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Experimental Study on Hydrate Safe Flow in Pipelines under a Swirl Flow System

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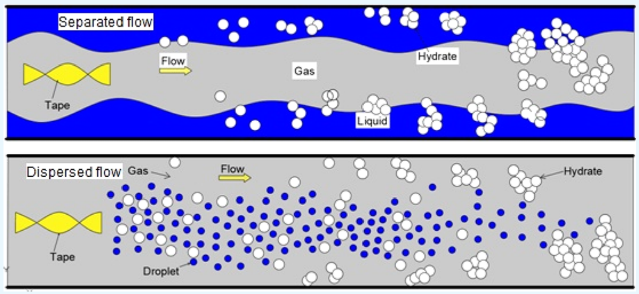
ABSTRACT: With the development of oil and gas resources gradually extending to the deep sea, the blockage of gas hydrate is attracting more and more attention. How to inhibit hydrate blockage efficiently and economically in oil and gas gathering transportation pipelines and ensure the safe operation has become a hot and difficult point in the field of oil and gas gathering and transportation research. At present, the research on the safe flow of gas hydrate is still in the exploratory stage, and applying swirl flow to hydrate risk control technology has a great engineering application value. A systematic experimental study on the safe flow of gas hydrate in a swirl flow system is carried out herein. The experimental results show the following: (1) The laws of gas hydrate flow, transport, deposition, and pipe plugging under various experimental conditions of the swirl flow system are obtained, the safe flow region of hydrate under the swirl flow system in the pipeline is obtained, and the safe flow boundary of hydrate is expanded. (2) Beginning with the theoretical analysis of the safe flow of gas hydrate in a pipeline, the flow characteristics of gas hydrate in the flow system are described; the special flow form of swirl flow has a great influence on the safe flow law of hydrate. (3) The growth and coalescence mechanisms of spiral hydrate in two mainstream systems of separated flow and dispersed flow are explored and researched. The critical tangential velocity of flow is taken as the standard of criterion.



INTRODUCTION

There are many elements that affect the safety of oil and gas pipelines, and hydrate pipe plugging is one of the most common problems. Natural gas hydrate is a cage crystalline compound similar to an ice structure formed under high pressures and low temperatures.[1,2] In the process of natural gas pipeline transportation, a high-velocity gas flow, low-temperature and high-pressure pulsation, and a special structure have a great impact on the formation of hydrate. Hydrate is easily generated and accumulates at the elbow of a pipeline, the bottom of a low-lying section, and so forth. When the accumulated hydrate continues to grow, the volume fraction of hydrate in the pipeline increases gradually, it exceeds the critical value that the air flow can carry and transport smoothly, and the pipeline delivery pressure fluctuates violently. In addition, due to the adhesion between particles and between particles and the pipe wall, the pipeline is gradually blocked by the hydrate.[3] The formation and accumulation of gas hydrate in the pipeline not only cause the blockage of pipelines and valves and reduce the ability of pipeline to transport gas but, in serious cases, also cause pipeline damage and burst, resulting in serious production safety problems.

At present, the main methods to control hydrate formation are heating, adding inhibitors, and so on; this is achieved by breaking the equilibrium conditions for hydrate formation.[4] However, the current inhibition methods still have the problems of high cost, strong pollution, and large dosage, especially the use of thermodynamic inhibitors. According to statistics, the global consumption of methanol for natural gas hydrate prevention and control is as high as US$220 million every year.[5]

In the early 1980s, the prevention and control strategy of natural gas hydrate gradually changed; the focus of attention of scholars in various countries has gradually shifted from inhibiting hydrate formation to inhibiting hydrate blockage because hydrate blockage is the key problem of flow safety in gathering and transmission pipelines. Hydrate dynamic control technology or hydrate cold flow technology has gradually entered people's vision.[6,7] Its characteristics are without heating and insulation, hydrate formation is allowed, inhibition of hydrate coalescence and blockage by various means. It is concluded that finding, researching, and expanding the safe

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flow boundary of hydrate is the core of hydrate risk management technology in pipelines.

Hydrate risk management technology is one of the ways to solve the problems of pipeline blockage in oil and gas gathering and transportation pipelines, and understanding the flow characteristics of hydrate in the pipeline is the premise and foundation of mastering the hydrate risk management technology. In the following, the hydrate flow characteristics and pipe plugging characteristics are combined.

Hydrate Flow Research. The flow law of hydrate in pipelines is the core of hydrate risk management technology. Scholars from various countries have made exploratory experimental and theoretical studies on the flow process, flow law, influencing factors, rheological properties, and the flow model of hydrate in pipelines.

In 2002, American scholar Lingelem[10,11] and others carried out experiments on the formation and flow characteristics of freon hydrate in the pipeline; the results show that hydrate is first formed at the gas−liquid interface, and the hydrate at the interface increases gradually with the progress of hydrate flow. In 2008, Canadian scholar Turner and others[12] conducted the hydrate slurry flow experiment on a high-pressure loop. The research results show that the strength of hydrate increases with the increase of the liquid content and fluid flow rate. In addition, bubble flow can also enhance the fluidity of hydrate, and the formation mechanism of oil, gas, and water three-phase hydrate in the pipeline is obtained. In 2010, Wang[13] of the China University of Petroleum (East China) researched the flow characteristics of tetrahydrofuran hydrate slurry, observed the transformation between hydrates with different properties, and obtained the critical volume fraction of hydrate to determine whether the pipeline is blocked. In 2011, Liu[14] of Southwest Petroleum University conducted the experiment of gas flow blocking hydrate on the high-pressure hydrate flow platform. The results show that the temperature of hydrate blockage in the pipeline decreases with the increase of gas flow. It is concluded that the promoting effect of gas flow on hydrate blockage is much less than the destructive effect. In 2011, Sun[15,16] of China University of Petroleum (Beijing) carried out the research on the formation and flow characteristics of oil, gas, and water multiphase hydrate under a polymerization inhibitor system. The research results show that the hydrate slurry in the pipeline is not a typical Newtonian fluid, which is characterized by shear viscosity reduction and belongs to pseudoplastic fluid. The presence of a polymerization inhibitor significantly increases the fluidity of hydrate. In 2012, French scholar Clain[17] and others researched the rheological properties of tetrabutyl phosphorus bromide hydrate slurry through dynamic circulation and the Ostwald method; they found that with the formation of a large number of hydrate particles, the hydrate slurry in the window gradually changes from the initial transparent liquid to a milk hydrate slurry. In 2014, Australian scholars Lorenzo and Kozielski[18] carried out an experiment on the formation and flow law of gas hydrate, with ethylene glycol dominated by the gas phase and liquid volume fraction of 5%. It was found that the hydrate formation rate decreased with the increase of ethylene glycol concentration. Generally, the initial formation point of hydrate in a gas transmission pipeline is located at the inner wall of the pipeline. With the increase of hydrate production, the pipeline flow area decreases gradually, which makes the operation condition of gas transmission pipeline more complex. Then, the hydrate formation and flow characteristics of the natural gas−water system in the pipeline were researched.[19] The gas−liquid and hydrate particles in the pipeline were observed in detail with a high-speed camera. It was found that the hydrate particles were taken away by the high-speed gas flow, and the hydrate particles were deposited and blocked in the rear section of the pipeline; it was considered that hydrate deposition and pipe plugging were closely related to the volume fraction of hydrate. In 2014, American scholar Sum[20] systematically summarized the research status of hydrate slurry flow characteristics. The research results led to the belief that the core of hydrate safe flow research is to master the coupling mechanism of hydrate formation and multiphase flow. The natural gas hydrate research center at the Colorado School of Mines proposed a transient natural gas hydrate formation kinetic model and developed a calculation software to calculate hydrate formation and flow in the field of actual oil and gas pipeline engineering.[21] In 2014, Lafond,[22] an American scholar, carried out experiments on the flow characteristics of hydrate particles, focusing on the effects of hydrate volume fraction and fluid conversion velocity on the movement of hydrate particles in the pipeline, which can provide experimental reference for the movement law of hydrate particles and controlling hydrate slurry blockage. In 2015, American scholar Majid et al.[8] carried out experiments on hydrate flow characteristics with the high-pressure loop of Tulsa University as the experimental platform to solve the problem of hydrate flow guarantee in the pipeline. The experimental results show that the liquid velocity and water content have a great influence on the hydrate flow in the pipeline. In addition, the viscosity change in the hydrate formation process also has a great impact on the hydrate flow. The viscosity is greater, and the fluidity is worse.

Generally, relevant scholars have carried out a lot of research on the macro-parameters of hydrate flow and the flow and deposition characteristics of hydrate in the pipeline, but no scholar has introduced swirl flow into the field of safe hydrate flow, and there are few studies on the flow attenuation and deposition characteristics of hydrate particles.

Hydrate Pipe Plugging Research. The research on pipe plugging is the key to the research on the safe flow of hydrate. To ensure the safe flow of hydrate in the pipeline is to prevent pipe plugging in the pipeline.

