

Experimental Study on the Slugging Characteristics of Gas–Liquid Slug Flow in Horizontal Pipes

Xiao Wu, Zhaoting Wang,* Longfei Dong, Yanping Xin, and Huiqing Cao

Cite This: *ACS Omega* 2022, 7, 21643–21653

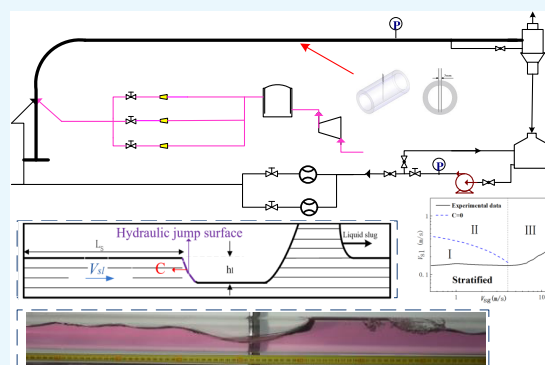
Read Online

ACCESS |

Metrics & More

Article Recommendations

ABSTRACT: This study investigates the slugging characteristics of the gas–liquid slug flow interface in horizontal pipes. Using air and water as the experimental media, an experimental system was established using double-parallel conductance probes in a pipe with an inner diameter of 5 cm. By capturing the transient development process of the gas–liquid interface, the slugging characteristics of the gas–liquid two-phase flow interface in different flow regions were revealed. The results show that the value of gas-phase superficial velocity has an important influence on the shape and development of the interface wave during the slugging process. When the gravity wave generated during the slugging process can propagate upstream, the slugging phenomenon is periodic, and when the gravity wave cannot propagate upstream, the slugging phenomenon is random. The experiment verified the correctness of the interface instability theory and the liquid slug stability theory, and clarified the definitions of h_o and h_s . In addition, the paper analyzed the influence of gas–liquid velocity on slugging distance, h_o and h_s , and liquid slug frequency.



1. INTRODUCTION

Mixed pipelines on the seabed are mainly in a horizontal and near-horizontal alignment. Slug flow is the most common flow pattern in the mixed oil and gas transportation in horizontal and near-horizontal pipelines.¹ Owing to the randomness, complexity, and intermittent nature of slug flow, the flow characteristics and phase interface structure have not yet been understood clearly. The fluctuations in pressure and flow caused by the slug flow have a significant impact on deep-sea oilfield development and production equipment design. Therefore, an in-depth study of the flow characteristics of a horizontal-pipe slug flow has important engineering significance and academic value.

Two theoretical models are used to explain the mechanism of slugging at the gas–liquid interface: the liquid slug stability theory and interface instability theory. The liquid slug stability theory analysis considers a volumetric liquid balance between the front and the tail of a slug. Jepson² used the transient burst model to simulate the liquid discharge process at the tail of a liquid slug and solved the critical liquid-level height of the slug flow under the stable condition of the liquid slug. Bendiksen and Espedal³ calculated the moving velocity V_t of the head of the liquid slug using the mass conservation equation and obtained the moving velocity V_b of the gas bomb using the theoretical model of Bendiksen.⁴ The predicted results of the liquid slug stability conditions were in good agreement with the experimental results under high-pressure conditions. Ruder et al.⁵ ignored the gas content inside the liquid slug and used

the inviscid potential flow theory of Benjamin⁶ to define the amount of liquid leakage at the tail of the liquid slug. The predicted results of this theory are in good agreement with the experimental results at low gas velocities; however, at high gas velocities, the experimental results are remarkably different from the predicted results. Lunde and Ashelm⁷ used a method similar to Bendiksen⁴ to theoretically analyze the liquid slug stability conditions and obtained the minimum liquid phase holdup of the liquid film in front of the liquid slug when the liquid slug was stable. Woods and Hanratty⁸ used dual-parallel conductance probes to measure the leakage rate at the tail of a liquid slug inside a horizontal pipe. The conditions for the stability of the liquid slug were obtained according to the principle of phase balance between the amount of liquid entrained in the head of the liquid slug and the amount of liquid discharged at the tail. Sanchis⁹ studied the effect of wave interaction on hydrodynamic slug formation in a two-phase pipe flow at a relatively low apparent gas–liquid velocity. The hydrodynamic slug formed by wave interaction was found to

Received: March 13, 2022

Accepted: June 6, 2022

Published: June 16, 2022



Table 1. Research Summary of Slugging Mechanism

researchers	the main work	conclusion
Bendiksen ³	calculate the velocity of aerosol movement using the model of Bendiksen ⁴	liquid slug stability conditions: $V_t = U_{g1} \frac{\alpha_{g1} - \alpha_{g3} \frac{U_{g3}}{U_{g1}}}{\alpha_{g1} - \alpha_{g3}}$
Ruder ⁵	simulation of the liquid leakage at the tail of the liquid slug using the nonviscous potential flow theory of Benjamin ⁶	liquid slug stability conditions: $\frac{(V_t - U_{t1}) 4A_{t1}}{(gD)^{0.5} \pi D^2} = 0.542$
Lunde and Ashelm ⁷	calculate the liquid-phase holdup of the liquid film in front of the liquid slug using the model of Bendiksen ⁴	liquid slug stability conditions: $\alpha_{l1} = \frac{(C_0 - 1)\alpha_{l3} + U_d \frac{\alpha_{l3}}{U_{l3}}}{1 + (C_0 - 1) + \frac{(U_d - U_{l1})}{U_{l1}}}$
Woods and Hanratty ⁸	calculate the liquid-phase holdup of the liquid film in front of the liquid slug using the model of Bendiksen ⁴	liquid slug stability conditions: $\alpha_{l1} = \frac{\left[C_0 - \frac{1}{(s-1)\alpha_{g3}} \right] U_{l3} + U_d}{C_0 U_{l3} + U_d - U_{l1}} \alpha_{l3}$
Wallis and Dobson ¹⁰	K–H stability analysis of square tube	interface instability conditions: $U_g - U_l = 0.5 \sqrt{\rho_l / \rho_g} g h_1$
Taitel and Dukler ¹¹	K–H stability analysis of circular tube	interface instability conditions: $U_g - U_l = \left(1 - \frac{h_1}{D} \right) \sqrt{\frac{\rho_l g \cos \theta A_g}{dA_1 / dh}} \rho_l$
Lin and Hanratty ¹⁶	K–H stability analysis of circular tube (considering shear stress)	interface instability conditions: $(U_g - C_R)^2 + \frac{A_l \rho_l}{A_g \rho_g} (C_R - U_l)^2 = \frac{A_l \rho_l g \cos \theta}{A_g \rho_g dA_1 / dh_1}$
Barnea and Taitel ¹⁷	K–H stability analysis of circular tube (considering shear stress)	interface instability conditions: $U_g^2 = K \left[(\rho_l \alpha_g + \rho_g \alpha_l) \left(\frac{\rho_l - \rho_g}{\rho_l \rho_g} \right) g \frac{A}{dA_1 / dh_1} \right]$

be different from that predicted by the liquid slug stability theory.

