

Article

Experimental Study on Gas–Liquid Interface Evolution during Liquid Displaced by Gas of Mobile Pipeline

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Abstract: The mobile pipeline is the most effective and reliable means for the emergency oil transfer task, which is temporarily laid on the field. After completing the task, the oil in the pipeline should be emptied before the mobile pipeline is removed. The oil in pipeline gradually displaced by the air is a main method of pipeline evacuation, which is the only choice of jet fuel pipeline. Due to the convection between gas and oil phases, the length of the oil–gas mixing section and the evolution of the oil–gas interface change with time. The evolution of the gas–liquid interface directly determines the different flow patterns of oil–gas two phases, which are very important for the mobile pipeline evacuation. In this paper, the characteristics of the gas–liquid interface evolution during the water displaced by air are studied, using the multi-phase pipeline experiment. Through the change of the gas–liquid interface in the initial stage of gas cap evacuation, it is found that the gas–liquid interface can be divided into smooth, wavy, and dispersed forms under different initial gas flow rates and different inclination angles. Slug phenomenon may occur in the process of gas-carrying liquid flow in the pipeline. The emergence of slug is mainly affected by hydraulic conditions and pipeline operating conditions. The liquid plug body is complex and unstable, and there will be a mutual transition between different liquid slug shapes. The increase of the inclination angle and gas phase velocity will accelerate the occurrence of liquid slug frequency.

Keywords: mobile pipeline; gas cap evacuation; gas–liquid interface evolution; gas–liquid slug flow; liquid displacement



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1. Introduction

The introduction mobile pipeline is an assembled system composed of oil pipes, mobile oil pumps, valves, measuring and detecting instruments, communication devices, etc., and is connected by quick couplings [1]. It is directly laid on the field ground during combat, military training, or rescue and disaster relief operation, featuring rapid laying and withdrawing. The oil in the mobile pipeline must be evacuated and recycled to the oil tank or tanker when the mobile pipeline is withdrawn, stopped for a long time, and repaired [2,3]. The gas cap evacuation, which refers to the use of an air compressor to charge compressed air at one end of the line to push the oil in the pipe out of the other end until all the oil is pushed out of the pipeline, is a main method of pipeline evacuation [4].

In the process of oil displaced by gas of a mobile pipeline, the gas–liquid mixing section migrates downstream with the gas phase continuously entering the pipeline. Due to the convection of oil and gas phases, the length of the gas–liquid mixing section and the shape of the gas–liquid interface constantly change with time. The evolution of the gas–liquid interface directly determines the gas–liquid two-phase flow pattern transformation from stratified flow to slug flow and then to disperse flow. Different flow patterns make the gas–liquid mixing section different flow characteristics and oil-mixing characteristics. The evolution of the gas–liquid phase interface is a unique feature of the two-phase flow, which is of decisive significance for the description and prediction of the two-phase flow process

together with the mechanical properties of interface fluctuations and the characteristic parameters of the phase interface (such as local phase distribution, phase interface concentration distribution) [5,6]. However, the phase distribution and the interface concentration distribution interact with the turbulent characteristics in the multi-phase fluid. Therefore, the characteristics and evolution of the air–liquid interface are the basis for the study of gas cap evacuation [7,8].

Guo et al. [9] analyzed the linear instability of the gas–liquid two-phase flow interface by mathematical methods, studied the influence of gas–liquid two-phase flow rate, liquid viscosity, surface tension, and pipeline inclination on the stability of the interface, and achieved good research results in factors such as flow rate, surface tension, and pipeline inclination. Due to the complexity of the effects of liquid viscosity, further research is still needed. Roitberg et al. [10] conducted an experimental research on the gas–liquid two-phase flow in the downward inclined pipeline by using tubular endoscopy technology and obtained the gas–liquid interface morphology under different inclination angles and gas flow rates. García et al. [11] studied different nonlinear instability mechanisms that promote interfacial wave saturation or rapid amplification in stratified flows by numerical simulation methods. Barmak et al. [12] studied the non-modal transient growth of two mutually immiscible fluids perturbed in horizontal and inclined channel flow. Mandal et al. [13] conducted experimental studies on the gas–liquid two-phase flow in undulating pipelines. At low flow rates, the flow pattern is mainly stratified flow, and the slug that starts in the uphill area will partially or completely dissipate in the downhill area; at high flow rate, the flow type is dominated by slug flow, and the pipe undulation will not affect the slug flow type. Khaledi et al. [14] conducted experimental research on the flow characteristics of viscous oil–gas two-phase flow, and proposed a new steady-state flow model and, compared with other research data, found that the consistency in the average liquid content and pressure drop was high, but the model ignored the effect of the change of the gas–liquid interface, and the transition prediction of the flow pattern was quite different from the actual situation. Al-Safran et al. [15] and Zhao et al. [16] studied the flow characteristics of the slug flow in the high viscosity gas–liquid two-phase flow in the horizontal pipe, the liquid content, and bubble characteristics of the slug, and found that under normal circumstances, the regional area and the liquid content of the slug increase with the increase of the viscosity of the liquid, but this will not happen on the soda–water two-phase flow, because the higher surface tension will entrain larger bubbles, resulting in the decrease of liquid content of the slug. Kesana et al. [17] visualized the pseudo slug flow in the gas–liquid two-phase flow by the wire-mesh sensor. The pseudo slug flow is a special flow type that appears at a high gas phase surface velocity because the gas liquid is highly mixed in the liquid plug, resulting in an increase in the void ratio, and the gas phase distribution in the pseudo slug flow is obviously different from the slug flow, showing unique flow characteristics. Soedarmo et al. [18] proposed a new cell model of pseudo slug flow, which considered the gas–liquid mixture, slip, and interfacial momentum exchange in the pseudo slug flow, and compared it with the existing pseudo slug flow model. The original model cannot predict some variables accurately and still needs a large amount of experimental data to verify and correct. Wang et al. [19] conducted experimental studies on the gas–liquid two-phase flow in the horizontal pipeline under high-pressure conditions. With the increase of pressure, the density of gas phase increased significantly, and the interaction between gas phase and liquid phase was significantly enhanced, while the increase of gas phase density inhibited the growth of amplitude, delayed the transition from stratified flow to slug flow, and verified a newly proposed calculation model for interfacial friction coefficient.

The gas–liquid interface evolution during liquid displaced by gas is quite different from conventional gas–liquid two-phase flow. In the conventional gas–liquid two-phase flow experiment, gas and liquid phases enter the test tube simultaneously. The liquid first fills the tube, and then the liquid is displaced by the gas in the gas cap evacuation

experiment. The convection characteristic between gas and liquid, and the gas–liquid interface evolution, are different for these two experiments.