In 1992, Norwegian scholars Austvik et al.[23] carried out an experimental study on the plugging characteristics of hydrate in the pipeline and the plugging mechanism in view of the problem of hydrate plugging in the actual pipeline. The research results show that the accumulation of hydrate particles is the cause of pipe plugging in the pipeline, and the accumulation of hydrate particles is due to the liquid bridge force of the liquid layer on the surface of hydrate particles. In 2002, Petrobras scholars Camargo et al.[24] carried out the rheological property experiment of hydrate suspension in asphaltene crude oil by using the high-pressure experimental loop. The experimental results show that the accumulation of hydrate is due to two reasons. One is the capillary force between particles and between particles and water droplets; in addition, the liquid layer between hydrate particles is gradually transformed into hydrate under the action of low temperature and high pressure. The two aspects work together to produce a great quantity of hydrates and accumulate continuously. It is considered that the wettability of particles is the main cause of hydrate blockage in pipelines. In 2005, French scholars Palermo et al.[25] found different particle aggregation reasons from the former through experimental research on the formation and flow of hydrate. It is considered that the accumulation of hydrate particles is not due to the adhesion between particles but mainly due to the generation of a large number of hydrate particles. In 2008, American scholar Nicholas[26] also studied the hydrate deposition and pipe plugging characteristics in the pipeline but focused on the adhesion between hydrate particles and the pipe wall. It is found that the adhesion between hydrate particles and the pipe wall is much less than that between hydrate particles. Therefore, it is concluded that the adhesion between hydrate particles and the pipe wall is not the main reason for hydrate deposition and pipe plugging in the pipeline. In 2008, Canadian scholars Myriam and Hung[27] used the advanced laser-focusing reflective particle measurement device to observe the crystallization process of water−oil emulsion hydrate in the pipeline in detail, described the particle size distribution characteristics and particle aggregation process of hydrate and considered that the high hydrate volume fraction was the cause of pipeline blockage. In 2008, Wang of the Guangzhou Institute of Energy, Chinese Academy of Sciences,[28] conducted an experimental study on hydrate blockage in the pipeline with CH_3CCl_2F hydrate as the experimental working medium. The experimental results show that the experimental system maintains good fluidity when the hydrate volume range is 30−40%. It is considered that the critical hydrate volume fraction is 30%. In order to ensure the safe flow of hydrate, the hydrate volume fraction should be less than 30%. In 2008, Brazilian scholars Dellecase et al.[29] focused on the effects of water content, flow pattern (liquid load, velocity), and oil−water phase content on hydrate blockage in the pipeline through the high-pressure hydrate flow experimental loop according to the feasibility of hydrate risk control technology strategy. The experimental results show that the plugging behavior of hydrate changes with the change of variables and the chemical properties of oil and water. It is concluded that the critical moisture content to ensure the safe flow of hydrate is 25%. In 2009, American scholar Boxall et al.[30,31] focused on the hydrate pipe plugging problem in the actual oil and gas gathering and transmission pipeline and, using the existing experimental data and the established hydrate dynamics (CSMHyK) model, studied the effects of pump speed and water content on hydrate flow and pipe plugging. The experimental results show that a high pump speed and a low water content can ensure the safe flow of hydrate in the pipeline. At the same time, CSMHyK combined with OLGA software can predict the formation position and time of hydrate plugging in the streamline. In 2012, Li[32] of the China University of Petroleum (Beijing) systematically carried out experimental research on hydrate flow and pipe plugging in pipelines under different flow conditions by using the built high-pressure loop according to the current situation of hydrate blockage in pipelines. The experimental results show that the flow and pressure have a great impact on the risk of hydrate plugging in the pipeline. The flow rate has little effect on the particle size of hydrate particles but has a great effect on the coalescence between hydrate particles. In 2013, American scholars Zerpa et al.[33] carried out experimental research on the hydrate slurry flow pattern and studied the hydrate pipe plugging mechanism on the basis of flow pattern analysis. The experimental results show that when the hydrate volume fraction is low, there is stratified flow in the pipe. With the progress of the reaction, the volume fraction of hydrate increases gradually, and finally pipe plugging occurs. Rao et al.[34,35] studied the flow characteristics of gas−liquid two-phase spiral flow and hydrate formation characteristics based on spiral flow. In 2015, American scholar Majid et al.[8] carried out experiments on hydrate flow and pipe plugging characteristics on the high-pressure loop of Tulsa University. The experimental results show that the growth of hydrate particles on the pipe wall, the agglomeration of hydrate particles, and the settlement of hydrate in the flow process are the main reasons for pipe plugging. In 2017, Ding et al.[9] from the China University of Petroleum (Beijing) carried out research on hydrate flow and pipe plugging characteristics in oil and gas gathering and transmission pipelines. Based on the experimental results, the hydrate deposition and pipe plugging mechanism under different hydrate slurry flow patterns are obtained, and the method of quantitative calculation of deposition is deduced.

At present, in the actual natural gas transmission pipeline, adding thermodynamic inhibitors is still the main means to prevent hydrate formation, and the green and efficient hydrate flow guarantee technology is still immature. With the attention of scientific and technological workers at home and abroad on hydrate flow guarantee technology, relevant scholars at home and abroad have made preliminary research on the formation characteristics of gas hydrate and the flow characteristics of hydrate in pipelines and achieved some theoretical and practical results. However, there is still lack of hydrate prevention and control methods to meet the safe operation of the actual pipeline, the hydrate safe flow technology based on swirl flow has not yet been fully understood, and the relevant research is in its infancy. How to realize the safe flow of hydrate in the pipeline requires more in-depth research on the formation and flow characteristics of hydrate in the pipeline, the flow and deposition law of hydrate particles, and the related swirl flow characteristics.

In summary, this study carries out the research on the safe flow of gas hydrate in the pipeline, obtains the safe flow law of swirl flow gas hydrate, explores the safe flow conditions of hydrate under the swirl flow system in the pipeline, expands the safe flow boundary of hydrate, and provides technical support for the development and transportation of deep-sea natural gas and gas hydrate.

EXPERIMENTAL SECTION

Experimental Device. Figure 1 shows the experimental device for the formation and flow of high-pressure hydrate,

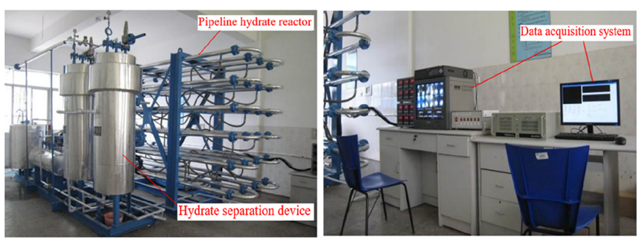

Figure 1. High-pressure hydrate formation flow experimental device.

which is mainly responsible for the study of the formation law, flow law, and pipe plugging law of gas hydrate in the pipeline. The device is equipped with a pipeline data acquisition and processing system with a length of 97 m, an inner diameter of 25 mm, a maximum pressure of 8 MPa, and a design temperature of −5 to 30 °C. Figure 2 shows the experimental

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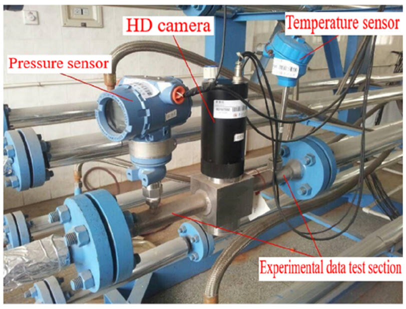

Figure 2. Experimental data test section.

data test unit, including the pressure sensor, HD camera, and temperature sensor. Figure 3 shows a high-definition camera with four auxiliary lights. Figure 4 presents the flow chart of the pipeline gas hydrate formation experimental device. Six observation points are set in the experimental device, which are recorded as VA1, VA2, VA3, VA4, VA5, and VA6.

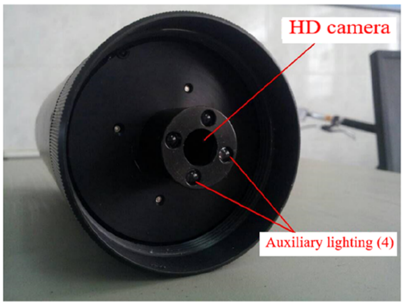

Figure 3. HD camera.

Hydrate Generating Unit. The hydrate generating unit is the main part of the high-pressure hydrate experimental loop, as shown in Figure 5. The pipeline of the hydrate generating unit is a casing structure, and the cooling water flows in the casing to cool the experimental pipe section. The swirl flow is generated by a twisted band installed in the pipe. The twisted tape used in this experiment is a short, twisted tape with a length of 0.5 m, which is installed at the entrance of the transparent pipe section.

Supply System and Data Acquisition System. The supply system includes a water supply system, an air supply system, and a cooling system. The volume of the water tank is 180 L, and the volume of the low-temperature water tank is 250 L. The cooling equipment adopts the German Lauda cooling water circulator, and the working temperature range is −10 to 40 °C. The monitoring and data acquisition system is mainly composed of a high-resolution recorder, a light source system, and a data acquisition card, which can realize the monitoring and recording of hydrate formation and flow characteristics under the swirl flow system in the pipeline.

The high-pressure hydrate experiment loop is equipped with a differential pressure sensor (Honeywell STD720), a pressure sensor (Rosemount 3051), a turbine flowmeter (recording liquid flow, Dalian Youke, YK-LWGY-04), and a mass flowmeter (recording gas flow, Emerson, CMFS010M323N2BZMCZZ). The temperature and pressure data and pressure difference data in the experiment are collected and recorded by a computer.

The six-phenomenon observation and data acquisition points of the high-pressure hydrate experimental loop are unevenly distributed, taking the pipeline inlet as the coordinate origin, and the coordinates of each observation point are shown in Table 1. The experimental pressure range is 1−6.5 MPa, and the experimental temperature range is 1.5−8.5 °C. The experimental gas is carbon dioxide with a purity of (mol) ≥99%. The water content of the fluid in the experiment is 10, 15, 20, 25, and 30%, respectively. The velocity range of hydrate is 0−1.5 m/s. The pressure drop is the difference between the pressure gauges at both ends of the section to be tested. In order to ensure the fluidity of hydrate, certain amounts of low-dose inhibitor and polymerization inhibitor were added during the hydrate flow experiment in the pipeline.