The interface instability theory states that the slugging phenomenon is caused by the instability of the gas–liquid interface wave. The critical conditions of the gas–liquid interface slugging were determined by analyzing the critical conditions of the interface wave instability. Wallis and Dobson¹⁰ studied the gas–liquid interface wave in the square tube and believed that gravity has a stabilizing effect on the interface wave, and the interface lift generated by aerodynamics can promote the growth of the interface wave. Taitel and Dukler¹¹ investigated the K–H instability (Kelvin–Helmholtz instability) of a gas–liquid interface in a circular tube. The analysis shows that the Bernoulli force causes a pressure change at the gas–liquid interface, which in turn causes instability in the interface wave. Kordyban^{12,13} believed that limited-amplitude interface waves could develop into liquid slugs, and the slugging was caused by the local instability of the interface waves rather than the global instability; however, Trapp¹⁴ did not support the local K–H instability theory. Minato et al.¹⁵ determined that the slugging phenomenon is related to the energy level of the two phases and that the kinetic energy of the liquid phase can promote the growth of the interface wave. Lin and Hanratty¹⁶ considered the shear stress between phases, and that between phases and walls and concluded that when the interface is unstable, the wave velocity of the gas–liquid interface is greater than that of the liquid phase. Barnea and Taitel¹⁷ used a method similar to that of Lin and Hanratty¹⁶ to analyze the K–H stability of the interface and obtained the slugging criterion for the gas–liquid interface. Fabre and Line¹⁸ determined that the nonviscous K–H stability theory is not applicable to high-viscosity fluids, whereas Barnea and Taitel¹⁹ demonstrated that the analysis results of high-viscosity fluids using the viscous K–H stability

theory and nonviscous K–H stability theory are relatively close. However, the analysis results of the two theories for low-viscosity fluids are significantly different. Wu and Ishii²⁰ used a nonlinear theoretical analysis to study the effect of higher-order wave components on the stability of the gas–liquid interface. They found that the linear analysis can better predict the critical superficial gas velocity for small-scale interface wave instability, but it is inaccurate for large-scale interface wave instability. Barmak²¹ used the turbulent Orr–Sommerfeld (TOS) method flow for a “quasi-steady-state” description. The Orr–Sommerfeld (O–S) formulation combines the mechanisms of density and viscosity stratification, velocity profile curvature, and shear effects for inviscid K–H instability. For turbulent gas flow over laminar liquids, TOS analysis shows similar instability mechanisms to laminar–laminar stratified flows for both shallow and deep liquids.^{22,23} Thus, for the transition from stratified flows to wavy flows, K–H and laminar/turbulent O–S interfacial instabilities provide the relevant stability predictions. The limitation of these works is the linearity of their methods, which fails to describe the subsequent transition from wavy to slug flow, where nonlinearity should be important. A summary of the work to obtain clear critical conditions for slugging for the liquid slug stability model or the interface instability model is shown in Table 1.

Regarding the phenomenon of slugging and the development of liquid slug, Vallée²⁴ determined that after the liquid slug passes through a certain section, the liquid level of the section first drops and then gradually rises until it reaches the critical height, and the liquid slug appears again. The velocity of the liquid at the top of the liquid slug head is greater than that of the liquid slug body, and it falls under the action of gravity, forming a vortex at the head position of the liquid slug. Ujang²⁵ reported that with the development of the liquid slug,

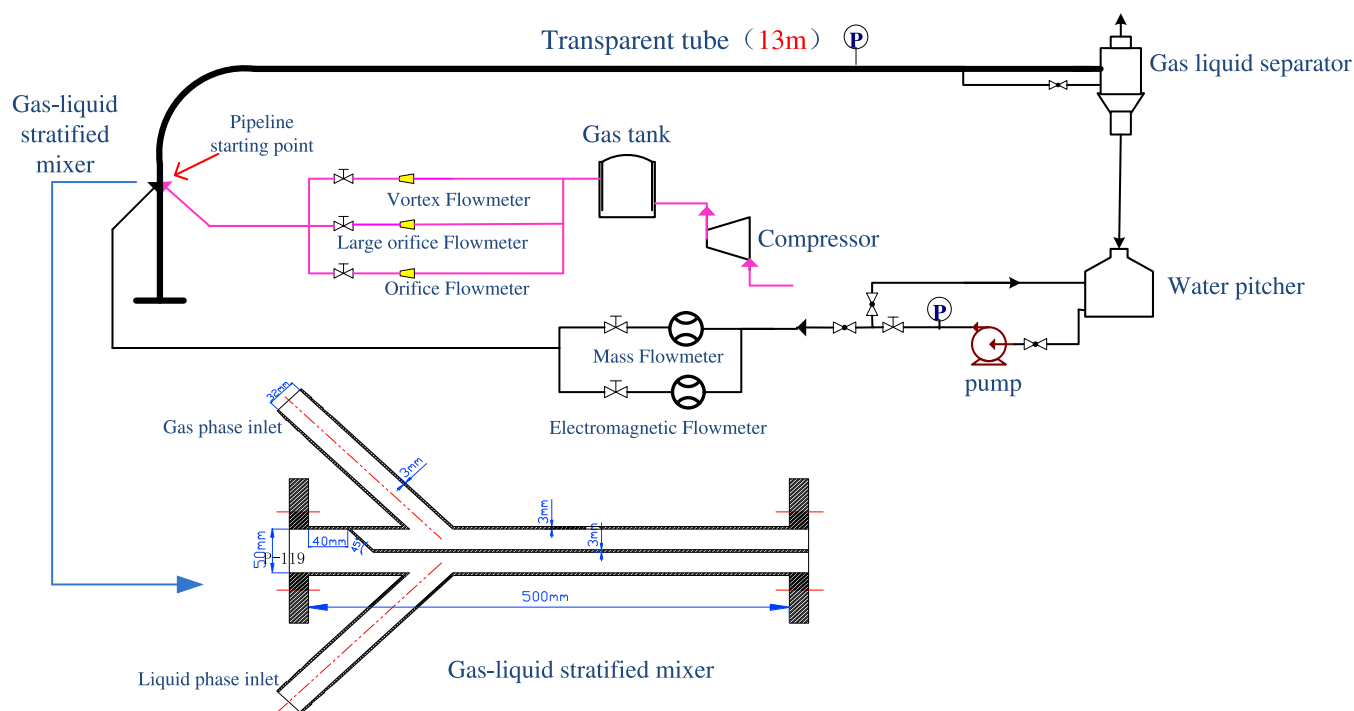


Figure 1. Experimental system.

the liquid slug frequency gradually decreased to a stable value, and the change in the liquid slug frequency was affected by the gas–liquid velocity. The increase in the gas-phase pressure has an inhibitory effect on the formation and development of liquid slugs. Lu²⁶ experimentally demonstrated that the liquid slug frequency attained its maximum value at the inlet, and the liquid slug frequency gradually decreased along the flow direction. The geometrical condition of the pipe inlet had a significant influence on the formation of the liquid slug, and this influence gradually weakened with the flow direction.

In summary, there are still significant differences in the slugging prediction of the gas–liquid interface between the liquid slug stability theory and interface instability theory, and a discussion on the relationship between the two models is lacking. In this paper, the gas–liquid two-phase flow experimental system is used to capture the transient development process of the gas–liquid interface and reveal the slugging mechanism and liquid slug development characteristics of the gas–liquid two-phase flow interface in different flow regions.

2. EXPERIMENTAL FACILITY

The experimental system includes three components: a gas-phase circulation system, liquid-phase circulation system, and gas–liquid stratified mixing experimental system. The experimental test tube consists of a plexiglass tube of inner diameter of 50 mm and length of 13 m. The experimental schematic is shown in Figure 1.

To provide a stable gas–liquid two-phase flow, a gas–liquid stratified mixer was designed in the experiment. The mixer is 500 mm long and can realize two-phase layered mixing and three-phase mixing. In the experiment, 20 sets of double-parallel conductance probes were arranged from the inlet to the outlet (Table 2 and Figure 2).

Double-parallel conductance probes enable the measurement of flow parameters. The principle is that the electrical

Table 2. Measuring Point Position

device name	number	the position from the starting point of the pipe (L/D)
double-parallel conductance probes	20	6, 8, 18, 20, 32, 34, 38, 40, 50, 52, 64, 66, 100, 110, 148, 158, 198, 208, 248, 258
pressure sensor	1	252
differential pressure sensor	1	152–242

conductivity of water and air is different. When the gas–liquid two-phase flow passes through the probe, there is a functional relationship between the resistance between the two parallel probes and the phase holdup of the two-phase flow. Then, the functional relationship between the voltage measured by the probe and the liquid holdup in the tube is established. The cross-correlation method refers to the function calculation of the two-column signals of the double-parallel probes to obtain the cross-correlation function R_{XY} .

$$R_{XY}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T Y(t + \tau)X(t)dt \quad (1)$$

The distance between the abscissa and the ordinate axis corresponding to the maximum value of R_{XY} is the time delay of the two columns of signals. The distance between the two sets of probes is ΔL , and the liquid slug velocity is $V_s = \Delta L/\Delta t$. Further parameters such as the length of the liquid slug area, the length of the liquid slug unit, and the slug frequency are calculated.

The range of the liquid phase superficial velocity in the experimental pipe is 0.2–1.2 m/s; the range of the gas-phase superficial velocity is 0.6–4.5 m/s. Figure 3 shows the distribution of experimental points on the Mandhane flow pattern.