The visualization experiment of the gas-carrying liquid flow in the process of gas cap evacuation is carried out by using the multi-phase pipeline experiment system. At first, the multi-phase flow pipeline experimental system is introduced, which mainly consists of four parts: water circulation system, aerodynamic system, pipeline system, and data acquisition system. Then, the experimental procedures are described, using air and water as media. The simulation of liquid displaced by gas of mobile pipeline is carried out by filling the pipeline with water in advance, and then using compressed air to drive the liquid in the pipeline. Finally, the gas–liquid interface evolution and slug characteristic during the liquid displaced by the gas flow process are analyzed under different inclination angles and different initial gas phase flow rates.

2. Experiment

2.1. Experimental Setup

The multi-phase flow pipeline experimental system mainly consists of four parts: water circulation system, aerodynamic system, pipeline system, and data acquisition system, as shown in Figures 1 and 2. A platform with variable inclination angle is set up in the observation section to simulate experimental conditions with different up-comer inclination angles.

The gas phase supply system is mainly composed of an air compressor and a gas storage tank to provide continuous and stable compressed air to the pipeline. An Autus oil-free mute air compressor is selected. The model is 3×1500 W–100 L, the rated power 4500 W, the rated displacement 420 L/min, the maximum exhaust pressure 0.7 MPa, and a 100 L air receiver is included. The gas storage tank is made of carbon steel with the volume being 2 m^3 and the maximum working pressure 1.6 MPa. The surface of the tank is equipped with a pressure gauge, which can indicate the real-time pressure in the gas storage tank, and after the compressed air generated by the compressor is introduced into the gas storage tank, it can provide a stable gas phase under the rated pressure condition for subsequent experiments and avoid pressure fluctuations caused by the vibration of the air compressor.

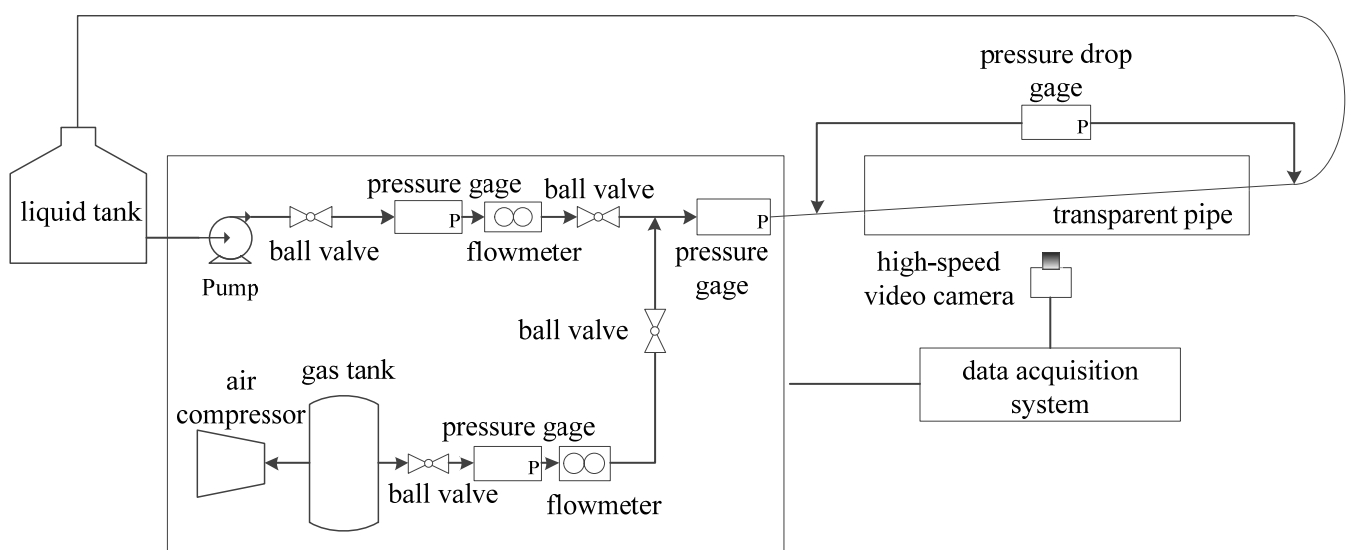


Figure 1. Experimental flow chart.



Figure 2. Image of experiment site.

Flowmeters are mainly used to measure the flow of gas and liquid in the pipeline and monitor whether the gas–liquid transmission is stable. The liquid flowmeter, the SC-LWGY intelligent liquid turbine flowmeter produced by Huai'an Sanchang Instrument Company, is selected. It is composed of a turbine flow sensor and display instrument, its measurement range is $0\sim30\text{ m}^3/\text{h}$, the measurement accuracy level is $\pm0.5\%$, its ambient temperature is $-20\text{ }^{\circ}\text{C}\sim50\text{ }^{\circ}\text{C}$, medium temperature is $-20\text{ }^{\circ}\text{C}\sim120\text{ }^{\circ}\text{C}$, and the maximum tolerable medium pressure is 6.4 MPa. The gas flowmeter, the SC-LWGQ integrated gas turbine flowmeter produced by Huai'an Sanchang Instrument Company, is selected. It has a measuring range of $0\sim30\text{ m}^3/\text{h}$, a measurement accuracy level of $\pm1.5\%$, the ambient temperature is $-20\text{ }^{\circ}\text{C}\sim50\text{ }^{\circ}\text{C}$ and gas temperature is $-20\text{ }^{\circ}\text{C}\sim80\text{ }^{\circ}\text{C}$, and the maximum tolerable gas pressure is 6.4 MPa.

The pressure difference transducer, Honeywell STD720, measures the changes of pressure difference at both ends of the variable inclination test pipe. Its measuring range can reach $-100\text{ KPa}\sim100\text{ KPa}$. The combination of pressure difference and static pressure as well as temperature compensation on the transducer chip can provide extremely high measurement accuracy and stability under a wide range of static pressure and temperature. The calibrated range accuracy can reach 0.05%, and the maximum static pressure resistance capacity can reach 31.5 MPa.

Since this paper mainly studies the characteristics of the gas-carrying liquid flow in the inclined pipeline, it is necessary to achieve the gas–liquid two-phase flow at different inclination angles during the experiment. The original multi-phase flow experiment pipeline is mainly applied for horizontal conditions, so in order to achieve the purpose of the experimental research, a platform with variable inclination angle is selected to superimpose a section of inclined pipe in the original multi-phase flow experimental pipeline. The variable inclination experimental platform can realize the inclination adjustment of $\pm180^{\circ}$. It is equipped with a mechanical inclination angle adjustment stabilizing device, and a fixed bracket is on the surface of the platform to stabilize the pipeline. The 3 m long DN25 plexiglass round tube is on the platform with a maximum pressure of up to 1 MPa, both ends of which are connected to the multi-phase flow experiment pipe with the plastic hose, as shown in Figure 3.