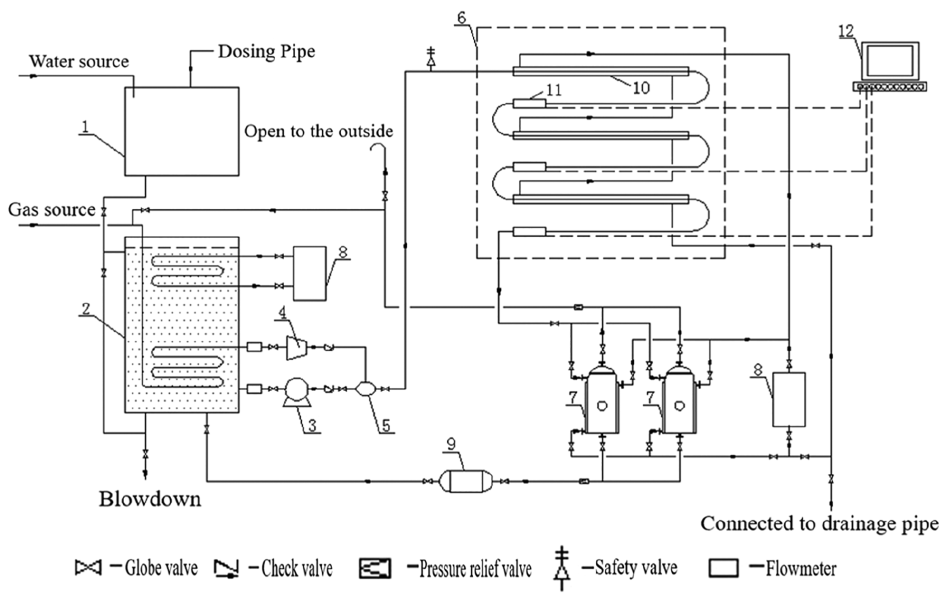

Figure 4. Flow chart of the high-pressure hydrate experiment loop. (1) Water tank, (2) low-temperature water tank, (3) magnetic pump, (4) booster pump, (5) mixer, (6) generating unit, (7) separator, (8) cold water bath, (9) buffer tank, (10) bushing, (11) monitoring pipe section, and (12) data acquisition device.

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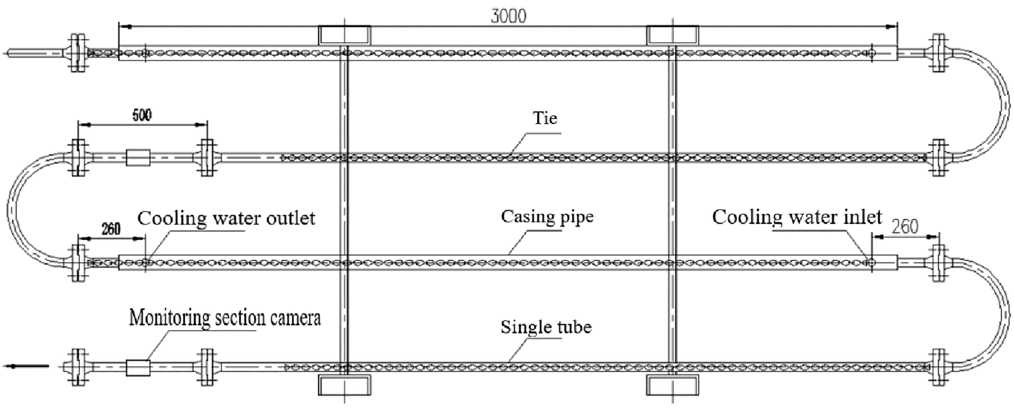

Figure 5. Structural diagram of the swirl flow hydrate generating unit.

Table 1. Location of Observation and Data Acquisition Points

observation and data acquisition points	location of observation and data acquisition points/m
1#	6.42
2#	30.14
3#	37.38
4#	61.10
5#	68.34
6#	92.06

Twisted Device. The starting device is a twisted tape, which is made of a polymer material, as shown in Figure 6. The

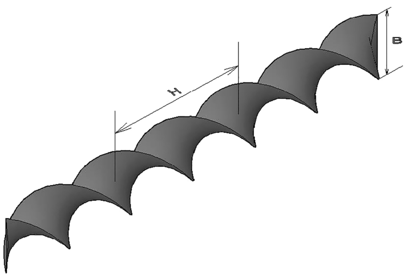

Figure 6. Structure of the twisted tape.

twisted rate y of the twisted tape is 6.2, 7.4, and 8.8. The twisted rate y of the twisted tape is the rate of the length h of the twisted tape rotating for one cycle to the width b of the twisted tape, as shown in formula 1.

$$Y = H/B \tag{1}$$

Experimental Steps. *Hydrate Formation Experiment.* The experimental steps of hydrate formation experiment are as follows: (1) install spiral twisted tape and start the monitoring equipment. (2) Prepare the test liquid and open the pipeline valve. (3) Turn on the refrigeration equipment and preset the experimental temperature. (4) When the temperature of the experimental liquid is the preset temperature, start the compressor to obtain the preset pressure value in the high-pressure flow loop. The experimental liquid gradually enters the experimental loop, and the hydrate gradually begins to form and flow. (5) Start the experimental data-monitoring system to find the induction time and formation time of the hydrate. (6) After the experiment, clean the experimental device and turn off the power.

Hydrate Flow Experiment. The experimental steps of hydrate flow experiment are as follows: (1) Before the experiment, clean the experimental pipeline with a vacuum pump and set the vacuum degree in the pipe at 0.02 MPa. (2) Start the data recording system; turn on the double plunger pump, inject water into the pipeline, turn on the low-temperature water bath, and set the system temperature. (3) Start the circulating pump to make the fluid flow at a certain speed in the pipe. Open the air inlet valve to make the experimental device reach the preset pressure and then close the air valve to fully dissolve the experimental gas. (4) Continue to cool the experimental system and closely observe the formation of hydrate; the data-recording system will record the pressure, temperature, flow, differential pressure, and other data. When the fluid velocity is zero, the hydrate is formed to the end of the plugging experiment, and the experiment is stopped.

■ RESULTS AND DISCUSSION

Study on Hydrate Flow Characteristics. On the experimental platform of swirl flow gas hydrate formation and safe flow, through the experimental research on the hydrate formation characteristics under the swirl flow system in the pipeline, the hydrate formation characteristics under the influence of different factors are preliminarily mastered. Next, the safe flow characteristics of swirl flow gas hydrate in the pipeline under the conditions of different moisture content, initial pressure, concentration, and torsion are studied.

Figures 7 and 8 show the variation trend of hydrate formation and flow rate, pressure drop, and temperature with time under the conditions of a pressure of 4.5 MPa, a moisture content of 15%, a flow rate of 0.4 m/s, and a twisted rate of 6.2. It can be seen from the figure that at the beginning of the experiment, the temperature in the pipeline continues to decrease and the pressure in the pipeline also begins to decrease gradually. Because the system is still in the hydrate induction period, the fluid flow rate in the pipeline is basically unchanged. As the reaction continues, the pressure in the pipeline continues to decrease, and the temperature decreases from the initial 4.5 °C to about 3.5 °C, reaching the hydrate formation conditions. A large number of hydrates begin to form in the pipeline, and the fluid flow rate begins to decrease rapidly, from the initial 0.4 to 0.2 m/s; that is, with the large amount of hydrate, the fluid flow rate gradually decreases and the fluid fluidity gradually deteriorates. With the progress of the reaction, the flow velocity in the pipeline increases slowly.

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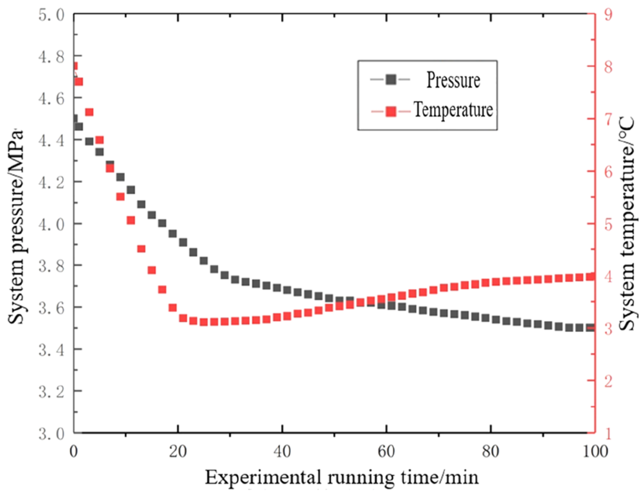

Figure 7. Temperature−pressure curve of hydrate formation and flow process in the pipeline (pressure, 4.5 MPa; moisture content, 15%; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

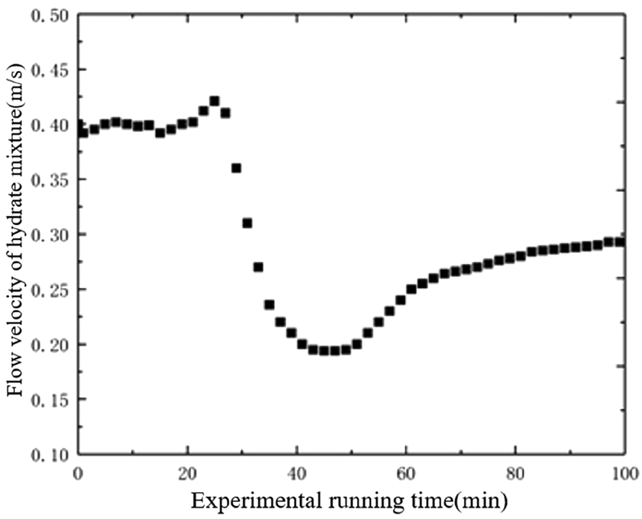

Figure 8. Variation of flow velocity during hydrate formation and flow in the pipeline (pressure, 4.5 MPa; moisture content, 15%; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

The authors believe that, on the one hand, the flow friction increases gradually due to the sharp increase of hydrate volume fraction; on the other hand, the collision and merging of hydrate particles in the pipeline cause the accumulation of larger hydrate particles. Both of them lead to a significant decrease in the flow velocity in the pipeline. Then, the velocity rise is due to the aggregation and formation of larger hydrate particles, which are separated under the higher tangential velocity of swirl flow and strong shear action; that is, the larger hydrate particles are gradually broken and dispersed into smaller hydrate particles, and the fluidity of hydrate in the pipeline is gradually enhanced, so the velocity is gradually increased. However, the increased velocity is still less than the initial velocity of the fluid in the pipeline.