To capture a clear photograph of the gas–liquid interface, a small amount of potassium permanganate was added to the

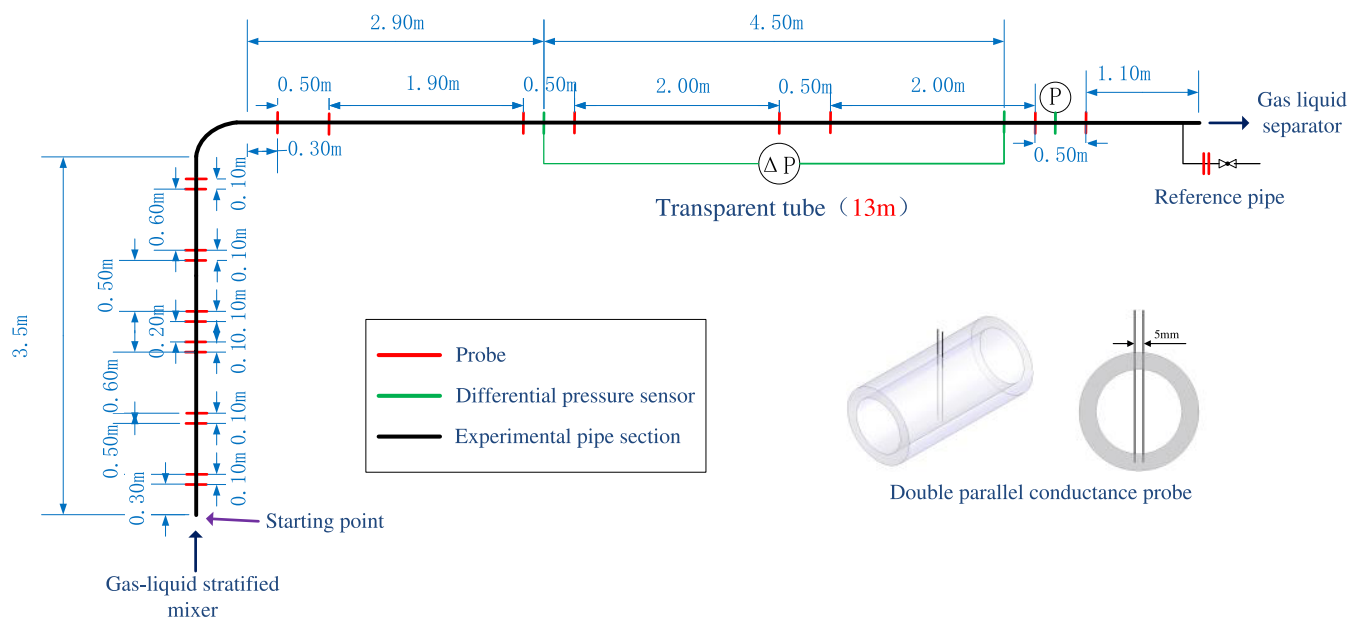


Figure 2. Test-section layout.

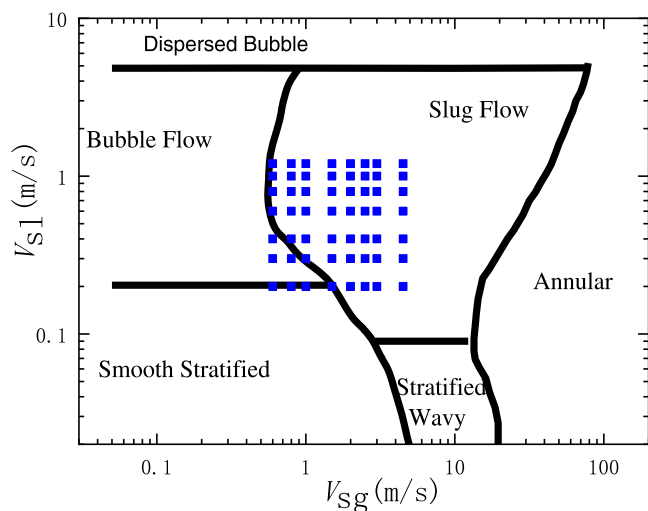


Figure 3. Operating points in Mandhane map.

water to dye it, a yellow ruler was attached to the bottom of the experimental pipeline, and high-definition cameras were used to collect the slugging distance (the distance from the slugging phenomenon to the pipe inlet) and interface wave motion data.

3. ANALYSIS OF SLUGGING CHARACTERISTICS OF GAS-LIQUID INTERFACE

3.1. Slug-Flow Area Division. According to the experimental observation of slug flow and the study of slugging experiments by Li²⁷ and Gu,²⁸ it was found that when the gas-liquid interface slugging phenomenon occurs near the inlet of the pipeline, the gas-liquid interface is generated after the slugging point. When the liquid velocity is low, the gravity wave generated by the sudden drop in the liquid level is transmitted upstream. Figure 4 shows the propagation model²⁸ of the gravity wave in a gas-liquid two-phase flow pipeline.

where C is the propagation velocity of the gravity wave generated by the hydraulic jump surface in the stationary liquid phase²⁹

$$C = \sqrt{gh_1} \quad (2)$$

If the upstream liquid film moves forward with velocity V_l , the propagation velocity of the gravity wave generated by the hydraulic surface is

$$C = \sqrt{gh_1} - V_{sl} \quad (3)$$

It can be seen from the above formula that if V_{sl} is large enough, the gravity wave velocity is less than 0, and the wave does not propagate upstream and will not affect the upstream

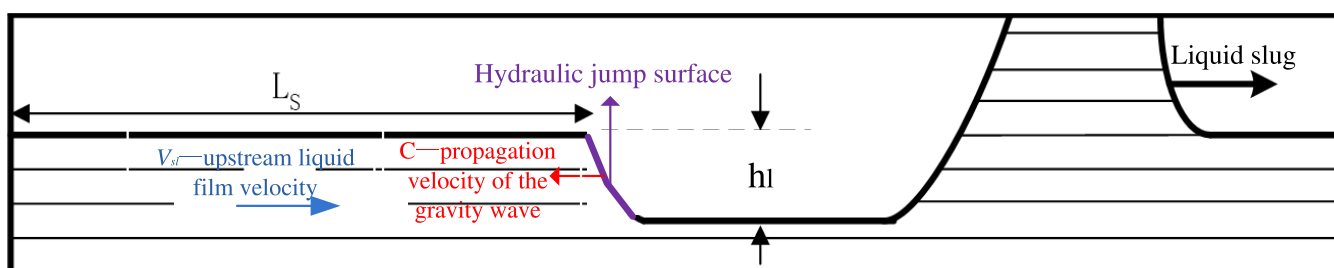


Figure 4. Schematic diagram of gravity wave propagation.

liquid film area; if V_{sl} is small, the gravity wave velocity is greater than 0, and the wave will propagate upstream.

In this study, the slug flow region is divided into three regions, as shown in Figure 5, based on the gas and liquid

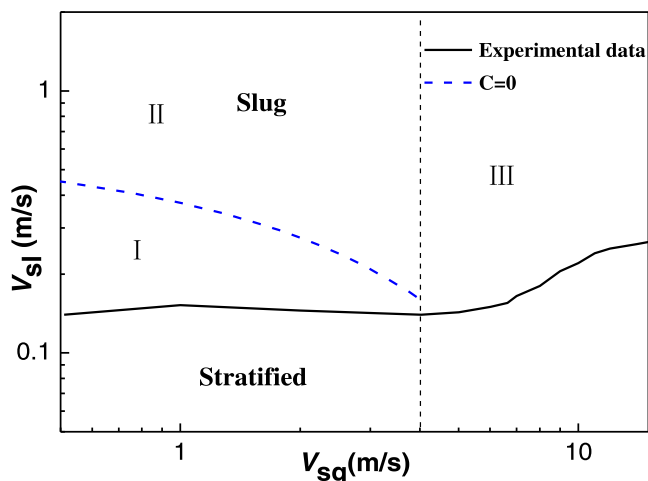


Figure 5. Gas–liquid flow pattern in the horizontal pipeline ($D = 50$ mm).

velocity curves and different morphological characteristics of the gas–liquid interface when the gravity wave velocity is 0: region I is the slug flow region where the propagation velocity of the gravity wave is less than 0; region II is the slug flow region where the propagation velocity of the gravity wave is greater than 0 and $V_{sg} < 4$ m/s; and region III is the slug flow region with $V_{sg} > 4$ m/s.