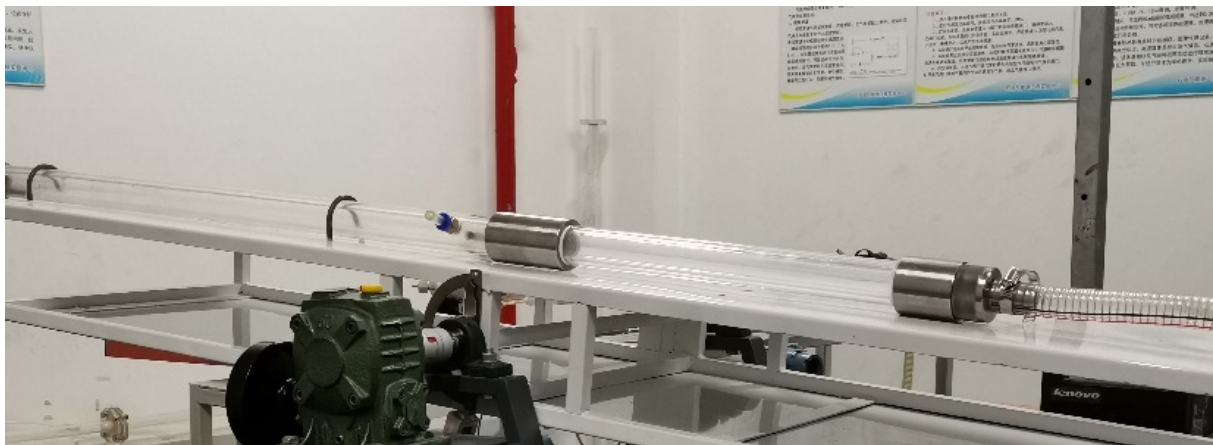


Figure 3. Visible transparent pipe.

In order to capture a clear picture of the flow of the gas-carrying fluid, a high-speed camera needs to be set up at a distance of 1 m from the visible glass pipe to capture the instantaneous changes in the gas–liquid interface and the characteristics of the slug during the flow of the gas-carrying fluid. The Flare 2M360-CL split high-speed high-resolution camera with IO Industries in the United Kingdom can achieve a capture speed of 250–10,000 frames per second and a maximum video recording frame rate of 31 fps. Because a high-speed camera requires a high number of frames to obtain an instantaneous picture, and the higher the number of frames is, the lower the image brightness and the pixels of a single photo are, in the process of shooting with high-speed camera, it is necessary to adjust and set the camera position and camera parameters, and at the same time a BL-1000A camera light by Bailing Image Equipment Co., Ltd. from Fuzhou of China is used as an auxiliary tool to fill light on the shooting pipe to ensure the clarity of the shot images.

2.2. Experimental Procedures

This experiment mainly uses two media: air and water. The experiment is carried out in the laboratory by using the multi-phase flow pipeline experimental system with the indoor temperature being maintained between 20 °C and 30 °C, the liquid phase inlet pressure being atmospheric pressure, and the gas phase inlet pressure being 0.2 MPa. The experiment mainly uses air and water as media with the pipe diameter being 25 mm, and the plexiglass material is used for observation and shooting. The specific experimental procedures are as follows.

- (1) Switch on the power supply and start the multi-functional oil–gas transmission experimental device and data acquisition system.
- (2) Confirm that valves no. 4 and no. 5 are closed, open valves no. 6 and no. 7, start the centrifugal pump, and pump water from the liquid storage tank to the pipeline so that the entire pipeline is filled with liquid.
- (3) After the pipeline is filled with liquid, stop the operation of a centrifugal pump, and close the valves no. 6 and no. 7. Then, the entire experimental system is left to stand for 30 s, so that the liquid in the pipeline is in a stable state.
- (4) Start the air compressor, inflate the gas storage tank, and when the air pressure in the gas storage tank reaches the experimental preset value, close the air compressor.
- (5) Open valve no. 4, open the high-speed camera, and slowly open valve no. 5 to the gas flow value required for the experiment to make the compressed air enter the pipeline smoothly.
- (6) The high-speed camera is used to record the flow process of the gas–liquid interface in the transparent glass pipeline during the gas cap evacuation experiment, and

the pressure, flow, and other data in the pipeline are collected through the data acquisition system.

- (7) Fully open valve no. 5, purge the liquid in the pipe, and then close valves no. 4 and no. 5.
- (8) Change the gas flow, repeat the experiment steps 2 to 7, and record the experimental data for different gas flow rates.
- (9) Adjust the variable inclination platform, repeat the experiment steps 2 to 8, and record the experimental data at different inclination angles.
- (10) Turn off the high-speed camera and data acquisition system, check whether the residual liquid in the pipeline is empty, check whether the valves, compressor, and centrifugal pump are in a closed state, close the multi-functional oil-gas transmission experimental device, and cut off the power supply.

3. Experiment Result Analysis

3.1. Changes of Gas–Liquid Interface at the Initial Stage of Gas Cap Evacuation

During the gas cap evacuation operation, the gas–liquid interface will be mixed with each other to form a gas–liquid mixing section due to complex reasons such as the differences in gas and liquid physical properties and the changes of pipeline working conditions. The characteristics of the gas–liquid mixing section are complex, and are significantly related to the interfacial morphology changes when the gas phase enters the liquid phase at the initial stage of gas cap evacuation [7].

As shown in Figure 4, the gas–liquid front-end interface presents different flow patterns at different initial gas phase flow rates. When the initial gas phase flow rate U_{sg} is 0.96 m/s, as shown in Figure 4a, the gas phase front end enters into the liquid phase similar to a bullet. The gas phase is in the upper part of the pipeline, while the liquid phase is at the bottom. The gas–liquid flow is a stratified flow as a whole, and the gas–liquid interface is smooth without a wave. In the bullet-shaped head of the gas phase, there are a small number of liquid droplets, mainly existing near the gas–liquid phase interface. The rest of the gas phase has no obvious liquid droplets, and there are no obvious bubbles in the liquid phase. When the initial gas phase flow rate U_{sg} increases to 1.16 m/s, as shown in Figure 4b, there are obvious fluctuations between the two-phase interface. A large number of bubbles and liquid droplets appear at the gas–liquid-front interface to blur the shape. The interface wave in the gas phase head is close to the top of the pipeline, forming a pseudo slug. The fluctuation near the middle of the gas–liquid interface increases, making a small number of liquid droplets leave the liquid phase into the gas phase. The detached droplets are mainly concentrated in the position of large amplitude, and these droplets fall back to the liquid phase by gravity after rising to the middle of the pipeline. In the liquid phase near the gas–liquid interface, a large number of tiny bubbles appear and move forward along with the dispersion of the liquid phase. As the initial gas phase flow rate U_{sg} continues to increase to 1.36 m/s, as shown in Figure 4c, the gas–liquid two-phase flow begins to show signs of transition from stratified flow to disperse flow. Continuous irregular interface waves appear in the gas phase bullet-shaped head, and a large number of independent bubbles and droplets appear at the front interface, making the gas–liquid interface blurred. There are violent fluctuations in the middle of the gas–liquid interface, near which a large number of independent bubbles and droplets also appear. At the large fluctuations, the liquid phase has moved upward to the top of the pipeline, resulting in a temporary discontinuity of the gas phase here, forming a local slug.

