1. Introduction

Gas hydrate is a kind of crystalline material formed by natural gas and water in the low-temperature and high-pressure environment [1], most of which is distributed in continental permafrost, polar continental shelf, and deep water [2]. Gas hydrate is featured in rich reserves and wide distribution. It is considered a new type of energy with high value because of the low pollution and high energy density. The commonly used mining methods include pressure drop method, heat injection method, and CO₂ replacement method. The pressure drop mining method is regarded as the most promising method for the future exploitation of gas hydrate due to its lowest energy consumption [3]. However, there still exists a problem of phase change during the exploitation of gas hydrate, which seriously restricts its development as energy. Under the production condition of the natural gas hydrate pressure drop method, gas hydrates in underground reservoirs move with the change in environmental pressure and are mainly decomposed into methane and water [4]. The decomposition of natural gas hydrate releases formation water, sand, and mud into the sand control screen pipe which enters the wellbore. There exists multiphase flow confluence in the hole part of the screen pipe [5]. Therefore, it is of great significance to describe the confluence flow law for gas hydrate production.

Since the gas hydrate was discovered in the gas transmission pipeline in the 1930s, there have been numerous studies on the clogging of gas hydrate [6]. Anmadi et al. designed the one-dimensional model of gas hydrate single well mining for numerical simulation of the pressure drop mining method [7]; Li et al. established a model to analyze the gas hydrate flow law under different production pressures and formation temperatures [8]; Huang et al. regarded
the pressure drop mining process of gas hydrate as a boundary dynamic propulsion process and divided the hydrate reservoir into gas zone and hydrate zone [9]; Du et al. carried out the sensitivity analysis of the parameters affecting the phase change in the gas hydrate flow process [10]; Wu et al. performed the numerical simulation of gas hydrate mining process in the single vertical well to analyze the influencing factors of pressure drop decomposition [11]. To summarize, these research studies mainly focus on the mechanism of blockage caused by phase change when gas hydrate flowed in the wellbore, while ignoring the clogging phenomenon at the confluence of the completion section during the production process [12, 13].

When the gas and water flow from the formation to the wellbore, there is a confluence process between the fluid of the sieve section and the fluid of the wellbore lifting section in the completion section. In the confluence process, the large pressure drop and temperature drop cause the phase of gas hydrate to change, which result in the formation of solid gas hydrate particles and the blockage of pipes [14, 15]. Gas hydrate formation sand production is the phenomenon that the formation sand is carried into the wellbore by the fluid or gas after the gas hydrate formation has plastic yield. It is a multicomponent dynamic problem of phase transition. The determination of sand production in gas hydrate formation is based on the following equation [16]:

\[ V = \eta (1 - \Phi) C_1 v_w, \]

where \( V \) is the sand production rate in the formation; \( \Phi \) is the formation porosity; \( C_1 \) is the particle density in a fluid; \( v_w \) is the fluid velocity in the pore; and \( \eta \) is the coefficient of formation sand production.

Considering the influence of sand production, two-phase seepage, and gas hydrate decomposition kinetics in the mining process, the T-type pipe confluence model was established in this paper. Based on the model, the P-T environment of the completion confluence section was simulated. By comparing the simulation results with the actual gas hydrate phase diagram, the critical velocity can be determined at the confluence when the solid blockage occurs. It was proved that the established experimental model could accurately simulate the actual situation and predict the critical velocity of the phase change. In addition, the research results could provide the technical basis for preventing gas hydrate blocking measures.

2. Simulation

2.1. Simulation Method. The pressure drop method was selected for the mining method [17]. The pressure drop mining method is designed to reduce the pressure by drilling with low-density mud or extracting the free gas in the gas hydrate reservoirs so as to decompose and extract the gas hydrate. The schematic diagram of the pressure drop method is shown in Figure 1.

The three-dimensional model was established by Fluent software to simulate the process of fluid flowing from the branch pipe to the main pipe. This process occurred in the completion section of the gas hydrate pressure drop mining process.

2.2. Simulation Process. The grid and model were designed by Fluent software in order to simulate the change of formation temperature and pressure during the gas hydrate mining process.