3.2. Slugging Phenomenon Analysis. Figure 6 shows the gas–liquid interface images obtained by photographing the experimental points in region I with $V_{sg} = 2$ m/s and $V_{sl} = 0.2$ m/s at $L/D = 20, 28,$ and 54 . The time interval of each image in (a) and (b) is $1/50$ s, and the time interval of each image in (c) is $3/50$ s. From (a), it can be seen that the wavelength of the interface wave at $L/D = 20$ is about 2.5–3 cm, and based on the image time difference and the interface wave forward distance, it can be calculated that the interface wave velocity is about 0.5 m/s, the wave frequency is about 17–20 Hz, and the wave amplitude is about 3–4 mm. Similarly, the wavelength of the interface wave at $L/D = 28$ in (b) is about 5–5.5 cm, the wave velocity is about 0.5 m/s, the wave frequency is about 9–10 Hz, and the wave amplitude is about 6–8 mm. The

wavelength of the interface wave at $L/D = 54$ in (c) is about 10–11 cm, the wave velocity is about 0.61 m/s, the wave frequency is about 5.55–6.1 Hz, and the wave amplitude is about 10–14 mm. It can be seen from (c) that when the wave crest of the interface wave reaches a certain height, a slugging phenomenon occurs due to instability. After slugging, the liquid level decreases rapidly and a hydraulic jump surface appears.

Comparing (a) and (b), it can be found that from $L/D = 20$ to 28, the interface wave velocity remains the same, the wavelength doubles, the wave frequency halves, and the interface wave amplitude doubles. Comparing (b) and (c), it can be seen that from $L/D = 28$ to 54, the interface wave velocity increases slightly, the interface wave wavelength doubles, the wave frequency halves, and the interface wave amplitude doubles.

Therefore, the slugging phenomenon can be summarized as follows: the gas–liquid two-phase flow in the horizontal pipe forms relatively regular interface waves near the inlet due to the difference in gas and liquid velocities. The interface wave moves forward in the fusion mode of constant wave velocity, doubling wavelength, doubling amplitude, and halving frequency until the wave amplitude reaches a certain height and then becomes unstable and slugging occurs. It is consistent with the theory of Lin and Hanratty.¹⁶

3.3. Slugging Characteristics of the Gas–Liquid Interface. Figure 7 shows the gas–liquid interface conditions at different positions along the pipeline when $V_{sg} = 2$ m/s and $V_{sl} = 0.2$ m/s. The working condition is in the slug flow region I of the flow pattern diagram in Figure 5. As shown in the figure, the slugging process of the gas–liquid interface is similar to that described by Taitel and Dukler.³⁰ With the injection of the inlet gas and liquid phase, an obvious interface wave is generated at $32D$, and the interface wave amplitude increases at $38D$. When the gas–liquid interface reaches the critical liquid-level height of $0.67(h/D)$ at $50D$, the interface wave becomes unstable and slugging occurs.

Overall, it can be observed that the liquid slugs appear periodically and multiple times, as shown in S1 and S2 in Figure 7. When the liquid level reaches the critical liquid-level height, slugging occurs (S1), and the gravity wave generated by slugging is transmitted upstream. Because the upstream region is in a high-liquid-level state, the critical liquid level for slugging is satisfied. When disturbed by the gravity wave (red circle in Figure 7), secondary slugging was induced at $50D$ (S2). Slugging (S2) causes the upstream liquid level to drop

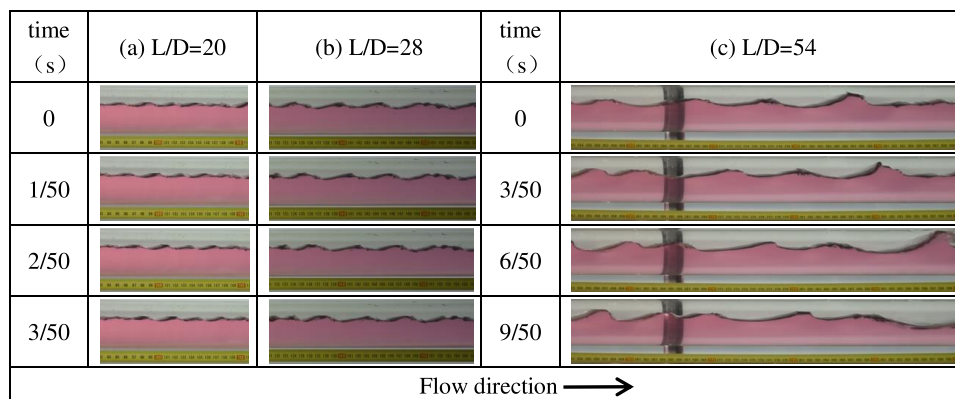


Figure 6. Image of interface wave ($V_{sg} = 2$ m/s, $V_{sl} = 0.2$ m/s) under the following conditions: (a) $L/D = 20$, (b) $L/D = 28$, (c) $L/D = 54$.

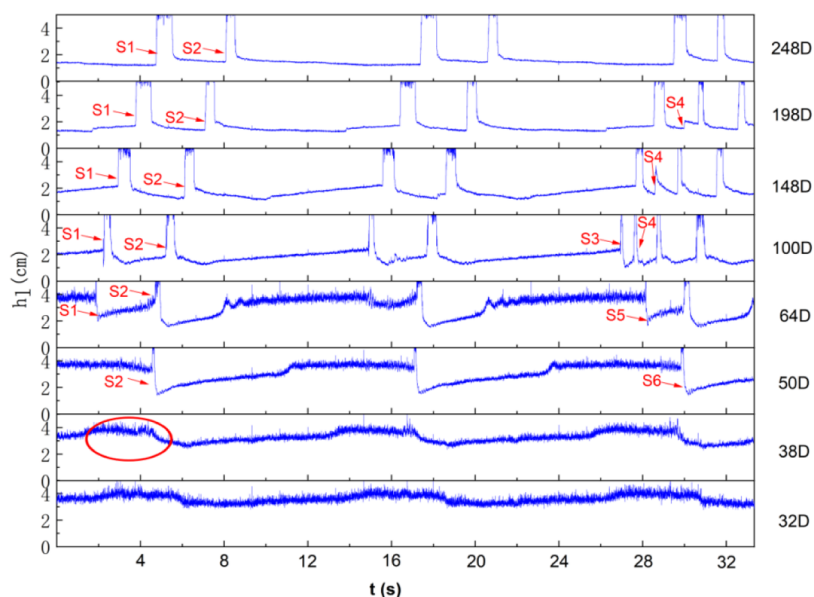


Figure 7. Development of gas–liquid interface in region I ($V_{sg} = 2$ m/s, $V_{sl} = 0.2$ m/s).

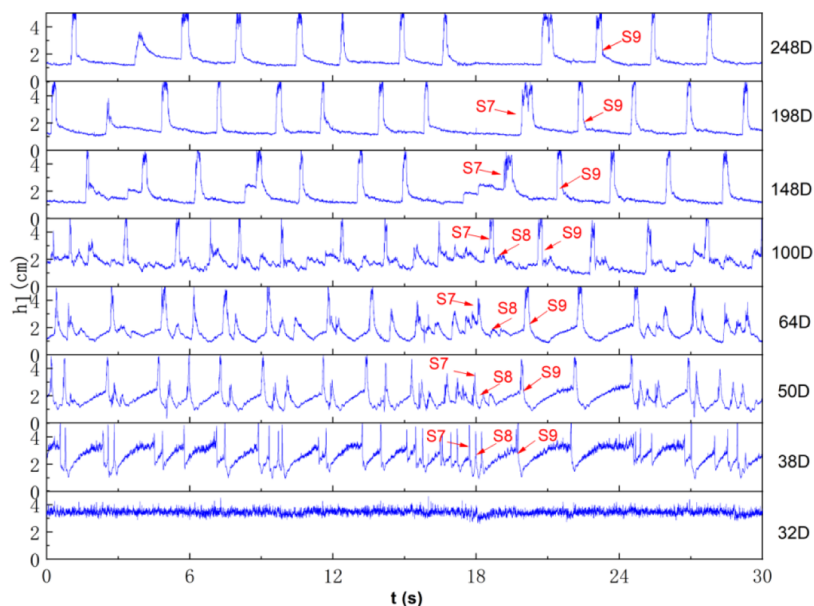


Figure 8. Development of gas–liquid interface in region II ($V_{sg} = 2$ m/s, $V_{sl} = 0.4$ m/s).

rapidly. Because the upstream liquid level is lower than the critical liquid level for slugging, the gravity wave caused by slugging (S2) cannot be transmitted upstream to cause slugging again. After a period of time, the liquid level gradually increases to the critical liquid level under the equilibrium of the gas and liquid phases, and the slugging phenomenon occurs again. The periodic phenomenon of the interface at 32D is caused by the upstream transmission of gravity waves at low liquid velocities.