During gas cap evacuation of the horizontal pipeline, with the increase of the initial gas phase flow rate, it can be seen that the initial gas–liquid contact interface gradually transitions from stratified-smooth flow to dispersed flow. A large number of bubbles and droplets are mixed with each other near the gas–liquid interface, and the interface becomes blurred gradually. Guo et al. [2,4] studied the gas–liquid two-phase flow characteristics in a pump-assisted evacuation process for hilly terrain pipeline system. They indicate that there appear to be two flow patterns: stratified flow and slug flow. By means of reducing

upstream back pressure, the pump-assisted evacuation can increase the liquid flow rate, promoting the transition of flow pattern.

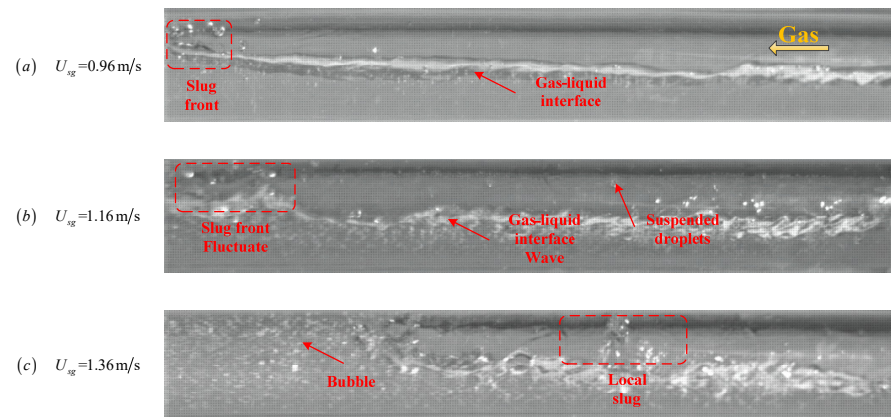


Figure 4. Gas–liquid interface in the horizontal pipeline.

When the inclination angle of the pipeline is changed to the upward, the force of the gas–liquid two-phase flow in the process of gas cap evacuation of the pipeline changes compared with that in the horizontal pipeline. The gravity acts on the gas–liquid two-phase flow along the reverse direction of the movement, and the changes of the gas–liquid interface at different initial gas phase flow rates are shown in Figures 5–7.

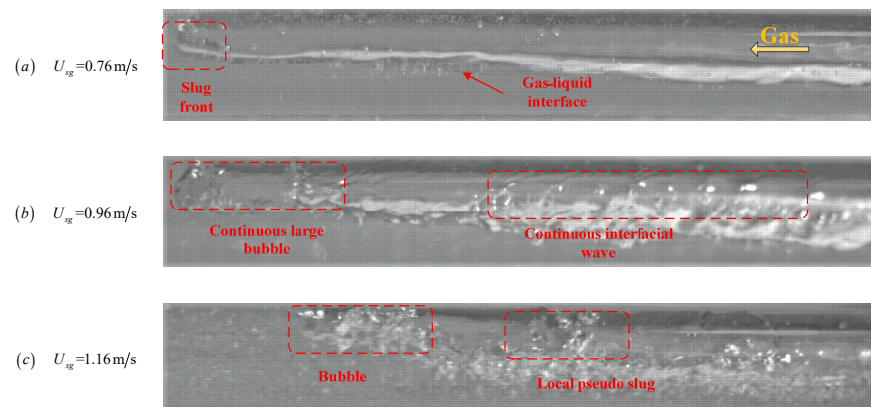


Figure 5. Gas–liquid interface in +5° pipeline.

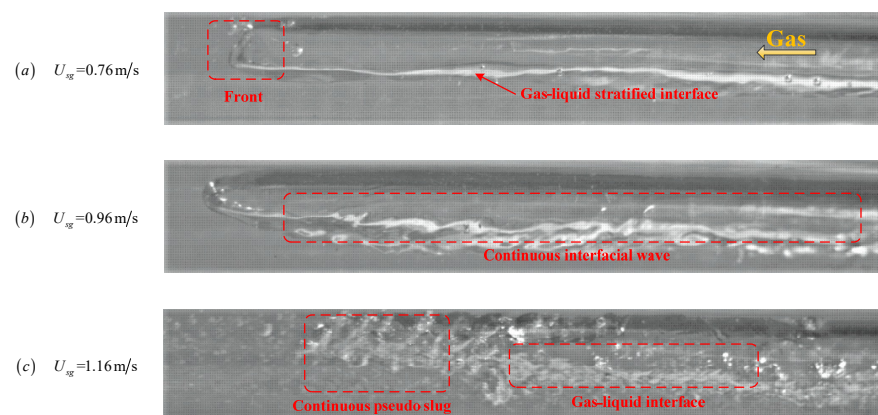


Figure 6. Gas–liquid interface in +10° pipeline.

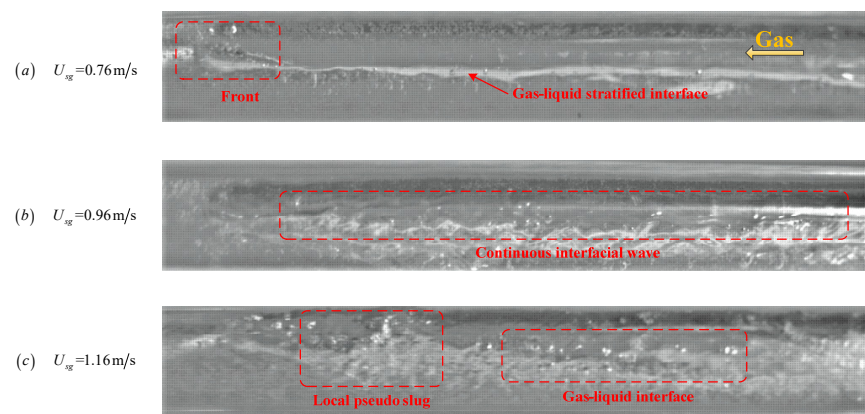


Figure 7. Gas–liquid interface in +15° pipeline.