In addition, it can be seen from the figure that with the progress of the experiment, in addition to the trend of first decreasing and then increasing, the fluid velocity in the pipeline fluctuates in a very short time, and the vibration amplitude of the velocity curve becomes more and more intense with the increase of hydrate production. The authors believe that this is mainly due to the continuous impact and merging of hydrate particles under the shear action of pipeline flow, especially under the impact of tangential velocity of swirl flow, which leads to the continuous change of hydrate volume fraction in the pipeline and then to a certain degree of oscillation of hydrate flow velocity in the pipeline. To sum up, due to the gradual formation of hydrate, the flow law of hydrate in the pipeline changes gradually, especially when the hydrate begins to form in large quantities with the progress of reaction, the fluidity of hydrate in the pipeline is also greatly affected; at the same time, it can be seen from the velocity change curve of hydrate in the pipeline that the rapid and large-scale formation stage of hydrate is a high-risk stage of hydrate blockage. When the actual oil and gas transmission pipeline is running, we should pay close attention to the flow change at this stage.

Influence of Water Content. Moisture content is one of the important elements affecting the safe flow of hydrate in the pipeline. The authors conducted experiments on hydrate flow characteristics in the pipeline under different water content conditions to explore the influence of water content on hydrate flow characteristics, as shown in Figures 7, 9, and 10. It can be seen from the figure that under the conditions of two moisture contents (15 and 25%), the variation trend of flow rate, pressure, and temperature with time is roughly the same, but the variation degree of each factor is different. Under the same conditions of pressure, temperature, flow velocity, and torsion, the pressure and temperature gradually decrease with the increase of water content. However, the comparison found that the degree of pressure reduction was greater; in addition, the flow rate also began to decrease after maintaining a certain value, but after the water content increased, the flow rate began to decrease gradually after 20 min of reaction, indicating that the hydrate began to form 5 min earlier than the formation process under the condition of 15% water content. The authors believe that the main reason for the above phenomenon is that the higher the water content is, the larger the contact area between gas and liquid phases is, and the faster the hydrate formation speed is; that is, the increase of water content promotes the hydrate formation in the pipeline. In addition, the higher moisture content makes the hydrate

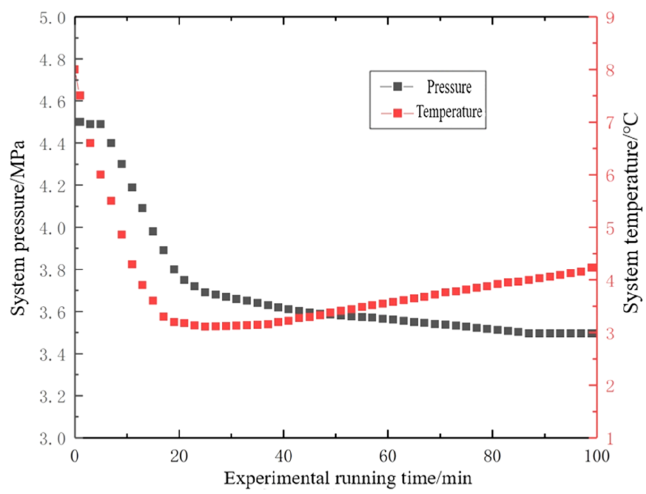

Figure 9. Temperature−pressure curve of hydrate formation and flow process in the pipeline (pPressure, 4.5 MPa; moisture content, 25%; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

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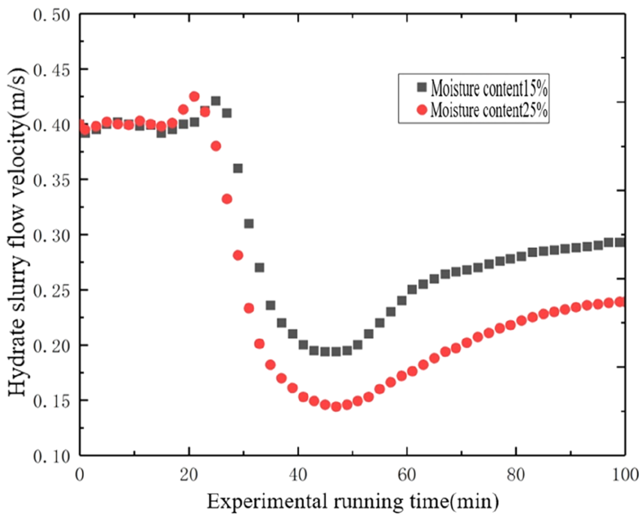

Figure 10. Variation of flow velocity during hydrate formation and flow in the pipeline (pressure, 4.5 MPa; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

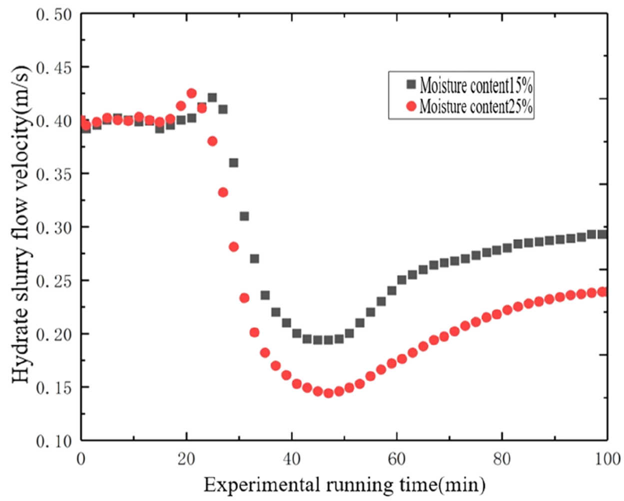

Figure 11. Temperature−pressure curve of hydrate formation and flow process in the pipeline (temperature, 3.5 °C; pressure, 4.5 MPa; moisture content, 15%; velocity of flow, 0.6 m/s; and twisted rate, 6.2).

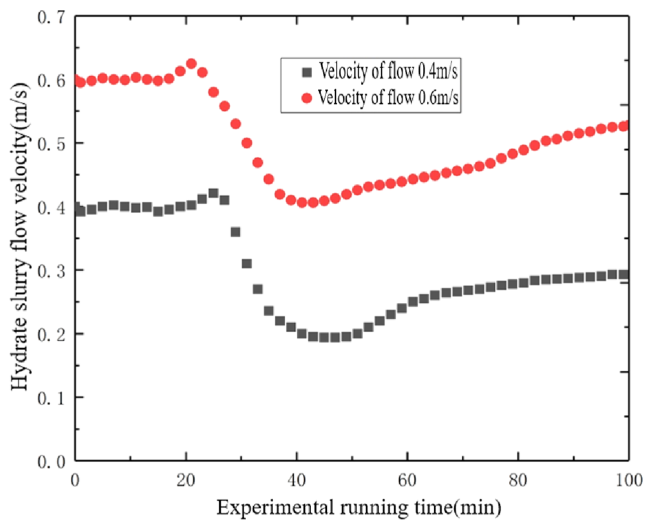

Figure 12. Variation of flow velocity during hydrate formation and flow in the pipeline (temperature, 3.5 °C; pressure, 4.5 MPa; moisture content, 15%; and twisted rate, 6.2).

particles in the flow more likely to collide and merge, which increases the concentration of hydrate particles and the risk of hydrate blocking the pipeline; similarly, due to the existence of swirl flow, under the action of tangential velocity, the larger hydrate particles are broken due to shear, which makes the hydrate velocity in the pipeline increase slowly. Generally speaking, under the condition of a high water content, the formation of hydrate in the pipeline is accelerated, which makes the fluctuation of hydrate flow in the pipeline more obvious; that is, the high water content increases the risk of hydrate blocking the pipeline, which should be controlled in the actual operation process.

Effect of Initial Velocity. Velocity of flow is an important parameter in the process of hydrate formation and flow in the pipeline. The magnitude of velocity is closely related to the fluidity of fluid in the pipeline. In order to realize the safe transportation of hydrate in the pipeline, certain velocity must be guaranteed. The hydrate flow law in the pipeline under different initial flow rates is shown in Figures 7, 11 and 12. It can be seen from the figure that the change in the initial flow rate has little impact on temperature and pressure, but it will have a great impact on the formation and flow of hydrate. The greater the initial flow rate, the lower the decrease of hydrate flow rate in the pipeline, which means that the formation of hydrate slows down, and after the flow rate is accelerated, the hydrate particles are not easy to coalesce due to the impact of flow rate, which improves the dispersion and fluidity of hydrate particles in the pipeline. In addition, when the velocity increases, the tangential velocity of swirl flow increases accordingly, and the shear force in the pipeline increases gradually, which greatly reduces the coalescence number of hydrate particles. In short, a higher hydrate flow rate in the pipeline will reduce the occurrence of hydrate pipe plugging accident. The experimental results are different from the non-swirl experimental results. The authors believe that it is mainly due to the existence of tangential velocity in addition to the axial velocity after adding the twisted tape in the pipeline. The tangential velocity is perpendicular to the flow direction of the axial velocity, which can effectively promote the dispersion and carrying of hydrate particles and improve the fluidity of hydrate, effectively preventing the occurrence of hydrate pipe plugging.