Figure 8 shows the gas–liquid interface conditions at different positions along the pipeline when $V_{sg} = 2$ m/s and $V_{sl} = 0.4$ m/s. The working condition is in the slug flow region II of the flow pattern diagram in Figure 5. As shown in Figure 8, the slugging process of the gas–liquid interface is still similar to the slugging process described by Taitel and Dukler.³⁰

Compared with Figure 7, the frequency of liquid slugs in Figure 8 is significantly increased, and the liquid level of the

gas–liquid interface at the slugging position exhibits obvious periodic changes, whereas the gas–liquid interface at 32D upstream of the slugging position has no periodicity. The change is due to the increase in the liquid velocity, and the gravity wave caused by the slugging cannot be transmitted upstream. There is no obvious periodic fluctuation at the upstream interface, which shortens the time required for the transformation from the lowest liquid level to the slugging liquid level so that the frequency of liquid slugs increases, which also explains the phenomenon that when the gas velocity is constant, the increase in liquid velocity increases the frequency of liquid slugs.³¹ This is consistent with the flow pattern division shown in Figure 5, indicating that the propagation of gravity waves has a significant influence on the slugging law of the gas–liquid interface.

Figure 9 shows the images of the slugging process in regions I and II. It can be observed in the figure that when $V_{sg} = 2$ m/s

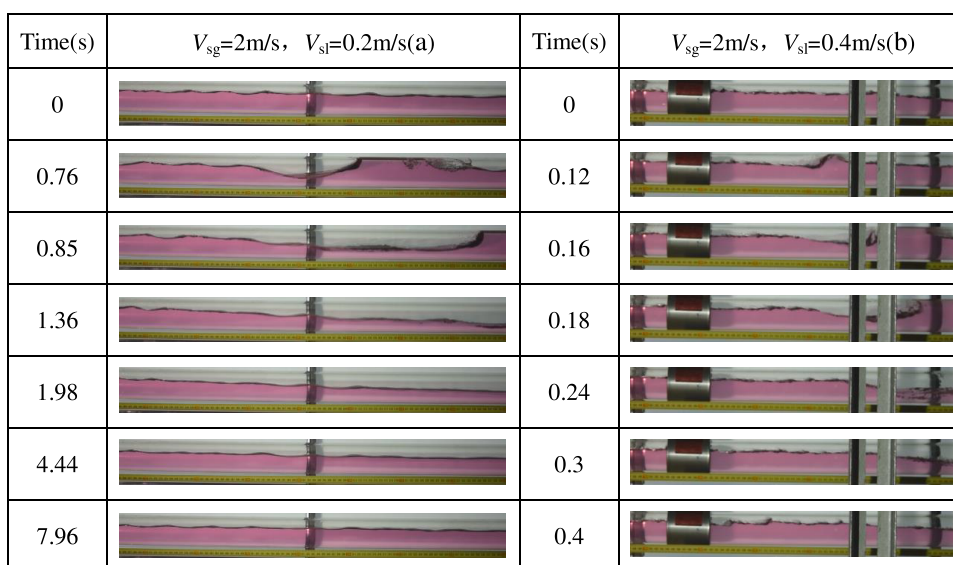


Figure 9. Image of slugging process under the following conditions: (a) $V_{sg} = 2 \text{ m/s}$, $V_{sl} = 0.2 \text{ m/s}$; (b) $V_{sg} = 2 \text{ m/s}$, $V_{sl} = 0.4 \text{ m/s}$.

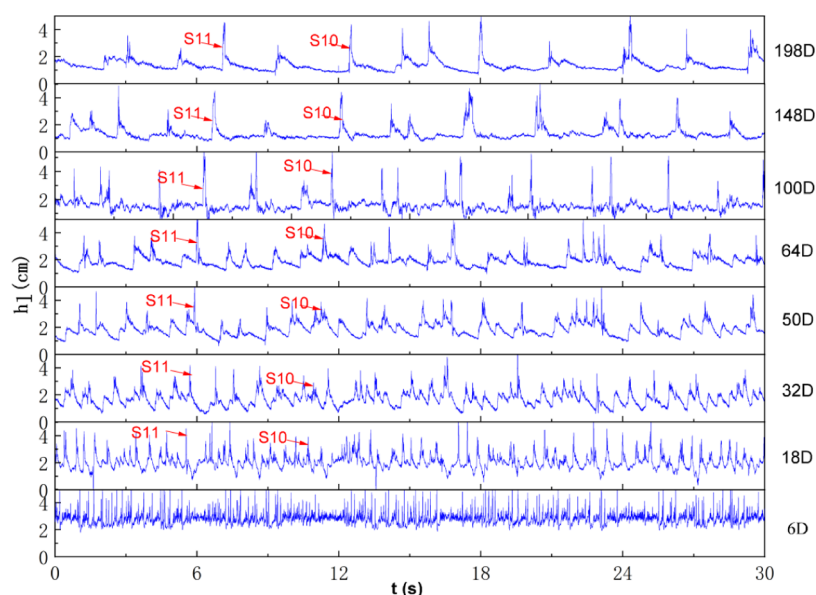


Figure 10. Development of gas–liquid interface in region III ($V_{sg} = 4.5 \text{ m/s}$, $V_{sl} = 0.4 \text{ m/s}$).

and $V_{sl} = 0.2 \text{ m/s}$, the liquid level of the hydraulic jump surface formed by the slugging is low, and the gravity wave caused by the hydraulic jumping surface causes the upstream liquid level to drop. After the liquid slug passes through, the liquid level gradually rises to the initial level, which is consistent with the law presented in Figure 7. When $V_{sg} = 2 \text{ m/s}$ and $V_{sl} = 0.4 \text{ m/s}$, the liquid level of the hydraulic jump surface formed by slugging is relatively high. During the formation of the liquid slug and the downstream movement, there is no significant change in the upstream liquid level. From the comparison of the slugging process in regions I and II, it can be observed that the increase in the liquid velocity prevents the gravity wave from being transmitted upstream, and the propagation of the gravity wave has a significant influence on the shape of the gas–liquid interface.

Figure 10 shows the gas–liquid interface at different positions along the pipeline when $V_{sg} = 4.5 \text{ m/s}$ and $V_{sl} = 0.4 \text{ m/s}$. The working condition is in the slug flow region III of

the flow pattern diagram in Figure 5. Compared with Figures 7 and 8 at a low gas velocity, Figure 10 shows that the slugging is more random, the frequency of short slugs at the inlet increases significantly, and there is no periodic fluctuation of the interface at the slugging position. Before a stable liquid slug is formed, it moves forward in the form of rolling waves and forms a stable liquid slug in the form of rolling-wave merging. This is due to the large inlet disturbances at high gas velocities, resulting in high-frequency short slugs. This short slug is similar to the interface wave with a large amplitude, which degenerates into a rolling wave under the blowing of high gas velocity. The rolling waves merge with each other to reach the critical liquid-level height of slugging, and slugging occurs (S10), forming a stable liquid slug. It can be seen that the slugging characteristics of the liquid slug at a high gas velocity are remarkably different from those at a low gas velocity.