The meshing module was selected to design the model and study the fluid flow influence law. Moreover, the main pipe was named "Pipe," and the branch pipes were named "Pipe1," "Pipe2," "Pipe3," and "Pipe4," respectively. Each pipe had its corresponding "Inlet" and "Outlet." The high-density mesh was set in the section where the gradient changes greatly, and the stress was relatively concentrated. The high-density mesh was used to achieve a more detailed reflection of data changes. The established model is shown in Figure 2. The established physical model is simplified based on geometrical similarity and partial dynamic similarity. This is because geometrical similarity is the basis of hydrodynamic similarity, and dynamic similarity is an important factor that determines kinematic similarity.

The double-layer branch pipe was connected to both sides of the main pipe. The process of gas hydrate slurry and gas flowing radially in the formation was simulated in the branch pipe section, and the process of the mixed fluid flowing vertically in the wellbore was simulated in the main pipe.

The initial parameters set of the model is shown in Table 1.

The design parameters of the model were selected based on the size of the column used in the oil field. And the branch pipe size and branch distribution density were designed in combination with the seepage process of gas hydrate in a low-temperature and high-pressure reservoir at a certain depth.

As for the choice of "Materials," since the gas hydrate had certain similar properties to the ice under low temperature and high pressure, the "Name" was set to ice. In order to eliminate the deviation in the physical properties, the parameters in the "Properties" were modified according to the physical parameters of the methane-based gas hydrate. Consequently, the "Density" was 910 kg/m³, the "Thermal Conductivity" was 0.55 W/(m·K), and the "Viscosity" was 1.72×10⁻⁵ kg/(m·s). In addition, the formation was considered to be infinite during the simulation process.

2.3. Simulation Results and Discussion

2.3.1. Change of Pressure with Well Depth. Figure 3 reveals the change of pressure with well depth. The high velocity of fluid in the branch pipe led to the large pressure. The average pressure of the branch pipe was 3.47 MPa while that of the main pipe was 0.82 MPa. The difference of power led to the fluid flowing from the branch pipe to the main pipe. During the process of fluid flowing radially in the branch pipe, the fluid pressure remained substantially constant, which was consistent with the formation pressure. The pressure in the main section was lower than the formation pressure, so the fluid flowed from the formation into the wellbore. As the flow rate changed, the pipe had the objective pressure condition for the clogging of gas hydrate particles, and the critical value of the clogging pressure should be further analyzed.
As for the law of variation, before the confluence occurred, the pressure change of the fluid in the main pipe exhibited a surrounding high pressure. The pressure was lower near the pipe wall and gradually increased as the fluid moved toward the center of the pipe. After the confluence occurred, although the pressure at the pipe wall was low and the pressure near the center of the tube was high, the range of pressure changes was no longer ruled by the influence of turbulence.

It should be noted that there was a low-pressure zone near the pipe wall 15 to 20 meters above the confluence. And the pressure drop of 1.721 MPa may lead to a sudden change in the gas hydrate phase.

2.3.2. Change of Temperature with Well Depth. Gas hydrate is mostly distributed in low-temperature regions, such as deep-sea sediments or permafrost on land. In actual production activities, the well temperature is slightly higher than the formation temperature, and the ground temperature was also higher than the downhole temperature. In this process, as the fluid flowed from the well bottom to the well top, the temperature gradually rises. With the increase of temperature, the methane gas overflowed from the gas hydrate and decomposition liquid, making the gas hydrate more easily to be produced, and decreased the density of the mixed fluid. The change of temperature variation along the well path is shown in Figure 4.
Before the confluence occurred, the growth trend of fluid temperature was linear. When the confluence occurred, the fluid temperature increased sharply at the confluence section and decreased gradually at the swirling flow. There was a low-temperature area 5 to 10 meters above the confluence section. The reason was that when the branch pipe fluid mixed with the main pipe fluid, the high-temperature fluid mainly moved along the center of the main pipe to the wellhead and the low-temperature fluid remained near the upper half of the confluence point. Therefore, attention should be paid to prevent the blockage caused by the gas hydrate generated here due to the low temperature.