Influence of Pressure. Pipeline pressure has a great influence on the formation of hydrate in the pipeline. The increase of hydrate can cause the change in fluid viscosity characteristics in the pipeline, so it also has a certain impact on the flow of hydrate. The hydrate formation and flow characteristics under different initial system pressures are shown in Figures 7, 13 and 14.

It can be seen from the figure that the initial system pressure has a significant impact on the flow rate during the formation of hydrate. After the initial pressure increases, the flow rate decreases rapidly in a short time. The authors believe that when the pressure in the pipeline increases, the formation rate and amount of hydrate increase rapidly. Therefore, compared with the experiment under the pressure system of 4.5 MPa, when the system pressure increases to 5 MPa, the fluid flow rate gradually decreases after 15 min, and the reduction range

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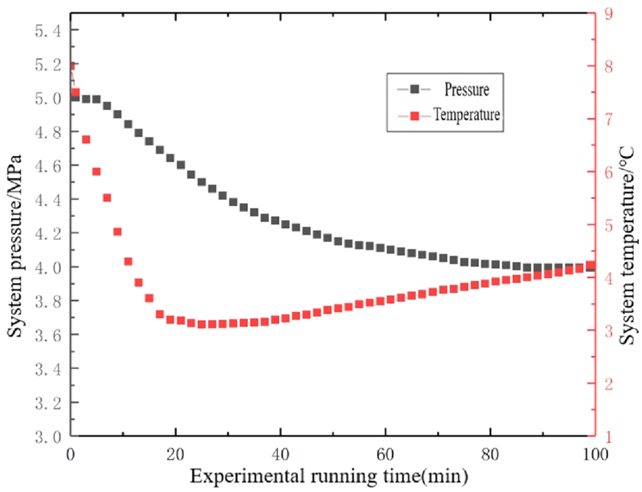

Figure 13. Temperature−pressure curve of hydrate formation and flow process in the pipeline (temperature, 3.5 °C; pressure, 5 MPa; moisture content, 15%; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

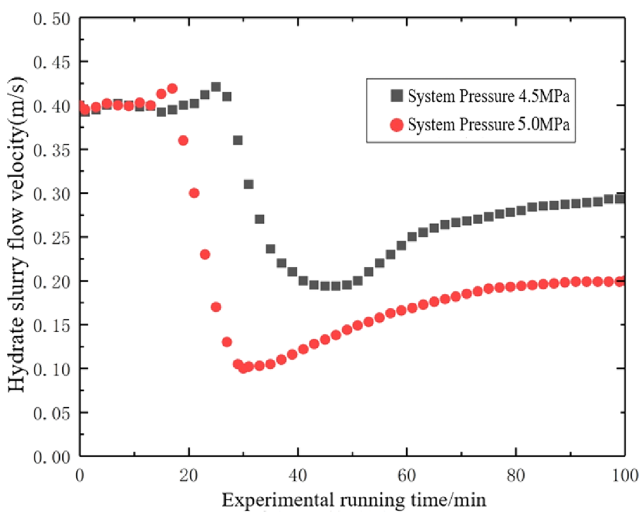

Figure 14. Variation in flow velocity during hydrate formation and flow in the pipeline (temperature, 3.5 °C; moisture content, 15%; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

is also large. It can be seen that pressure is the main control parameter in hydrate safe flow technology.

Effect of Twisted Rate. In addition to the axial velocity along the flow direction, swirl flow also has a tangential velocity perpendicular to the flow direction. The existence of tangential velocity can make the hydrate particles spiral forward in the pipeline, which can avoid not only bonding the inner wall of the pipeline but also the deposition of hydrate particles to a certain extent. It has a good effect on preventing hydrate particle deposition and promoting the safe flow of hydrate.

Figures 7, 15 and 16 compare the effect of twisted rate of different twisted bands on hydrate formation flow under the same flow conditions. It can be seen from the figure that the smaller the twisted rate of the twisted band, the faster the hydrate formation rate and the greater the hydrate formation amount, resulting in the gradual deterioration of the fluidity of hydrate in the pipeline. In addition, the twisted rate is smaller, the rotation degree of the twisted tape is stronger, the intensity

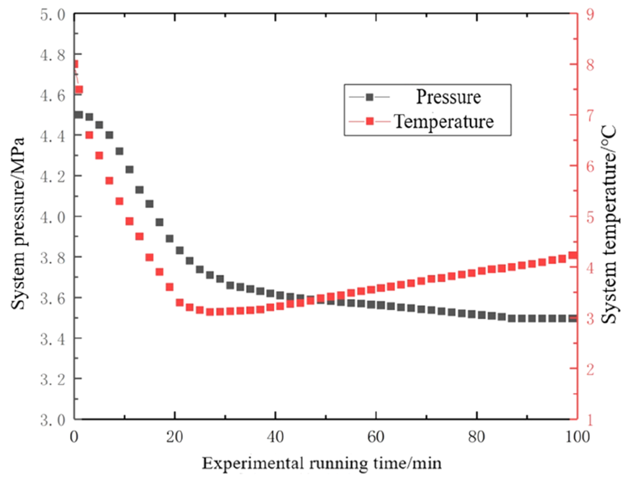

Figure 15. Temperature−pressure curve of hydrate formation and flow process in the pipeline (temperature, 3.5 °C; pressure, 4.5 MPa; moisture content, 15%; velocity of flow, 0.4 m/s; and twisted rate, 8.8).

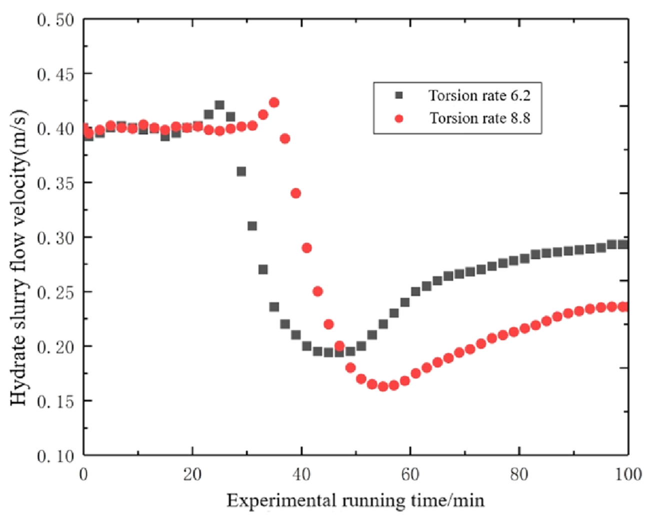

Figure 16. Velocity variation diagram of hydrate formation and flow process in the pipeline (temperature, 3.5 °C; pressure, 4.5 MPa; moisture content, 15%; and velocity of flow, 0.4 m/s).

of the swirl flow is greater, and the tangential velocity is higher, which improve the fluidity of hydrate in the pipeline.

Under the same conditions of initial velocity, moisture content, pressure, and temperature, when the twisted rate is small, the swirling intensity of swirl flow is high and the tangential velocity is large. Therefore, although the system in the pipeline reaches the phase equilibrium condition of hydrate formation and the amount of hydrate formation increases rapidly, due to the impact and carrying effect of higher tangential velocity, the hydrate in the pipeline can still maintain good fluidity, avoid deposition or bonding on the bottom or inner wall of the pipeline, and the hydrate particles still move forward at a certain velocity. It can be seen that swirl flow can improve the tangential velocity of hydrate particles, enhance the fluidity of hydrate particles, and prevent the deposition of hydrate particles.

Research on the Hydrate Pipe Plugging Law. The law of hydrate pipe plugging is the key to hydrate risk control technology. It is very important to clarify the pipe plugging mechanism of different systems for the determination of pipe

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plugging prevention methods in actual production. As there are certain risks in the pipe plugging experiment in the laboratory, the following is a preliminary exploration and research on the influence of water content, initial velocity of flow, pressure, and twisted rate on the pipe plugging law of hydrate under the swirl flow system.

Influence of Water Content. Water content is an important factor that affects hydrate formation and flow. Therefore, hydrate pipe plugging experiments under different water content conditions were carried out, as shown in Figure 17.

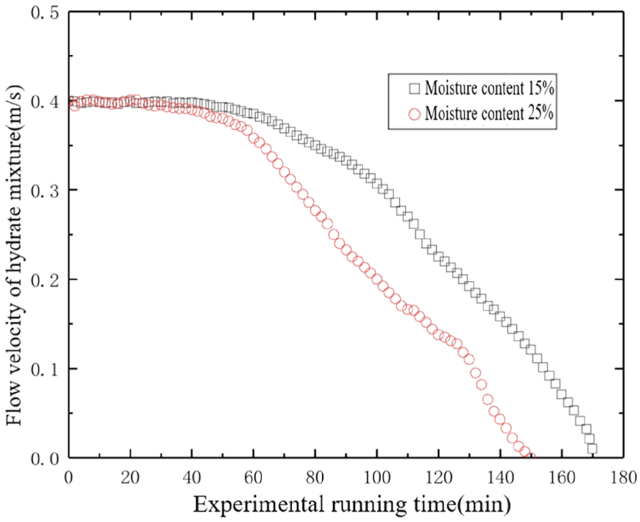

Figure 17. Variation in flow velocity during hydrate formation and flow in the pipeline (temperature, 4.5 °C; pressure, 3.5 MPa; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

It can be seen from the figure that when factors such as pressure, temperature, flow velocity, and torsion are the same, with the increase of water content, the flow velocity of the hydrate particle fluid in the pipeline decreases more obviously, and the time of pipe plugging is shortened accordingly. The authors believe that the main reason for the above phenomenon is that the higher the water content is, the larger the gas−liquid contact surface is, and the faster the hydrate formation speed is; that is, the increase of water content promotes the hydrate formation in the pipeline. In addition, the higher water content makes the hydrate particles in the flow more likely to collide and merge, increasing the risk of hydrate blocking the pipeline. Generally speaking, under the condition of high water content, the formation of hydrate in the pipeline is accelerated, and the flow fluctuation of hydrate in the pipeline is obvious; that is, high water content increases the risk of hydrate blocking the pipeline, which should be controlled in the actual operation process.