When the initial gas phase flow rate U_{sg} is 0.96 m/s, as shown in Figure 5b, the front end of the gas phase enters the liquid phase similar to a bullet and moves forward. A clear gas–liquid interface can be seen in front of the bullet-shaped head and the fluctuations in the bullet-shaped head are small, but there appear continuous big bubbles. It fluctuates greatly in the middle of the gas phase, and there is a continuous violent interface wave near the gas–liquid interface that is blurred. Some droplets leave the liquid phase and enter the gas phase at the large fluctuations, but they fall back to the liquid phase by gravity before reaching the top of the pipeline. The crests near the gas–liquid interface do not reach the top of the pipe to form a slug, at which point the gas phase is still a continuous phase. Reducing the initial gas phase flow rate U_{sg} to 0.76 m/s, as shown in Figure 6a, it can be observed that the gas liquid moves in the pipeline as stratified-smooth flow and the gas–liquid interface is smooth and clear without fluctuation and emergence of detachment droplets near the interface, but a small number of tiny bubbles are observed in the liquid phase and in the bullet-shaped head of the gas phase near the gas–liquid interface. When the initial gas phase flow rate U_{sg} is 1.16 m/s, as shown in Figure 7c, the gas phase causes huge fluctuations after entering the liquid phase. At this time, the bullet-shaped head cannot be observed in the front end of the gas phase where the gas and liquid are mixed with each other, forming a foam form. The gas–liquid interface is blurred, and there are many small bubbles in the liquid phase. The gas liquid in the middle of the gas phase still flows in stratified flow, but the fluctuations near the interface are severe, and the gas and liquid are mixed with each other, forming mass bubbles and droplets. Some droplets out of the liquid phase are wrapped and carried forward by the gas phase, and the local interface wave is blown apart by the gas phase when they reach the top of the pipeline, resulting in the formation of the pseudo slug. The gas–liquid two-phase flow pattern in the pipeline has begun to shift from stratified flow to dispersed flow.

Comparing the changes in the gas–liquid interface in the horizontal pipeline, it can be found that although the gas–liquid flow state still shows a trend from stratified flow to dispersed flow with the increase of the initial gas phase flow rate, the initial gas phase flow rate of the fluctuating and dispersing droplets near the interface during the flow of the gas cap liquid in the upward pipeline is significantly reduced.

The wave variation between the gas–liquid interface can most directly reflect the interface morphology and the changes of the gas–liquid two-phase flow regime. Figure 8 indicates the amplitude variation of the interface wave under the condition of different gas phase flow rates and pipeline inclinations. It can be observed that the amplitude of the interface wave increases with the increase of the gas phase flow rate. However, when the gas–liquid interface form is changed from fluctuation to dispersion, the amplitude of the interface wave will decrease slightly, which is due to the fact that with the increase of the gas phase flow rate, the disturbance of the gas to the surface of the liquid increases, and in the rising process of the interface wave, continuous blows on the crest by the high-speed gas make the liquid at the crest quickly disintegrate to form a large number of scattered

droplets carried forward by gas phase, reflecting the transition of interface from fluctuation to dispersion. At the same time, the amplitude of the interface wave also increases with the increase of the inclination of the pipeline, and with the increase of the inclination of the pipeline, the change rate of the amplitude gradually decreases. For the case of $+15^\circ$ up-comer inclination, when the gas–liquid interface form is converted to dispersion, the amplitude of the interface wave remains almost unchanged, which is the result of the joint action of high-speed gas disturbance and gravity, making the interface form no longer change in a certain range of gas phase flow rate, but the fluctuation will make the gas phase formulate more dispersed droplets. The changes of the interface wavelength in the pipeline are as shown in Figure 9. The interface wavelength decreases with the increase of gas phase velocity and the inclination angle of the pipeline, and in the up-comer pipeline, the change rate of interface wavelength decreases gradually with the increase of gas phase velocity.

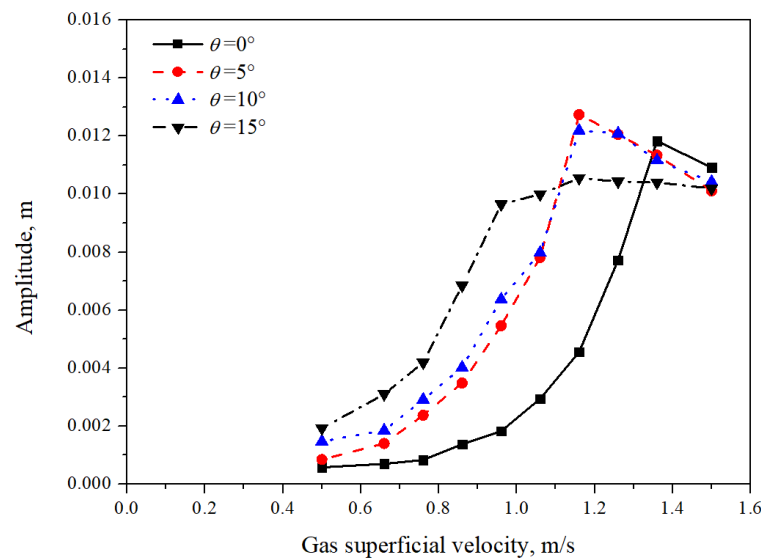


Figure 8. The amplitude of the interface wave in the pipeline with different gas phase velocity.

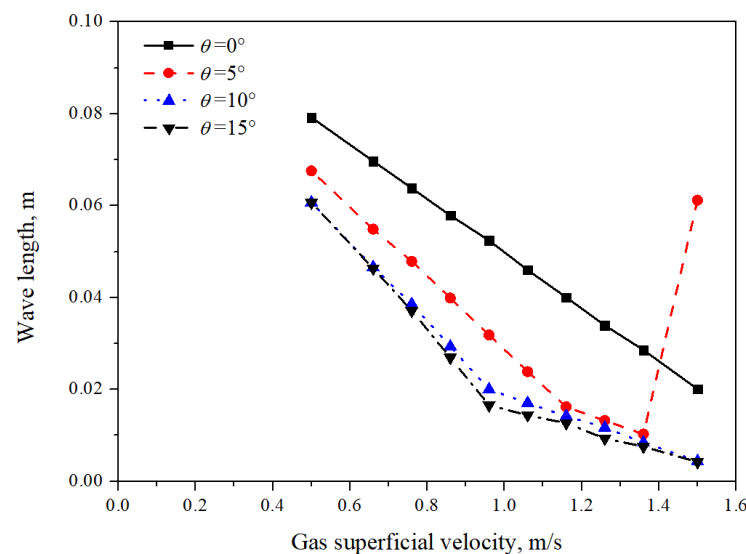


Figure 9. The wavelength of the interface wave in the pipeline with different gas phase velocity.