The temperature difference of the whole flow process was not large, which ranged from 275 K to 291 K, with an average production temperature of 276.75 K (3.6°C). And the temperature range of gas hydrate solid formation was 0 to 10°C. Therefore, it was possible to form the solid gas hydrate in the confluence process of the completion section, which may cause blockage, and further analysis of the plugging conditions was required.

2.3.3. Change of Velocity with Well Depth. The change of velocity with well depth is shown in Figure 5. The average velocity of the branch pipe section was 2.44 m/s, and the
average velocity of the fluid in the main pipe section was 0.72 m/s. Under the consistent production pressure, the velocity of the fluid in the branch pipe was high because of the small pipe diameter and the small hydraulic radius. At the same time, the velocity of the fluid in the main pipe was low because of the large diameter and large flow area. When the two pipes intersected, the high-velocity fluid flowed from the branch pipe to the main pipe. At the confluence point, the fluid velocity dropped, but it was still at the peak of the velocity in the main pipe.

For the vertical lifted section of the main pipe, the fluid energy and the velocity were both decreased since the gravity potential did negative work in the flow process of the mixed fluid in the main pipe, and the fluid needs to overcome the friction force. The simulation result on velocity change along the well was random. This was due to the existence of turbulence phenomena. And when the fluid velocity of the upper half of the wellbore was low, the liquid flow presented the characteristics of low-speed seepage flow, that is, because of the influence of the adsorbed thin layer, the velocity at the pipe wall was the lowest and gradually increased from the pipe wall to the pipe center.

2.4. Critical Velocity Analysis of Gas Hydrate Phase Transition. After obtaining the values of velocity, pressure, and temperature at different depths of the well, the X-axis was set to be the velocity and the Y-axis was set to be the pressure and temperature. The diagram of the effect of velocity on temperature and pressure is shown in Figure 6.

The values of temperature, pressure, and velocity at 100 points in different well depths in the simulation results were obtained to form a relationship diagram. As is shown in the diagram, the pressure drop and temperature drop were proportional to the velocity and had a nonlinear relationship. Because the gas hydrate solids were easily generated under high pressure and low temperature, the velocity marked by the red line where pressure increased and temperature decreased was the critical point to analyze the phase transition. At this point, the velocity was 0.171 m/s, the pressure was 2.83 MPa, and the temperature was 287.07 K.

The values of temperature and pressure in different main pipe depths were described in a scatterplot in the gas hydrate phase diagram [18], in order to verify the simulation results obtained from the analysis, as shown in Figure 7.

The red curve is the gas hydrate phase diagram, which is the equilibrium condition for gas hydrate formation under
different temperatures and pressures. On the left side of the phase curve is the gas hydrate formation area, while on the right is the nonformation area. In the temperature and pressures scatterplot, there were 49 points in the gas hydrate formation area, 46 points in the gas hydrate nonformation area, and 5 points on the curve. These five points were considered belonging to the mixed phase.

It is verified that the velocity at the critical point A was 0.171 m/s, which was consistent with the simulation results. Therefore, when the flow velocity reached 0.171 m/s in the process of gas hydrate pressure drop mining, it was easy to generate the solid phase of hydrate, which caused blockage in the lifting section of the main pipe.

3. Experiment Based on the T-Type Pipe Physical Model

3.1. Apparatus. The apparatus in this experiment is shown in Figure 8. In the experiment, the T-type pipe physical model is shown in Figure 9, which consists of the smooth slate. In order to simulate the path of gas hydrate from formation flowing to the wellbore, the channels were added inside the slate. The four channels indicated that the formation flow had a length of 5.9 cm and an inner diameter of 0.8 cm, and the other groove indicated that the wellbore flow had a length of 30.0 cm and an inner diameter of 18.2 cm. As for the physical model, the length, width, and thickness were 30.0 cm, 30.0 cm, and 5.0 cm, respectively. The deionized water and methane gas were stored in the container. The water and gas were delivered to the stirred hydrate reactor by using the piston pump (model 100DX, with flow accuracy <0.25 μL/min and pressure accuracy <±0.5%). The stirred hydrate reactor (model MORK, with the capacity of 9.5 L) was connected between the container and the physical model to produce gas hydrate. The two flowmeters (model LZB-3WB, with accuracy <0.1%) were used to measure the inlet and outlet gas hydrate flow rate of the T-type pipe physical model. Pressure sensors (with pressure accuracy <±0.1%) and temperature sensors (with temperature accuracy <±0.15°C) were used to monitor the pressure and temperature in the experiment. The two beaker flasks containing activated carbon and 10% sodium hydroxide (NaOH) were used for the treatment of a small amount of methane gas.