It can be observed from the development process of the gas–liquid interfaces of regions I, II, and III that the gas–

liquid interface has obvious periodic fluctuations at the slugging position at a low superficial gas velocity (regions I and II). Thus, the slugging phenomenon occurs when the interface gradually reaches the critical liquid level (h_s) from the lowest liquid level (h_o), and then the liquid level rapidly drops to the lowest liquid level (h_o) for the next cycle. It can be observed that h_o and h_s are important parameters for slugging at a low superficial gas velocity. Taitel and Dukler³⁰ pointed out that in the interface slugging model, h_o is the critical liquid-level height for generating interface waves, as predicted by Taitel.¹¹ h_s is the critical liquid-level height for quasi-steady stratified flow at a given gas–liquid velocity, as predicted by Dukler.³² The values calculated as per the slugging model of Taitel and Dukler,³⁰ liquid slug stability theory of Woods and Hanratty,⁸ and interfacial stability theory of Barnea and Taitel¹⁷ are compared with the experimental data of h_o and h_s , as shown in Figures 11 and 12.

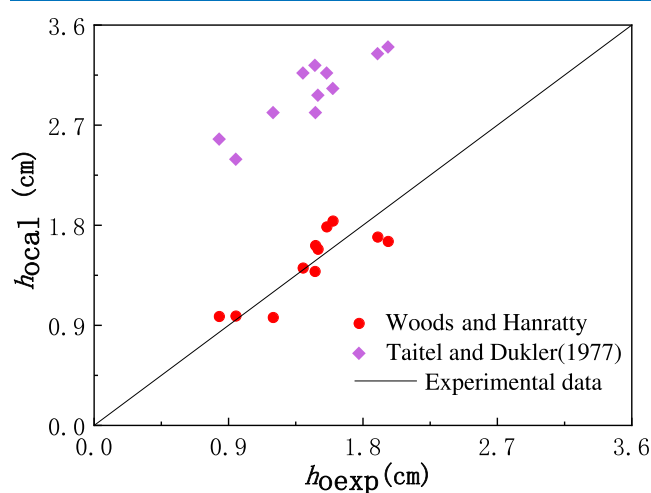


Figure 11. Comparison between experimental values and theoretical values of h_o .

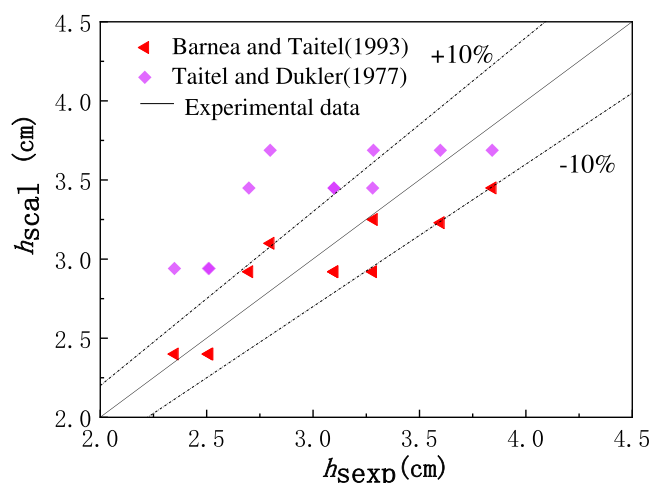


Figure 12. Comparison between experimental values and theoretical values of h_s .

It can be seen in Figure 11 that the value calculated as per the theoretical model of Taitel and Dukler³⁰ is considerably higher than the experimental data of h_o , whereas the theoretical value of the liquid slug stability calculated using the theory of Woods and Hanratty⁸ is in good agreement with the

experimental data of h_o . As shown in Figure 12, the liquid-level height of the quasi-steady stratified flow is significantly higher than that of the h_s experimental data, and the values calculated using the theoretical model of Barnea and Taitel¹⁷ are more consistent with the h_s experimental data (the deviation is within 10%). Through the development process of regions I, II, and III, gas–liquid interfaces, and the analysis of Figures 11 and 12, it can be inferred that h_o is not the critical liquid-level height for generating the interface waves but is the critical liquid-level height for the stability of the liquid slug, and h_s is the critical liquid-level height for the interface instability.

It is proved that the liquid slug stability theory and the interface instability theory model are in good agreement with the experimental data, especially the liquid slug stability theory. Combined with the slugging experiments in the three flow regions, it can be concluded that when the height of the gas–liquid interface reaches the liquid-level height h_s of the interface instability and slugging, slugging occurs, and the liquid-level height is reduced to the lowest level after the slugging. If the minimum liquid-level height can reach the critical liquid-level height h_o at which the liquid slug is stable, a stable liquid slug can be formed; otherwise, it degenerates into a rolling wave.

4. INFLUENCE OF GAS–LIQUID VELOCITY ON SLUGGING CHARACTERISTICS

4.1. Influence of Gas–Liquid Velocity on Slugging Distance. Figure 13 displays the change in the slugging

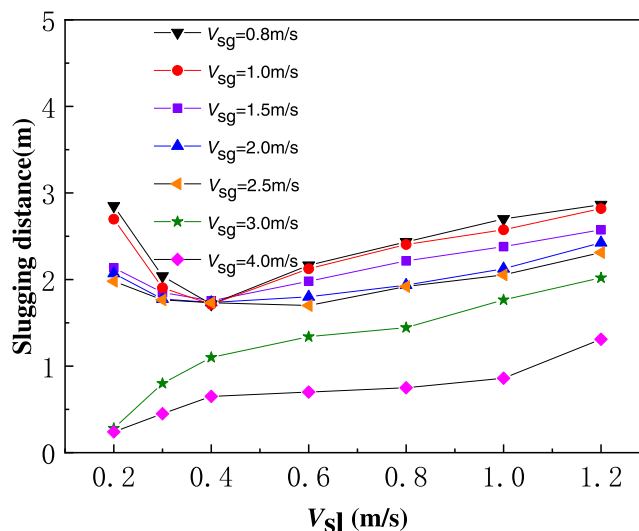


Figure 13. Variation of slugging distance with superficial liquid velocity.

distance with the superficial velocity of the liquid phase. When the gas-phase superficial velocity (V_{sg}) < 3 m/s, the slugging distance first decreases and then increases with the increase of the liquid-phase superficial velocity, and the liquid-phase superficial velocity (V_{sl}) is 0.4 m/s as the turning point. When $V_{sg} \geq 3$ m/s, the slugging distance increases monotonically with increasing liquid-phase superficial velocity.

4.2. Influence of Gas–Liquid Velocity on h_o and h_s . Figure 14 shows the change of the critical liquid-level height h_o for the stability of the liquid slug with the superficial velocity of the liquid phase. It can be seen from the figure that with the increase of V_{sl} , h_o gradually increases. With the increase of V_{sg} ,

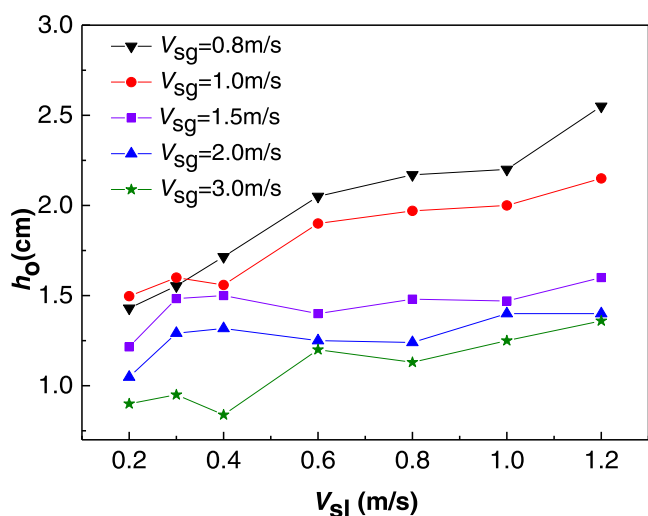


Figure 14. Variation of h_o with superficial gas and liquid velocity.

h_o decreases significantly, which is consistent with the liquid slug stability model. Figure 15 shows the change of critical

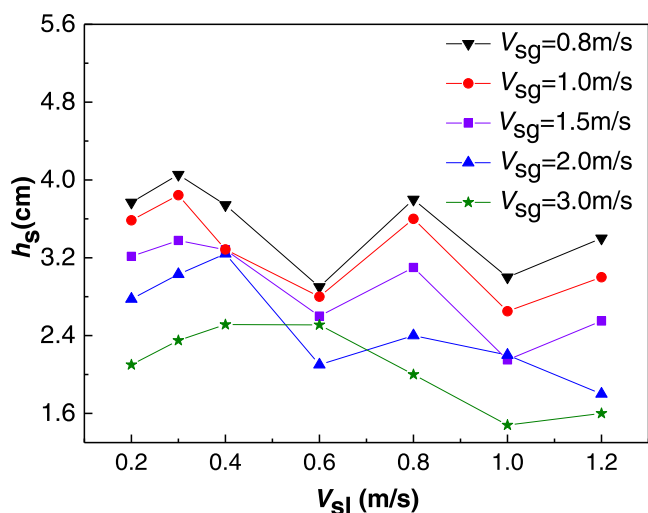


Figure 15. Variation of h_s with superficial gas and liquid velocity.

liquid-level height h_s for the interface instability with the superficial velocity of the liquid phase. It can be seen from the figure that h_s changes irregularly with V_{sl} , so the experimental value of h_s deviates from the prediction of the interface instability theory. With the increase in V_{sg} , h_s decreases significantly. This is because, with the increase in the gas velocity, the pressure of the gas space above the gas–liquid interface wave at the inlet decreases, and the lifting force increases under the action of the front-to-back pressure difference. The interface wave destabilizes and causes slugging at the lower critical liquid level.