From the comprehensive analysis of the gas–liquid interface changes in the pipeline in different inclination angles and different initial gas phase velocity, it can be found that the gas–liquid flow as a whole is mainly a stratified flow and the gas–liquid interface can be divided into smooth, wavy, and dispersed forms. With the increase in flow rate, the

gas–liquid interface blurs gradually, near which the fluctuation increases gradually and the blending intensifies. When the fluctuations or the independent droplets caused by fluctuation reach the top of the pipeline, it can be considered that the gas–liquid interface is in a dispersed form at this time. Comparing Figures 4–7, it can be seen that when the pipeline changes from the horizontal state to the up-comer inclination, the initial gas–liquid flow rate U_{sg} required for the fluctuation of the gas–liquid interface and the change of the interface morphology is significantly reduced, but when the up-comer inclination angles change in a small range from $+5^\circ$ to $+15^\circ$, the inclination angle has small influence on the initial gas phase flow rate U_{sg} required for the change of the gas–liquid interface. This may be because when the inclination angle of the pipeline is adjusted from horizontal state to the up-comer inclination, the gas–liquid force changes, and the gravitational force along the axial direction of the pipeline makes the gas–liquid have a reverse moving trend. In the flow process of gas cap liquid, the initial moving forward gas phase and the liquid phase in the pipeline are mixed with each other more rapidly and violently, but the change of the small inclination angle has little impact on the overall force situation. In the flow process of gas cap liquid, although the local part of the gas–liquid interface has different morphological changes, the overall trend has not changed much, so the inclination angle has small influence on the initial gas phase flow rate required for the change of the gas–liquid interface. At the same time, it can be observed that with the increase of the inclination angle of the pipeline, the bubbles that appear in the liquid phase of the pipeline also increase significantly during the flow of the gas cap liquid.

3.2. Slug Characteristics in the Process of Gas-Carrying Liquid Flow

In the process of gas cap evacuation, after the front end of the gas phase passes the pipeline, it formulates a gas–liquid stratified flow inside the pipeline with the gas phase in the upper part of the pipeline and the liquid phase in the bottom of the pipeline. At this time, there is gas entering into the pipeline continuously from the inlet end and carrying the remaining liquid in the pipeline to continue to move. Due to the continuous disturbance of the gas phase and the complex influence of different elbows and valves in the pipeline, the liquid plug body was observed under the different working conditions of the experiment.

In the horizontal pipeline, when the initial gas phase flow rate U_{sg} is 0.96 m/s, as shown in Figure 10, the first slug appears in the pipeline 0.5 s after the front end of the gas phase passes through. The length of the liquid plug body is relatively long and the overall liquid level is relatively high. Driven by the gas, the liquid plug, as a whole, moves forward evenly. The gas–liquid coupling effect in the liquid plug is relatively low, and the bubbles are mainly formed by the liquid film fluctuation and suction effect in the advance process of the liquid plug [20]. As shown in Figure 10, the second slug appears in the pipeline 1.35 s after the front end of the gas phase passes through. The liquid plug is a short triangular shape. The slug point is located in the tail of the liquid plug, and a large number of splashes can be seen in the head of the liquid plug, which is due to the fact that the flow rate of the liquid plug is significantly greater than that of the liquid in front, causing the liquid plug to collide violently with the liquid in front to form splashes by the speed difference. There are a large number of tiny bubbles in the liquid plug but no obvious large-volume bubbles, and many water droplets can be seen at the slug point in the end of the liquid plug, which shows that the gas here has a great disturbance to the liquid plug, making some liquid flow slower and be thrown off from the liquid plug. As shown in Figure 10, the third slug appears in the pipeline 3.86 s after the front end of the gas phase passes through. The form of the liquid plug is relatively vague. The liquid plug collides with the liquid in front of it violently under the impetus of the gas, forming a large number of water splashes, and the water splash margin runs axially through the entire liquid plug, extending the entire pipeline radially. A large number of splash droplets are formed before and after the liquid plug.

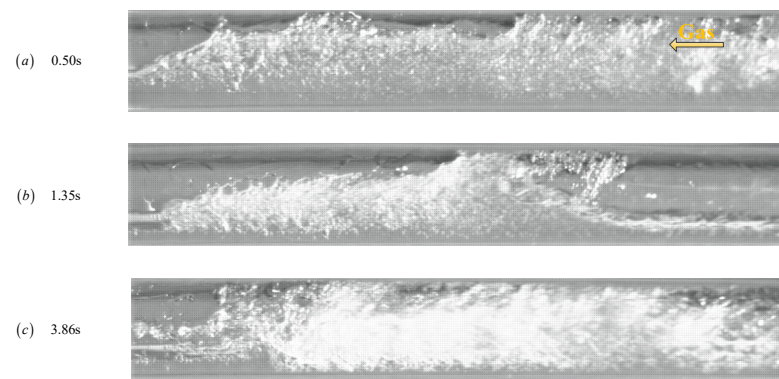


Figure 10. Image of slug in horizontal pipeline.

Figures 11–13 are the images of the slug in the pipeline when the inclination angle is $+5^\circ$, $+10^\circ$, and $+15^\circ$, respectively, and complex liquid plug body of different shapes can also be seen. Comparing Figures 10–13, various shapes of slugs appear in the pipeline under different inclination angles, and the slug shapes are complex and changeable, which does not have any obvious relationship with the inclination of the pipeline. However, with the increase in inclination, the time interval between the occurrence of slugs is significantly shortened. Figure 14 shows the frequency of slugs in the experimental pipeline. It can be seen that in the process of gas cap liquid flow, the frequency of slugs in the pipe is accelerated with the increase of the inclination angle of the pipeline as well as the increase of the flow rate of the gas phase, and the frequency of the slug in the upward pipe is significantly greater than that in the horizontal pipeline.

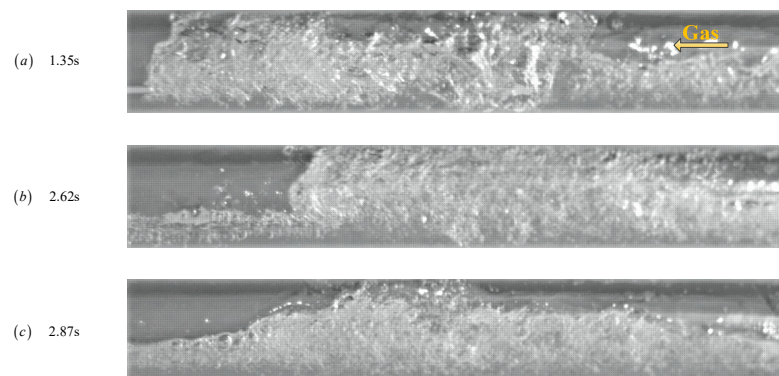


Figure 11. Image of slug in $+5^\circ$ pipeline.