3.2. Materials. In the experiment, methane gas with a purity of >99.9 wt.% was used as the gas phase to prepare gas hydrate, which was supplied by the laboratory. And in order to avoid the influence of water impurities on the gas hydrate formation, deionized water was employed to prepare solutions in the experiment.

3.3. Experimental Procedure. The procedures for the visualization flow experiment based on the T-type pipe model were as follows: (1) The T-type pipe physical model was cleaned with distilled water and dried to ensure that there was no liquid residue in the model and pipes. (2) The valve of the methane cylinder was opened, and the methane gas was injected at 1 MPa for 1 min to remove the impurity gas in the model and pipes. (3) The model was heated to the reservoir temperature (~20°C). (4) Deionized water and methane gas were injected into the T-type pipe physical model with an initial rate of 5 L/h and 2.3 L/h, respectively. (5) When the flowmeter connected to the outlet of the physical model had a stable reading, the injection rate of deionized water and methane gas was increased slowly by adjusting the valve. (6) The physical model was considered to have a blockage in the confluence section when the flow rate of produced liquid was dropped, and the gas hydrate flow rate at the model inlet was recorded. The temperature and pressure in the experiment under different injection rates also need to be recorded.

3.4. Experimental Results. The result of the designed experiments is shown in Table 2. In the experiments, the injection flow of deionized water and methane gas always remained constant to ensure the formation of gas hydrate. The change of pressure and temperature caused by increasing injection velocity in the confluence process led to the gas hydrate phase transition and blockage in the formation. As shown in Table 1, when the flow at the outlet of the model was reduced from 9.25 L/h to 1.09 L/h, gas hydrate was considered to be formed, resulting in blockage in the confluence section. Therefore, in the fourth set of experiments, it was considered that the blockage had been formed when the gas hydrate injection flow at the inlet of the physical model was 23.36 L/h.

Figure 10 demonstrates the flow rate at the inlet and outlet of the physical model of the experiment. The gas hydrate injection velocity at the model inlet increased almost linearly while the production velocity at the outlet of model increased first and then decreased. The reason for this phenomenon was that when the injection velocity exceeded 0.129 m/s, blockage occurred in the confluence section between the main pipe and the branch pipe. Because of the blockage, there was almost no liquid production, and the
Figure 8: Schematic of the experimental apparatus.

Figure 9: Structure of the T-type pipe model.

Table 2: The results of experiments.

| No. | Injection flow (L/h) | Production flow (L/h) | Pressure (MPa) | Temperature (K) |
|-----|----------------------|-----------------------|----------------|-----------------|
| 1   | 6                    | 2.76                  | 6.63           | 1.01            |
| 2   | 8                    | 3.68                  | 8.84           | 1.65            |
| 3   | 12                   | 5.52                  | 9.26           | 1.93            |
| 4   | 16                   | 7.36                  | 9.25           | 2.62            |
| 5   | 20                   | 9.2                   | 1.09           | 2.90            |

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| 5       | 20                   | 9.2                   | 1.09           | 2.90            |
production velocity at the outlet of T-type pipe was only 0.006 m/s.

Based on the experiment results, it was proposed that when the injection velocity reached 0.129 m/s during the production process, the temperature and pressure were changed, which generated the solid phase of gas hydrate and caused a blockage.

4. Comparison and Discussion

4.1. Simulation. In the simulation, a section of the established three-dimensional T-type confluence model was taken as the research surface and the change values of the velocity, pressure, and temperature at the boundary cut were measured. The result is shown in Figure 11.

As the fluid flowed from the bottom of the well to the wellhead, the velocity of the main pipe fluid was low and stable. Only when fluid passed through the two branch pipes, the velocity fluctuated significantly. And the closer the wellhead was, the greater the fluctuation range of the velocity was. After flowing through the branch pipe, the velocity returned to the initial value, and the fluid continued to flow to the wellhead at this velocity.