4.3. Influence of Gas–Liquid Velocity on Liquid Slug Frequency. Figure 16 shows the change in the liquid slug frequency along the flow direction of the pipeline under different gas–liquid apparent flow rates. It can be observed from the figure that the change in the frequency of the liquid slug along the pipeline under different gas–liquid velocities is constant. During slugging, the frequency of the liquid slug reaches its maximum, and the liquid slug merges or degenerates into a rolling wave during the flow of the liquid

slug along the pipeline. This reduces the frequency of the liquid slug until a stable liquid slug is formed, and the frequency remains stable. When the gas velocity is constant, the frequency of liquid slugs at different positions along the pipeline increases with increasing liquid velocity. When the liquid velocity is constant, a horizontal comparison of the four graphs in Figure 16 shows that the higher the gas velocity, the faster the liquid slug frequency decreases after the peak of the liquid slug frequency is attained. This indicates that the phenomenon of liquid slug merger and disappearance is likely to occur at a high gas velocity, which is consistent with the analysis in Figure 10. When the gas velocity is constant, as the liquid velocity decreases, the decreasing trend of the liquid slug frequency gradually becomes slower, and the liquid slug frequency remains unchanged along the pipeline at a low liquid velocity. This shows that with the decrease in the liquid velocity, the phenomenon of liquid slug merger and disappearance gradually decreases, and the proportion of stable liquid slug formed during slugging increases.

From Figure 16a–c, it can be deduced that with the increase in the superficial velocity of the liquid phase, the peak of the liquid slug frequency shifts to the right, which is caused by the increase in the liquid velocity, which causes the position of the slug to shift right. In Figure 16c,d, it can be observed that there is a small peak in the increase in the slug frequency at 100D, which may be caused by the limitation of the experimental loop. Before 100D, it was the turning part of the experimental pipeline. The fluctuation of the pressure at the elbow caused a new liquid slug, which increases the frequency of the liquid slug, indicating that the elbow has a certain influence on the development process of the liquid slug.

5. RESULTS AND DISCUSSION

- (1) At a low V_{sg} , the slugging occurs in the form of interface waves growth with a large frequency and small amplitude, and the slugging process is regular. At a high V_{sg} , the slugging process is irregular. Most liquid slugs move forward in the form of rolling waves and finally form a stable liquid slug in the form of merged rolling waves.
- (2) At a low V_{sl} , the gravity wave generated by slugging is transmitted upstream, causing periodic fluctuations at the upstream gas–liquid interface. At a high V_{sl} , the upstream interface does not experience periodic fluctuations.
- (3) The liquid slug stability theory and the interface instability theory model are in good agreement with the experimental data, especially the liquid slug stability theory. It can be inferred that h_o is the critical liquid-level height for the stability of the liquid slug and h_s is the critical liquid-level height for the interface instability.
- (4) h_o increased with increasing V_{sl} and decreased significantly with increasing V_{sg} . h_s changes more irregularly with the increase of V_{sl} and gradually decreases with the increase of V_{sg} .
- (5) When $V_{sg} < 3$ m/s, the slugging distance first decreases and then increases with the increase in V_{sl} . $V_{sl} = 0.4$ m/s is the turning point. When $V_{sg} \geq 3$ m/s, the slugging distance increases monotonically with increasing V_{sl} .
- (6) After slugging, the liquid slug frequency reaches a peak value, and the liquid slug frequency gradually decreases to a stable state. The higher the V_{sg} , the faster the liquid

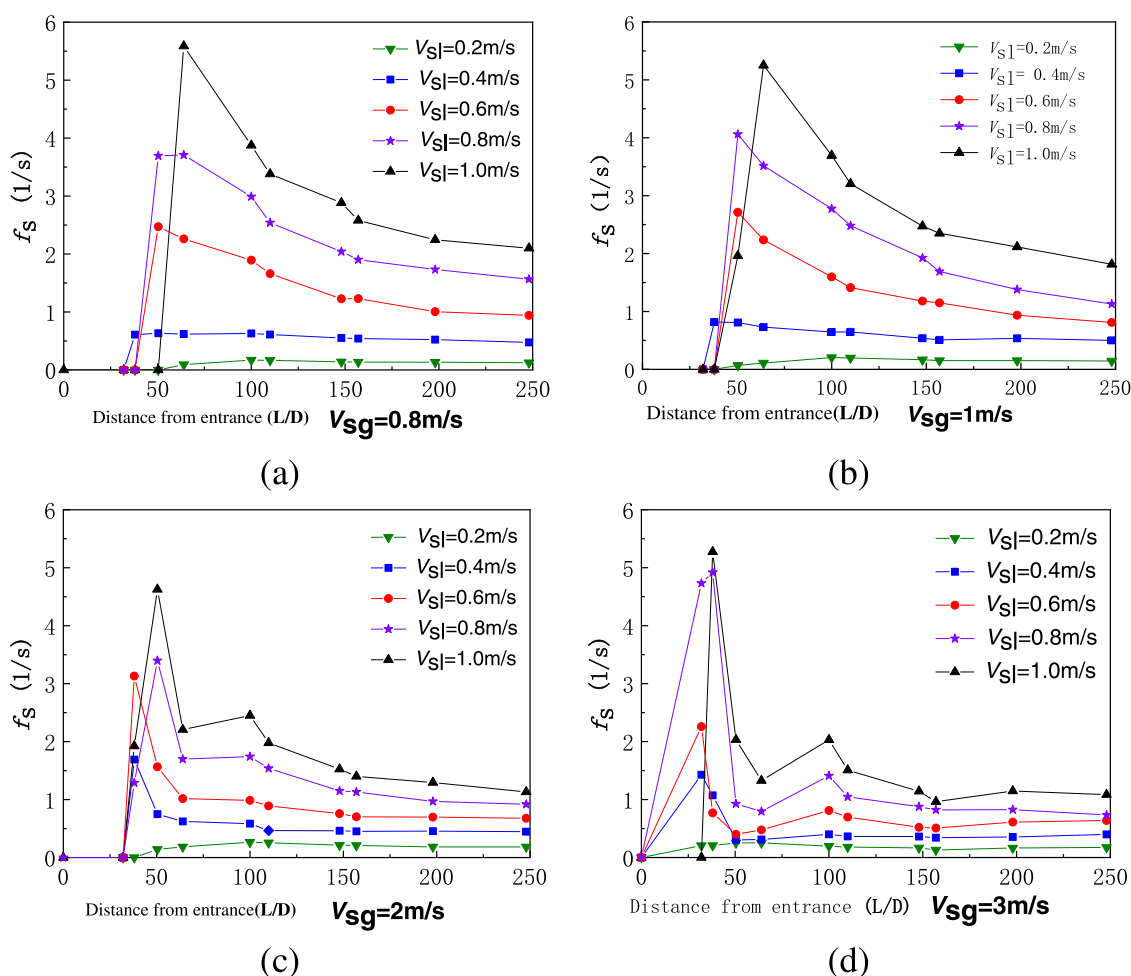


Figure 16. Variation of slug frequency along the flow direction under the following conditions: (a) $V_{sg} = 0.8$ m/s, (b) $V_{sg} = 1$ m/s, (c) $V_{sg} = 2$ m/s, (d) $V_{sg} = 3$ m/s.

slug frequency decreases after the peak of the liquid slug frequency is attained. With the increase of V_{sl} , the peak of the liquid slug frequency shifts to the right.