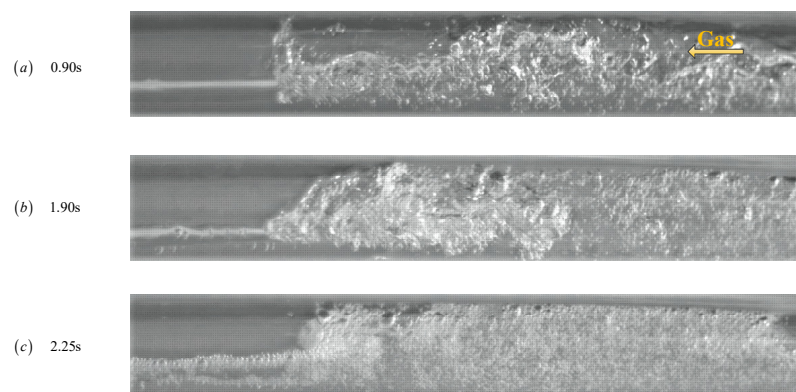


Figure 12. Image of slug in $+10^\circ$ pipeline.

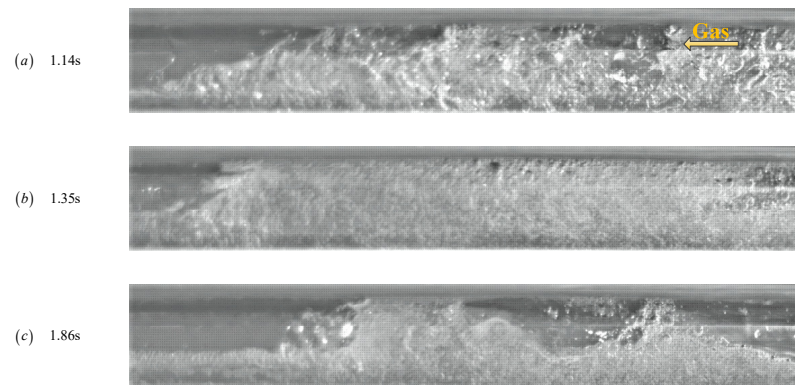


Figure 13. Image of slug in $+15^\circ$ pipeline.

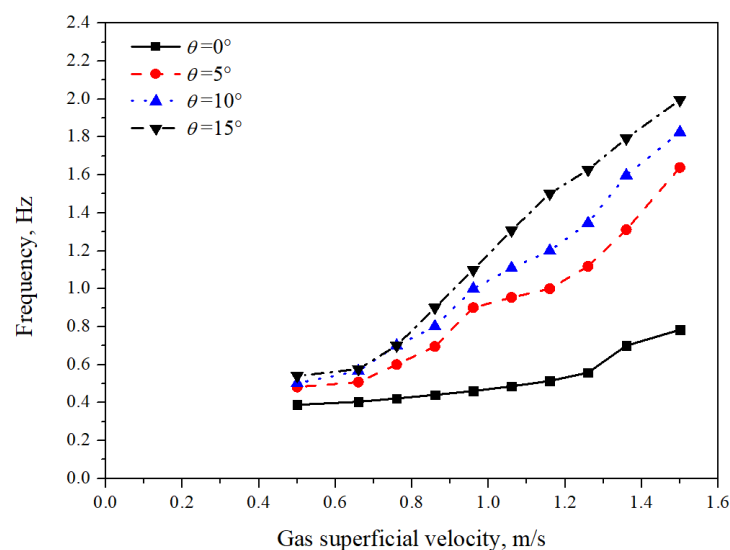


Figure 14. The frequency of the slug in the pipeline with different gas phase velocity.

Through experimental research, after observing the multi-group plug image under different working conditions, it was found that the morphology of the liquid plug body in the pipeline was complex and changeable, and at the same time, the shape of a liquid plug body would continue to change due to the influence of the gas phase during moving (see Figure 15). In the early stage of the formation of the plug, the high-speed flow of the gas disturbs the liquid film in the lower part of the pipeline, causing waves in the surface of the liquid film, the longitudinal fluctuations of which are superimposed on each other to form a larger wave, and when a certain peak reaches the top of the pipeline, a plug appears in the pipeline. At this time, the liquid plug body is triangular. The gas phase circulation area is rapidly reduced at the plug point, and the flow rate increases. The liquid plug body is pushed to move forward faster. Because the liquid at the top of the liquid plug is most affected by the gas phase and the speed is the highest, a tongue shape is obviously visible at the top of the liquid plug body. After the liquid plug body accelerates the movement, there is a speed contrast with the liquid in front. After colliding with each other, a huge wave is formed in the head of the liquid plug, resulting in the decrease in speed of the head of the liquid plug, while the gas behind the liquid plug still continuously pushes the liquid plug forward at high speed, and when the liquid at the top of the liquid plug moves forward to the front wave, they fuse with each other to form a larger slug point. At this time, the shape of the liquid plug body changes from the initial triangle to a rectangle, and the liquid plug as a whole is more stable, flowing forward evenly. The waves generated by the collision in front are constantly replenished, making the liquid plug body continue to grow and become larger. Since the gas cannot quickly break through the slug point at this

time, the pressure and gas flow rate behind the liquid plug body tend to be stable, and the fluctuation in the surface of the liquid film in the rear can be seen to be significantly reduced. In the upward pipe, due to the downward movement trend along the axial direction of the pipeline caused by liquid gravity, at this time the speed difference between the liquid plug body pushed forward by the gas and the liquid in front is greater, and the wave formed after the collision is also larger, resulting in the intensification of the change of the liquid plug body shape. With the increase of the pipeline inclination, the frequency of the slug in the pipeline increases, which is the same as the results obtained by the experiment.