With regard to the change of pressure, the pressure gradually decreased as the fluid flowed from the bottom of the well to the confluence. When the fluid flowed through the branch pipe, the pressure increased because the fluid in the branch pipe converged with the fluid in the main pipe. After flowing through the lower branch pipe, the pressure decreased again at a distance between the two branch pipes. As fluid flowed through the upper branch, the pressure increased again. Finally, both the pressure and the rate of pressurization gradually increased as the fluid flowed from the confluence to the wellhead.

As for the change of temperature, the sudden change of temperature also occurred in the process of fluid flowing through the two branch pipes. The temperature at the confluence of the branch pipe was higher than that at other parts. During the overall process of fluid flowing from the bottom of the well to the wellhead, the temperature increased gradually. The fluctuation was small and always within a range of 5°C. And the temperature variation amplitude of the branch side near the bottom of the well was slightly higher than that of the branch side near the wellhead.

4.2. Experiment. It is undeniable that the velocity is a very important factor for pressure and temperature. In the experiment, the pressure increases with the velocity and the temperature increases first and then decreases as shown in Figure 12. Before the blockage is formed, the pressure increased with velocity slowly while after the blockage was generated, the pressure increases rapidly because almost no fluid produced at the outlet of the physical model. The decrease in the temperature after the blockage formed results from the endothermic reaction.

4.3. Discussion. There have been few studies concerning the numerical simulation of main-branch pipe confluence in gas hydrate mining wellbore at present. As for the simulation of confluence flow, Naik-Nimbalkar et al. [19] used a model of 0.05 m main pipe and 0.025 m branch pipe with a diameter of 0.05 m, and the flow medium was monophase. Howard and Serre [20] studied and analyzed the confluence in the circular main-branch tube. Li and Wang [21] investigated the different mixed flows of the main-branch pipe under the Y-shaped structure. However, none of the existing models can simulate the flow process of well completion (sieve section: wellbore lifting section) in the gas hydrate mining process.

In the multiphase flow model, the VOF simulation model focuses on the analysis of the flow pattern, while the speed precision is not enough. The mixture and
Eulerian simulation model is very strong and suitable for handling mixed flows, but the interface flow pattern is not clear. Therefore, the T-type model was established in this paper.

The formation environment of gas hydrate has a certain particularity, which is caused by the formation of ballooning [22]. In deep water formation producing process, because the window between pore pressure and fracture pressure of formation is narrow and weak, when the equivalent circulating mud density which is close to the formation fracture pressure is larger than the equivalent mud density which is close to the induced or in situ microfractures, the formation of ballooning can be observed. This phenomenon occurred in the near-well area. In the experimental results, the hydrate solid formation rate was 0.129 m/s while the simulation result was 0.171 m/s. The reason for the difference was that the rock was designed in the experiment to simulate the real formation, and the formation ballooning was formed which affected the flow of fluid, with the degree of influence of about 24.34%.

Figure 11: The change value of the physical quantity at the research surface. (a) Velocity. (b) Pressure. (c) Temperature.
5. Conclusions

(1) In the experiment, when the velocity of the gas hydrate pressure drop method reaches 0.171 m/s, it was easy to generate a solid phase of hydrate. However, the velocity of forming the blockage was 0.171 m/s using the simulated result of Fluent software, which causes a block in the lifting section of the main pipe. The simulation result based on the physical model was compared with the actual phase state diagram of the gas hydrate. The results show that the critical points of phase change were consistent, indicating that the established physical model of T-type pipe confluence was in line with the actual situation.

(2) The pressure drop and temperature drop at the confluence are proportional to the mining velocity, and there is a nonlinear relationship between them. As for the pressure drop, it changes slowly in the main pipe direction with the increase in branch pipe flow and the branch pipe flow has little influence on the main pipe pressure drop.

(3) The simulation results show that high pressure will be formed in the retention area in the upstream and low pressure will be formed in the backflow area in the downstream in the main and branch pipe intersection of the T-type pipe. The formation ballooning influences the fluid flow in the near-well area, and the degree of influence is about 24.34%.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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