Effect of Initial Velocity. The influence of the initial flow rate of the system on the hydrate blocking law in the pipeline is shown in Figure 18. It can be seen from the figure that with the increase of flow velocity, the time of hydrate blocking in the flow system in the pipeline is prolonged. The authors believe that after the hydrate flow rate in the pipeline increases, the cooling rate of the reaction fluid slows down, the formation rate of hydrate is reduced, the fluidity of hydrate is increased, and the pipe plugging time is prolonged (i.e., the time when the fluid flow rate in the pipeline decreases to 0). On the other hand, after the initial velocity increases, the impact and carrying effect of the tangential velocity of the swirl flow on the

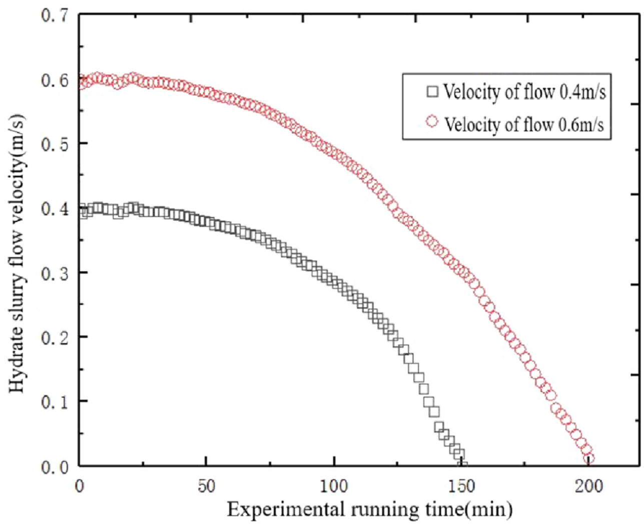

Figure 18. Variation in flow velocity during hydrate formation and flow in the pipeline (temperature, 4.5 °C; pressure, 3.5 MPa; moisture content, 25%; and twisted rate, 6.2).

hydrate delay or inhibit the success rate of the nucleation point at the gas−liquid contact surface. At the same time, the generated larger hydrate particles are dispersed and broken into smaller hydrate particles with better fluidity, so as to enhance the fluidity of the fluid in the pipeline and further prolong the pipe plugging time.

Effect of Pressure. The law of hydrate plugging in the pipeline under different pressure conditions is shown in Figure 19. It can be seen from the figure that the pressure has a

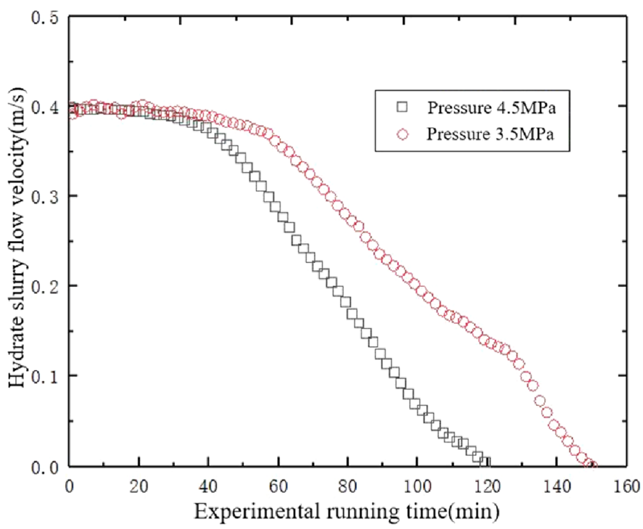

Figure 19. Variation in flow velocity during hydrate formation and flow in the pipeline (temperature, 4.5 °C; moisture content, 25%; velocity of flow, 0.4 m/s; and twisted rate, 6.2).

significant impact on the plugging time of hydrate. The blocking time of hydrate under high pressure is about 120 min, while the blocking time of hydrate under an experimental pressure of 3.5 MPa is about 150 min. The blocking time under high pressure is obviously less than that under low pressure.

It can be concluded that under the same conditions, the hydrate formation gradually increases with the increase of

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pressure and then the pipe plugging time gradually shortens. Therefore, in order to ensure the safe flow of hydrate particles in the pipeline, the pressure of the pipeline should be controlled.

Effect of Twisted Rate. The effects of different twisted rates on hydrate pipe plugging under the conditions of a pressure of 3.5 MPa and a temperature of 4.5 °C are studied, as shown in Figure 20. It can be seen from the figure that the twisted rate

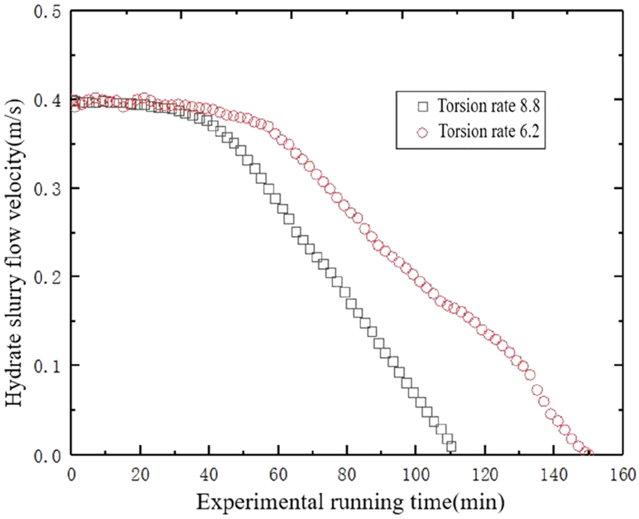

Figure 20. Variation in flow velocity during hydrate formation and flow in the pipeline (temperature, 4.5 °C; pressure, 3.5 MPa; moisture content, 25%; and velocity of flow, 0.4 m/s).

has a great influence on the flow of hydrate and the law of pipe plugging. Under the same conditions, the smaller the twisted rate of the twisted band, the longer the plugging time of hydrate. That is, the smaller the twisted rate of the twisted tape, the stronger the rotating strength of the twisted tape, the greater the tangential velocity, the increased the tangential motion intensity of hydrate particles in the pipeline, the longer the pipe plugging time, and the lower the risk of pipe plugging. The authors believe that when the twisted rate of the twisted tape in the pipeline becomes smaller, the rotating strength of the twisted tape increases, and the tangential momentum of the hydrate becomes greater after the initial rotation of the twisted tape; that is, the tangential velocity is higher and the centrifugal force is greater. When hydrate particles flow in the pipeline, they are affected by the tangential velocity. In addition to the axial velocity along the pipeline, they also have the tangential velocity perpendicular to the axial velocity. The tangential velocity can make the hydrate particles move spirally in the pipeline, which can not only avoid the deposition of hydrate particles in the pipe wall but also further reduce the aggregation between hydrate particles, so as to keep the hydrate particles flowing in the pipeline and then reduce the risk of hydrate blocking in the pipeline.

Research on the Hydrate Deposition Law. *Thickness of the Sedimentary Layer.* According to the hydrate generation pictures in the windows of six monitoring points, the thickness of hydrate deposition layer can be calculated according to the ratio of hydrate deposition thickness to pipeline inner diameter, and the variation curve of hydrate particle deposition thickness of the separated flow system and the dispersed flow system is shown in Figure 21.

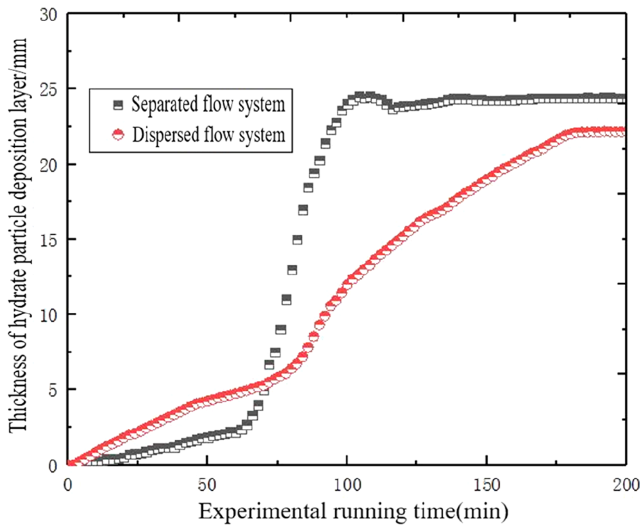

Figure 21. Variation law of hydrate particle deposition thickness (temperature, 4.5 °C; pressure, 3.5 MPa; moisture content, 25%; and twisted rate, 6.2).

For the separated flow system, there is no hydrate deposition layer in the loop system at the beginning; that is, the thickness of the hydrate deposition layer is zero. With the progress of the reaction, hydrate particles continue to form, and hydrate particles begin to gather to form a sedimentary layer, and its thickness presents the characteristics of fluctuation. At the initial stage of the reaction, the surface of the deposition layer fluctuates greatly, and the thickness of the deposition layer increases gradually with the progress of the reaction. When hydrate particles continue to gather, the thickness of the sedimentary layer increases rapidly until the pipeline is finally blocked.

For the dispersed flow system, a small number of hydrate particles are generated in the initial stage, but the amount of hydrate particles is small, which can move forward according to the mainstream, and there is almost no sedimentary layer. With the progress of the reaction, the bubbles dispersed in the liquid began to gradually form hydrate particles. With the gradual increase of hydrate particles, a deposition layer begins at the bottom of the pipeline. Then, with the continuous formation of hydrate in the pipeline, the thickness of the sedimentary layer gradually increases until the pipeline is finally blocked.

Therefore, when the flow state in the pipeline is in the separated flow, pay close attention to the deposition of hydrate particles to prevent the rapid change in the deposition height, resulting in the rapid blockage of hydrate in the pipeline and safety accidents.