AUTHOR INFORMATION

Corresponding Author

Zhaoting Wang – Shandong Institute of Petroleum and Chemical Technology, Dongying 257061 Shandong, China; Email: 2018001@sdipct.edu.cn

Authors

Xiao Wu – Shandong Institute of Petroleum and Chemical Technology, Dongying 257061 Shandong, China; orcid.org/0000-0001-7803-740X

Longfei Dong – Shandong Institute of Petroleum and Chemical Technology, Dongying 257061 Shandong, China

Yanping Xin – Shandong Institute of Petroleum and Chemical Technology, Dongying 257061 Shandong, China

Huiqing Cao – Shandong Institute of Petroleum and Chemical Technology, Dongying 257061 Shandong, China

Complete contact information is available at: <https://pubs.acs.org/10.1021/acsomega.2c01516>

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the Science Development Funding Program of Dongying of China (grant no. DJ2021006) and Science Development Funding Program of Dongying of China (grant no. DJ2021008).

NOMENCLATURE

V_{sl}	liquid-phase apparent velocity, m/s
V_{sg}	gas-phase superficial velocity, m/s
V_b	gas slug head moving speed, m/s
V_t	liquid slug head moving speed, m/s
U	average speed, m/s
U_d	drift speed of gas slug, m/s
h_o	minimum liquid-level height of the slugging interface, m
h_s	critical liquid-level height of the slugging interface, m
h_l	liquid-film thickness, m
h/D	liquid level (ratio of liquid-level height to pipe diameter)
D	pipe inner diameter, m
"148D"	position (148 times the pipe diameter from the starting point of the pipe)
"L/D = 64"	position (64 times the pipe diameter from the starting point of the pipe)
"S1" "S2"	liquid slug shown in Figures 7, 8, and 10

C_0	slug slip coefficient
α	phase holdup
ρ	density, kg/m ³
A	cross-sectional area, m ²

REFERENCES

- (1) Elhagar, M.; Awad, M.; Ahmed, A. Z.; Emam, N. E.; Aboul, T. M. Slug flow control hinges on integrated operations. *Oil Gas J.* **2019**, *117*, 56–64.
- (2) Jepson, W. P. Modelling the transition to slug flow in horizontal conduit. *Can. J. Chem. Eng.* **1989**, *67*, 731–740.
- (3) Bendiksen, K.; Espedal, M. Onset of slugging in horizontal gas-liquid pipe flow. *Int. J. Multiphase Flow* **1992**, *18*, 237–247.
- (4) Bendiksen, K. H. An experimental investigation of the motion of long bubbles in inclined tubes. *Int. J. Multiphase Flow* **1984**, *10*, 467–483.
- (5) Ruder, Z.; Hanratty, P. J.; Hanratty, T. J. Necessary conditions for the existence of stable slugs. *Int. J. Multiphase Flow* **1989**, *15*, 209–226.
- (6) Benjamin, T. B. Gravity currents and related phenomena. *J. Fluid Mech.* **1968**, *31*, 209–248.
- (7) Lunde, O.; Ashelm, H. In *An Experimental Study of Slug Stability in Horizontal Flow*, Proceedings of the 4th International Multiphase Flow Conference, France, 1989; pp 419–430.
- (8) Woods, B. D.; Hanratty, T. J. Relation of slug stability to shedding rate. *Int. J. Multiphase Flow* **1996**, *22*, 809–828.
- (9) Sanchis, A.; Johnson, G. W.; Jensen, A. The formation of hydrodynamic slugs by the interaction of waves in gas-liquid two-phase pipe flow. *Int. J. Multiphase Flow* **2011**, *37*, 358–368.
- (10) Wallis, G. B.; Dobson, J. E. The onset of slugging in horizontal stratified air-water flow. *Int. J. Multiphase Flow* **1973**, *1*, 173–193.
- (11) Taitel, Y.; Dukler, A. E. A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. *AIChE J.* **1976**, *22*, 47–55.
- (12) Kordyban, E. The transition to slug flow in the presence of large waves. *Int. J. Multiphase Flow* **1977**, *3*, 603–607.
- (13) Kordyban, E. Some details of developing slugs in horizontal two-phase flow. *AIChE J.* **1985**, *31*, 802–806.
- (14) Trapp, J. A. The mean flow character of two-phase flow equations. *Int. J. Multiphase Flow* **1986**, *12*, 263–276.
- (15) Minato, A.; Ikeda, T.; Naitoh, M. Mechanistic model of slugging onset in horizontal circular tubes. *J. Nucl. Sci. Technol.* **1986**, *23*, 761–768.
- (16) Lin, P. Y.; Hanratty, T. J. Prediction of the initiation of slugs with linear stability theory. *Int. J. Multiphase Flow* **1986**, *12*, 79–98.
- (17) Barnea, D.; Taitel, Y. Kelvin-Helmholtz stability criteria for stratified flow: viscous versus non-viscous (inviscid) approaches. *Int. J. Multiphase Flow* **1993**, *19*, 639–649.
- (18) Fabre, J.; Liné, A. Modeling of two-phase slug flow. *Annu. Rev. Fluid Mech.* **1992**, *24*, 21–46.
- (19) Barnea, D. On the effect of viscosity on stability of stratified gas-liquid flow—application to flow pattern transition at various pipe inclinations. *Chem. Eng. Sci.* **1991**, *46*, 2123–2131.
- (20) Wu, Q.; Ishii, M. Interfacial wave stability of concurrent two-phase flow in a horizontal channel. *Int. J. Heat Mass Transfer* **1996**, *39*, 2067–2075.
- (21) Barmak, I.; Gelfgat, A.; Vitoshkin, H.; et al. Stability of stratified two-phase flows in horizontal channels. *Phys Fluids* **2016**, *28*, No. 044101.
- (22) Náraigh, L. Ó.; Spelt, P.; Matar, O. K. Interfacial instability in turbulent flow over a liquid film in a channel. *Int. J. Multiphase Flow* **2011**, *37*, 812–830.
- (23) Náraigh, L. Ó.; Spelt, P.; Zaki, T. A. Turbulent flow over a liquid layer revisited: Multi-equation turbulence modelling. *J. Fluid Mech.* **2011**, *683*, 357–394.
- (24) Vallée, C.; Höhne, T.; Prasser, H. M.; et al. Experimental investigation and CFD simulation of horizontal stratified two-phase flow phenomena. *Nucl. Eng. Des.* **2008**, *238*, 637–664.
- (25) Ujang, P. M.; Lawrence, C. J.; Hale, C. P.; et al. Slug initiation and evolution in two-phase horizontal flow. *Int. J. Multiphase Flow* **2006**, *32*, 527–552.
- (26) Lu, M. Experimental and Computational Study of Two-Phase Slug Flow. Dissertation, Imperial College London: UK, 2015.
- (27) Li, G. J. Research on Interface Wave Characteristics of Gas-Liquid Two-Phase Flow in Pipelines. Dissertation, Xi'an Jiaotong University: China, 1996.
- (28) Gu, H. Y.; Guo, L. J. Experimental study on the development characteristics of gas-liquid slug flow in a horizontal pipe. *Chin. J. Chem. Eng.* **2008**, *16*, 171–177.
- (29) Stoker, J. J. Propagation of Gravity Waves. In *Water Waves*; Interscience Publishers Inc.: New York, 1957; pp 213–228.
- (30) Taitel, Y.; Dukler, A. E. A model for slug frequency during gas-liquid flow in horizontal and near horizontal pipes. *Int. J. Multiphase Flow* **1977**, *3*, 585–596.
- (31) Dong, C. S. Experimental Study on Flow and Heat Transfer of Gas-Liquid Two-Phase Slug Flow in Cooling Process Without Phase Change. Dissertation, China University of Petroleum: China, 2015.
- (32) Dukler, A. E.; Hubbard, M. G. A model for gas-liquid slug flow in horizontal and near horizontal tubes. *Ind. Eng. Chem. Fundam.* **1975**, *14*, 337–347.