. In Figure 13(h), OLGA accurately predicts the pressure fluctuation trend for regular-stable flow, but the pressure value is slightly lower.

6. Conclusion

This study investigated gas-liquid flow in a hilly-terrain pipeline-riser system. Using experimental observation and pressure detection, the flow pattern is scientifically and comprehensively divided. Four types of flow patterns were identified in this study: severe slugging (of type I, type II, and type III), DPS, oscillation flow (LFO and HFO), and stable flow (IST and RST). Among these, DPS is a special flow pattern caused by the hilly-terrain pipe and is composed of alternating periods of "large eruptions" and "small eruptions." In this paper, the division of flow patterns is more comprehensive and reasonable, which helps to deepen the understanding of gas-liquid flow in pipeline-riser systems.

The hilly-terrain unit was included in the pipeline-riser system studied in this paper. This study showed that the hilly-terrain pipe obstructs the transportation of gas downstream, which results in a slower gas accumulation rate. Therefore, the gas-liquid eruption in the riser is weakened and the period of severe slug flow increases. However, for a particular hilly-terrain pipe, a critical gas velocity exists. When the inlet gas velocity exceeds this value, the influence of the hilly-terrain pipe can be ignored.

No obvious boundary exists between flow patterns, and the change of the flow state is a slow process. In this study, gas was regarded as the driving force of the observed gas-liquid flow, and the accumulation of liquid in low-lying places is regarded as an obstacle. By analyzing the occurrence time of gas-liquid eruptions, the mechanism underlying the flow pattern transition in the hilly-terrain pipeline-riser system is described.

Furthermore, the accuracy of OLGA's simulation of gas-liquid flow in the hilly-terrain pipeline-riser system was investigated. By comparing the pressure fluctuation curves at the bottom of the riser, OLGA was found to be more accurate in calculating both severe slugging and stable flow and can predict the pressure trend and change characteristics. However, the calculation accuracy of OLGA for DPS and oscillation flow is poor, and the sensitivity to gas changes is insufficient.

Slug dissipation and generation behaviors will be infected by the inclination angle of hilly-terrain section. So, the effect of different styles of pipe section on the two-phase flow behaviors can be studied in the future.

Data Availability

All data, models, and code generated or used during the study are included within the article.

Additional Points

Highlights. The gas-liquid flow pattern was classified more scientifically and comprehensively. A new flow pattern was identified: dual-peak slug flow. Hilly-terrain pipelines are included in the studied riser system, and their influence on flow is discussed. The simulation accuracy of OLGA 7.0 on gas-liquid flow in the hilly-terrain pipeline-riser system was evaluated.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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