Critical Volume Fraction. The variation of pressure drop with hydrate volume fraction at different flow rates is shown in Figure 22. It can be seen from the figure that the pressure drop of hydrate has experienced the process of increasing, decreasing, and then increasing with the increase of volume fraction, which is basically consistent with the research results of the literature.[13] When the hydrate volume fraction is less than 40%, the pipeline pressure drop increases with the increase of hydrate volume fraction. In the range of 40−50%, the pressure drop decreases with the increase of hydrate volume fraction. When the volume fraction of hydrate particles is greater than 50%, hydrate gradually increases with greater pressure drop gradient. The authors believe that in the initial stage of hydrate formation, the amount of hydrate formation is

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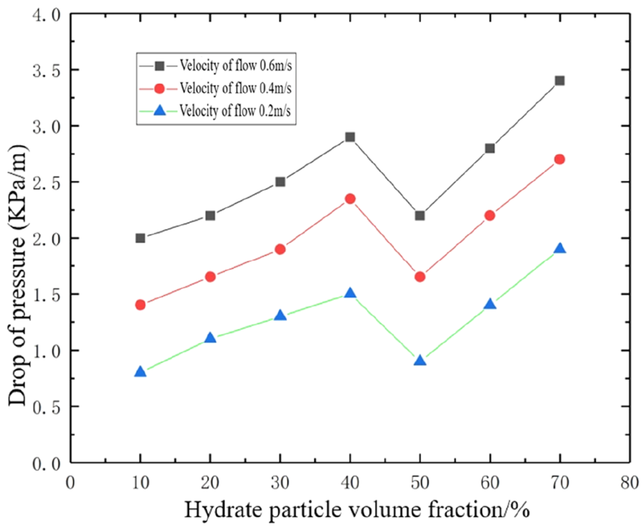

Figure 22. Variation in pressure drop with hydrate volume fraction at different flow rates (temperature, 4.5 °C; pressure, 3.5 MPa; moisture content, 25%; and twisted rate, 6.2).

less, and the pipeline is in a normal flow state. With the progress of the experiment, the hydrate formation and the flow pressure drop increase. When the hydrate volume exceeds 40%, the hydrate particles show better follow-up and fluidity, so the pressure drop is reduced. However, when the volume fraction of hydrate increases further, the fluidity of hydrate becomes worse and the gradient of pressure drop increases more. Therefore, when the volume fraction of hydrate is less than 40%, the safety zone of hydrate flow in the swirl flow system is 33.3% higher than the critical volume fraction of hydrate under the non-swirl condition, which effectively expands the safe flow boundary of hydrate.

THEORETICAL ANALYSIS

Stress Analysis. Swirl flow can be divided into axial velocity, radial velocity, and tangential velocity. The forces on particles are generally divided into three categories: (1) Forces that do not depend on the relative motion between fluid and particles, such as inertial force, gravity, and so forth. (2) Depending on the force of relative motion between fluid and particles, the direction of the force is consistent with the flow direction, such as friction resistance, basset force, and so forth. (3) Depending on the force of the relative motion between the fluid and particles, the direction of the force is perpendicular to the flow direction, such as lift, Magnus force, and Saffman force.[37]

The hypothesis of particle phase motion is introduced. Hydrate particles in swirl flow are mainly affected by Stokes resistance F_D, gravity F_g, buoyancy F_b, lift F_L, Saffman force F_S, Magnus force F_M, and so on.[37] According to the classical law of motion, the equation of motion of hydrate particles is as follows

$$\frac{1}{6}\pi D_s^3 \rho_s \frac{d\vec{u_s}}{dt} = F_D + F_L - F_b + \vec{F_S} + \vec{F_M} \tag{2}$$

where $F_D = \frac{1}{8}\pi d_s^2 C_D \rho u_\theta^2$, $F_L = \frac{1}{8}\pi d_s^2 C_L \rho u_\theta^2$, $F_b = \frac{1}{8}\pi d_s^2 g(\rho_s - \rho)$, C_D is the drag coefficient, C_L is the lift coefficient, d_s is the particle size, m; ρ is the fluid density, kg/m^3; ρ_s is the particle density, kg/m^3; and u_θ is the tangential velocity of particles, m/s.

According to the moving position of particles, the flow area in the pipe is divided into the mainstream area and the pipe wall area, which are discussed below.

1 Hydrate particles in the mainstream zone move in a circular motion along the pipe section under the carrying of tangential velocity. The forces mainly include the tangential drag, radial lift, particle gravity, and buoyancy.

The resultant force W of particle gravity and buoyancy can be decomposed into the tangential component W_θ and the radial component W_r

$$W_\theta = W \sin\theta \tag{3}$$

$$W_r = W \cos\theta \tag{4}$$

From the balance of radial force, we get

$$F_L - W_r = 0 \tag{5}$$

When the rising height of particles at a concentric circle is h, the force formula of particles is given by

$$F_D - W_\theta = 0 \tag{6}$$

Substituting each force into the above formula, we get

$$C_D \frac{\pi}{8} d_s^2 \rho u_\theta^2 - \frac{\pi}{6} d_s^3 (\rho_s - \rho) g \cdot \sin\theta = 0 \tag{7}$$

Sorting out, we obtain

$$u_\theta = \sqrt{\frac{4 d_s (\rho_s - \rho) \cdot \sin\theta}{3 C_D \rho}} \tag{8}$$

Equation 8 is the tangential flow rate required when the particle is at angle θ (or the rising height is h). The term u_θ is related to the particle size, density, drag coefficient, and equilibrium position. With the increase of particles, the tangential velocity under equilibrium condition increases.

As can be seen from Figure 23, the relationship of θ with h is as follows

$$\cos\theta = 1 - \frac{h}{r} \tag{9}$$

where r is the circular radius of particle motion. Therefore, eq 8 can also be expressed as

$$u_\theta = \sqrt{\frac{\frac{4}{3} g d_s \left(\frac{\rho_s - \rho}{\rho}\right) \left[\sqrt{1 - \left(1 - \frac{h}{r}\right)^2}\right]}{C_D}} \tag{10}$$

The authors define the standard that the particles are in a safe flow state (suspended state) in swirl flow because the particles rise to the center of the pipe diameter under the carrying of tangential velocity. Here, $\theta = 90°$ and $h = r$, so from eq 8 or 10, we get

$$u_{\theta c1} = \sqrt{\frac{4}{3} \frac{g d_s}{C_D} \left(\frac{\rho_s - \rho}{\rho}\right)} \tag{11}$$

where $u_{\theta c1}$ is the tangential critical velocity of hydrate particles in the mainstream area, that is, the critical tangential velocity of the safe flow of hydrate particles, m/s.

2 Near the pipe wall, the forces on hydrate particles mainly include tangential drag, radial lift, particle gravity and

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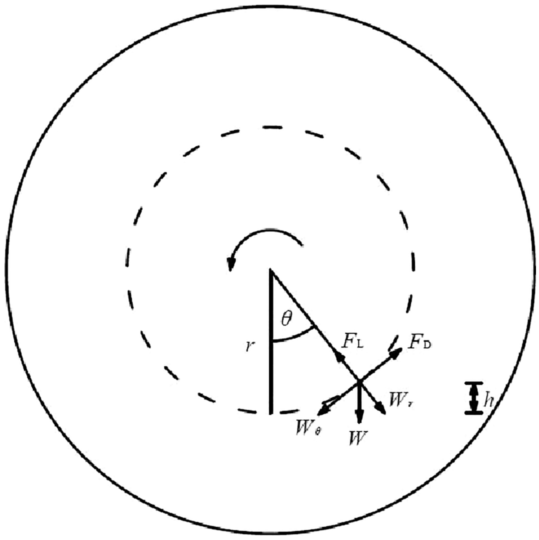

Figure 23. Stress analysis diagram of particle phase in the main flow area.

buoyancy, friction between particles and the wall, and pipe wall support reaction.

From the balance of radial force, we get

$$N_C + F_L - W_r = 0 \tag{12}$$

where N_C is the reaction force of the particles supported by the pipe wall, N. Therefore, the friction F_f between particles and the wall can be expressed as

$$F_f = fN_C = f(W_r - F_L) \tag{13}$$

where f is the friction resistance coefficient between particles and the wall.

When the rising height of particles on the pipe wall is h, the balance formula of the particle circumferential shear force is

$$F_D - W_\theta - F_f = 0 \tag{14}$$

Substituting each force into the above formula, we get

$$C_D\frac{\pi}{8}d_s^2\rho u_\theta^2 - \frac{\pi}{6}d_s^3(\rho_s - \rho)g\cdot \sin\theta - f\left[\frac{\pi}{6}d_s^3(\rho_s - \rho)g\cdot \cos\theta - C_L\frac{\pi}{8}d_s^2\rho u_\theta^2\right] = 0 \tag{15}$$

Sorting out, we obtain

$$u_\theta = \sqrt{\frac{4}{3}gd_s\left(\frac{\rho_s - \rho}{\rho}\right)\frac{\sin\theta + f\ \cos\theta}{C_D + fC_L}} \tag{16}$$

Equation 16 is the minimum tangential velocity required when hydrate particles are at angle θ (or rising height is h). With the increase of particles, the tangential velocity under equilibrium condition increases.