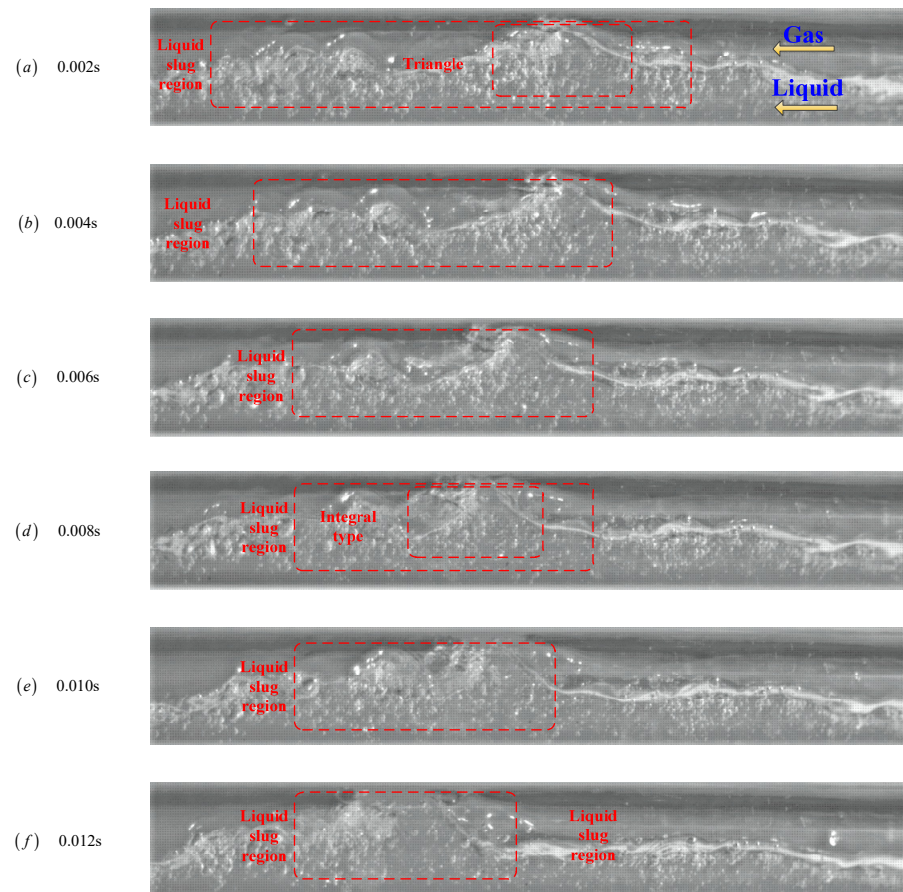


Figure 15. Schematic diagram of liquid plug body shape change process.

In the process of gas-carrying liquid flow, the gas–liquid flow is mainly a stratified flow with the gas phase in the upper part of the pipeline and the liquid phase at the bottom of the pipeline. When a slug is formed in the pipeline, the liquid plug body will block part of the pipeline, destroy the continuity of the gas phase, and make the pressure drop in the pipeline rise rapidly. Under the complex action of gas phase disturbance and gravity, the liquid plug body gradually disintegrates during moving and becomes a pseudo slug flow, at which time the gas phase in the pipeline restores continuity, and the pipeline pressure drop gradually decreases and returns to normal. Guo et al. [2,4] indicated that the pipe-bottom pressure increases firstly, then decreases, and slowly increases at last. During the process of pressure drop, there will appear a temporary buffer section for the slug accumulation. The pressure fluctuation does not increase with inlet superficial gas velocity. Figure 16 shows the pressure drop changes in the gas-carrying liquid flow in the upward pipeline. From the figure, it can be seen that the slug flow will lead to a sharp increase in pressure drop due to the complete blockage of the pipeline, and the increase in pressure drop will be maintained for a certain period of time, but when it is pseudo slug, because the pipeline is not completely blocked by the liquid plug body, the gas phase still

maintains continuity, making the pressure drop increase in the pipeline not violent, and the disturbance of the high-speed gas will quickly disintegrate the liquid plug body when it is pseudo slug, so the pressure drop fluctuation only lasts a very short time.

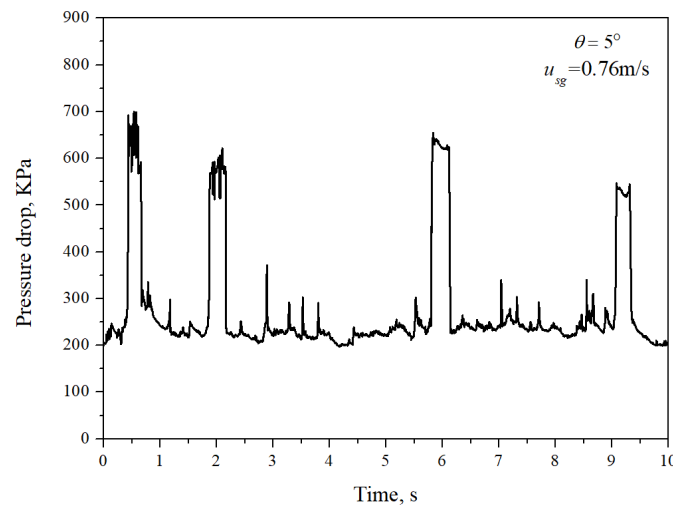


Figure 16. Pressure drop in the pipeline.

4. Conclusions

The gas cap evacuation process of the mobile pipeline is a complex gas–liquid two-phase flow, and the flow characteristics of the gas-carrying liquid have a profound influence on the scheme design and working condition adjustment of the evacuation, which is instructive for the actual evacuation operation. Through the simulation experiment of gas cap evacuation in the pipeline, the initial interface and slug characteristics of gas-carrying oil flow in the process of mobile pipeline evacuation are studied and analyzed by means of high-speed camera in this paper.

When the gas cap is evacuated, the gas–liquid-front interface can be divided into smooth, wavy, and dispersed forms with the change of the initial gas phase flow rate. When the initial gas phase flow rate is low, the gas–liquid interface is clear and smooth, so the gas–liquid interface is smooth at this time. When the initial gas phase flow rate increases until there is a large fluctuation or splash droplets near the gas–liquid interface but without reaching the top of the pipeline, the gas–liquid interface is wavy. With the initial gas phase flow rate further increasing, a large number of bubbles and liquid droplets appear at the gas–liquid-front interface to blur the shape. The interface wave in the gas phase head is close to the top of the pipeline, forming a pseudo slug. In the liquid phase near the gas–liquid interface, a large number of tiny bubbles appear and move forward along with the dispersion of the liquid phase. When the initial gas phase flow rate is further increased, the fluctuations between gas and liquid are intensified, and the interface is blurred. The crest or continuous splash reaches the top of the pipeline, at which time the gas phase continuity in the pipeline is destroyed and the gas–liquid interface is dispersed.

The change of the low inclination angle of the upward pipe does not change the shape of the gas–liquid interface, but compared with the horizontal pipe, the change of the inclination angle of the upward pipe advances the change of the gas–liquid interface shape and obtains different interface shapes under the condition of lower initial gas phase flow rate. When the pipeline changes from the horizontal state to the up-comer inclination, the initial gas–liquid flow rate U_{sg} required for the fluctuation of the gas–liquid interface and the change of the interface morphology is significantly reduced, but when the up-comer inclination angles change in a small range from $+5^\circ$ to $+15^\circ$, the inclination angle has a small influence on the initial gas phase flow rate U_{sg} required for the change of the gas–liquid interface.

During the flow of gas-carrying liquid, due to the influence of complex factors such as gas disturbance and pipeline vibration, there will be slug in the pipeline. The liquid plug body has a variety of shapes, and the overall uniform shape, triangular shape, and continuous wave shape are found in the experiment. The mutual transformation will occur between different liquid plug shapes, and the higher the gas content of the liquid plug body is, the more unstable the liquid plug becomes. The frequency of slugs in the pipe is accelerated with the increase of the inclination angle of the pipeline as well as the increase of the flow rate of the gas phase, and the frequency of the slug in the upward pipe is significantly greater than that in the horizontal pipeline. The liquid plug body in the emptying process lasts for a short time and cannot form a stable slug flow, but some liquid plug body will also increase the pressure in the pipeline several times in a short period of time, which will seriously affect the safety of the pipeline-emptying operation.

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