As can be seen from Figure 24, the relationship between θ and h is as follows

$$\cos\theta = 1 - \frac{h}{R} \tag{17}$$

where R is the pipe radius. Therefore, eq 16 can also be expressed as

$$u_\theta = \sqrt{\frac{4}{3}gd_s\left(\frac{\rho_s - \rho}{\rho}\right)\frac{\left[\sqrt{1 - \left(1 - \frac{h}{R}\right)^2} + f\left(1 - \frac{h}{R}\right)\right]}{C_D + fC_L}} \tag{18}$$

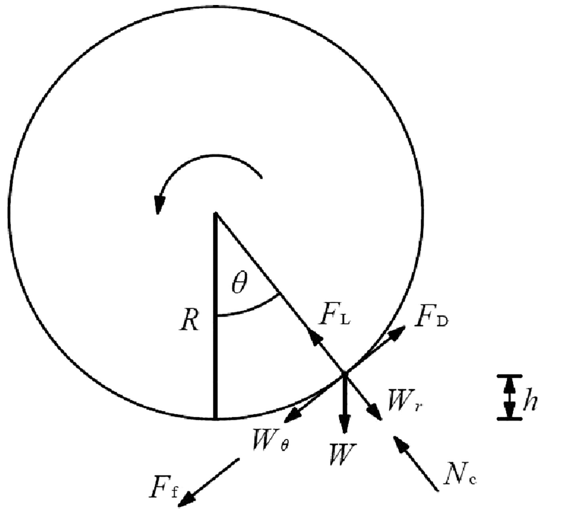

Figure 24. Stress analysis of the particle phase in the pipe wall area.

Similar to the mainstream area, the criterion for the safe flow of particles in swirl flow is that the particles rise to the center of the pipe diameter under the carrying of tangential velocity. Here, θ = 90° and $h = R$, so from eq 16, we get

$$u_{\theta c2} = \sqrt{\frac{4}{3}\frac{gd_s}{C_D + fC_L}\left(\frac{\rho_s - \rho}{\rho}\right)} \tag{19}$$

where $u_{\theta c2}$ is the tangential critical velocity of hydrate particles in the pipe wall area, that is, the critical tangential velocity of the safe flow of hydrate particles, m/s.

Criteria for Safe Flow. The essence of hydrate safe flow is the critical safe flow state (suspension state) of hydrate particles. According to the stress characteristics of the mainstream area and the pipe wall area, the motion characteristics of hydrate particles in the pipeline under the combined action of axial velocity and tangential velocity are analyzed. Whether the actual tangential velocity carrying hydrate particles is greater than or equal to the tangential critical velocity is taken as the criterion for the safe flow of hydrate particles.

1. If hydrate particles are in the mainstream area, when $u_\theta > u_{\theta c1}$, hydrate particles can rise to the center of the pipeline and enter a safe flow state (suspended state) and move forward with the swirl flow; when $u_\theta < u_{\theta c1}$, the tangential velocity cannot carry hydrate particles into the center of the pipe, and the hydrate particles gradually decline and settle to the pipe wall area.
2. If the hydrate particles are in the pipe wall area, when $u_\theta > u_{\theta c2}$, the tangential velocity can carry hydrate particles and bring them in a safe flow state (suspended motion state); when $u_\theta < u_{\theta c2}$, hydrate particles gradually sink and finally deposit at the bottom of the pipeline without moving.

Safe Flow Distance. Combined with the safe flow criterion of hydrate particles and based on the critical

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tangential velocity, the axial safe transportation distance of hydrate particles is calculated through eqs 11, 19, and 21. The calculation flow is shown in Figure 25. When the fluid velocity

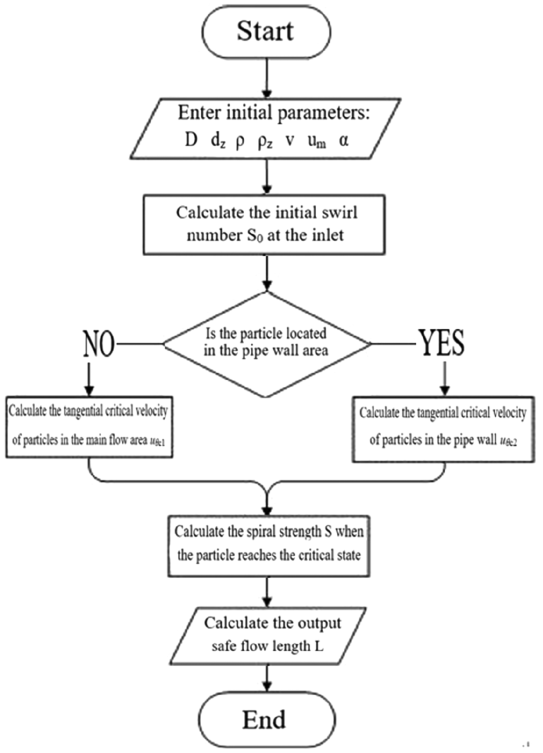

Figure 25. Calculation flow chart of hydrate particle safety distance in the swirl flow system.

is 8 m/s and the twisted rate of the twisted tape is 2, the safe transportation distance of hydrate particles is 115 M. It can be seen from Figure 26 that the swirl intensity of the horizontal

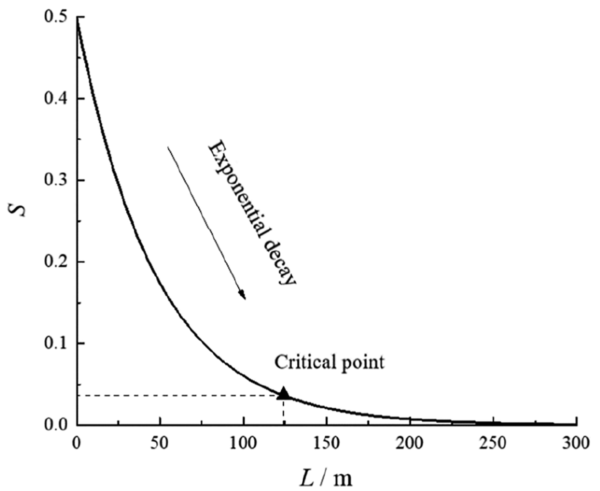

Figure 26. Swirl intensity attenuation diagram.

straight pipe section decays exponentially along the axial direction. The attenuation rate of spiral strength is closely related to the Reynolds number. The lower the Reynolds number, the faster the attenuation of swirl flow. On the premise of a certain twisted rate of the twisted band, the greater the fluid velocity, the smaller the attenuation degree of the spiral strength. At the same fluid flow rate, the smaller the twisted rate of the twisted band, the higher the spiral strength and the longer the safe flow distance of hydrate.

Integrating the swirl intensity S, we can get

$$S = \frac{u_\theta D}{4u_m r} \tag{20}$$

The formula of swirl intensity attenuation law is as follows

$$S = S_0 \exp\left(B_T \frac{L_x}{D}\right) \tag{21}$$

where B_T is the attenuation coefficient. Here, take the coefficient B_T fitted by the least square method in the literature,[36] which is $B_T = 0.123 - 0.0085 \ln Re$; S_0 is the initial swirl intensity; L_x is the distance from the initial position.

Combined with the safe flow criterion of hydrate particles and based on the critical tangential velocity, the axial safe transportation distance of hydrate particles is calculated through eqs 19, 19, and 21. The calculation flow is shown in Figure 25. When the fluid velocity is 8 m/s and the twisted rate of the twisted tape is 2, the safe transportation distance of hydrate particles is 115 m.

It can be seen from Figure 26 that the swirl intensity of the horizontal straight pipe section decays exponentially along the axial direction. The attenuation rate of spiral strength is closely related to the Reynolds number. The lower the Reynolds number, the faster the attenuation of swirl flow. On the premise of a certain twisted rate of the twisted band, the greater the fluid velocity, the smaller the attenuation degree of the spiral strength.[38,39] At the same fluid flow rate, the smaller the twisted rate of the twisted band, the higher the spiral strength and the longer the safe flow distance of hydrate.

■ CONCLUSIONS

Taking the flow of hydrate in the pipeline as the research object, the safe flow law of swirl flow gas hydrate in the pipeline is studied and analyzed through theoretical analysis and experimental research. The conclusions are as follows:

(1) Through the high-pressure hydrate experimental loop, the variation law of flow parameters, pipe plugging law, and hydrate deposition law in the process of hydrate flow under the swirl flow system in the pipeline are experimentally studied. The results show that the increase of water content, the decrease of initial flow rate, the increase of pressure, and the decrease of twisted rate of twisted band all make the fluidity of hydrate worse and increase the probability of hydrate plugging in the pipeline. Therefore, to realize the safe flow of hydrate in the pipeline, the above factors need to be controlled. The hydrate deposition characteristics of separated flow and dispersed flow were studied. The research shows that we should pay close attention to the deposition of hydrate particles to prevent the rapid change in the deposition height, resulting in the rapid blockage of hydrate in the pipeline.

(2) According to the experimental results, there is a "critical hydrate volume fraction" in the swirl flow system, and the "critical hydrate volume fraction" of the swirl flow system in the pipeline under laboratory conditions is 40%. When the volume fraction of hydrate in the pipeline is less than 40%, the hydrate is always in the flow state and therefore pipe plugging does not occur.

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When the volume fraction of hydrate is more than 40%, the pipeline is in a dangerous state, which should be avoided in an actual operation. The critical hydrate volume fraction in a swirl flow system is 33.3% higher than that in a non-swirl flow system, which effectively expands the safe flow boundary of hydrate.

3 Taking a single moving hydrate particle in the pipeline as the research object, the stress analysis is carried out. According to the stress characteristics of the mainstream area and the pipe wall area, the motion characteristics of hydrate particles in the pipeline under the combined action of axial velocity and tangential velocity are analyzed. Whether the actual tangential velocity carrying hydrate particles is greater than or equal to the tangential critical velocity is taken as the criterion for the safe flow of hydrate particles. Combined with the safe flow criterion of hydrate particles and based on the critical tangential velocity, the calculation model of safe flow distance of hydrate particles under the pipeline swirl flow system is deduced and established, which provides theoretical support for the research on the safe transportation of hydrate in the pipeline.

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Notes

The authors declare no competing financial interest.
The data presented in this study are available on request from the corresponding author.

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