Safety Assessment of Shallow Gas Diffusion in Exploration Wells in an Area

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Abstract

The study of shallow gas diffusion in exploration well in a sea area is in favor of the safety and reliability for offshore drilling platform. Firstly, based on the theory of computational fluid dynamics (CFD), the prediction and evaluation model of exploration well shallow gas diffusion is established. According to the user-defined function (UDF), the distribution of velocity of ocean current in vertical direction is given. Next, combined with the VOF model and turbulence model, the influence of different injection rates and velocity of ocean current on the diffusion behavior of shallow gas in seawater is explored. The results show that the diffusion behavior of shallow gas in seawater has orderly undergone the evolution of air mass, large bubble and small bubble. Moreover, the higher the velocity of shallow gas injection, the smaller the diffusion radius, the larger the volume fraction of gas arrived in the sea surface, and the shorter the time of gas arrived in the sea surface; besides, the larger the velocity of ocean current, the larger the diffusion radius of gas, the smaller the volume fraction of gas arrived in the sea surface, and the longer the time of gas arrived in the sea surface. Hence, the higher production of the shallow gas and the lower velocity of ocean current will be more harmful to the safe production of drilling platforms.

Keywords

Shallow gas; Methane; Diffusion; Fluid dynamics.

1. Introduction

During the exploration and development of oil and gas resources, it is easy to encounter natural gas in the shallow strata (1500m vertical distance from the surface). Shallow strata belong to the fast deposition area and are the typical high pressure gas reservoir [1]. In the process of drilling, the shallow gas is located in a loose stratum with low bearing capacity, so it is easy to cause leakage phenomenon. Meanwhile, it is difficult to predict the time when the drill bit encounters the shallow gas in the drilling process. Therefore, the diffusion of the shallow gas is suddenly, and serious blowout accidents are easy to happen [2]. In offshore drilling operations, the diffusion of shallow gas may cause the rig to catch fire or explode. Hence, to evaluate the hazard of shallow gas are importantly. Currently, the research on shallow gas is still in the prevention stage. Yang et al. analyzed the characteristics of shallow gas blowout and summarized the emergency treatment measures for blowout prevention in shallow gas drilling by combined with the actual situation of offshore work [1]. Hu and li studied the distribution characteristics of domestic shallow gas and the identification characteristics of shallow gas reservoirs, and then analyzed the factors that caused the blowout accidents [2, 3]. Aiming at the prevention and control of shallow gas, lv et al. studied the prevention and control technology of shallow gas diffusion from the aspects of drilling technology, cementing method, cement type and auxiliary measures, which ensured the safety of drilling operations [4]. Although, the prevention and control of shallow gas can be promoted by the above research, it has not been studied from the perspective of gas diffusion. At present, many scholars have studied the diffusion rules of gas and crude oil leakage in submarine pipelines. Li et al. used computational fluid dynamics theory to study the diffusion law of leaking natural gas in shallow water submarine pipelines. The influence of gas leakage velocity, velocity of ocean current and leakage pore size on the diffusion of natural gas was analyzed by orthogonal test [5]. Based on the VOF multiphase flow model and component transport model, Ji et al. established the numerical model of single-hole leakage with diffusion of submarine natural gas pipeline, to carry out numerical simulation calculation and analysis of the gas diffusion law of single-hole leakage and the formation process of shock wave [6, 7]. For submarine pipeline oil spill problem, the submarine pipeline oil spill diffusion wave environment drift model established by Cao et al. [8]. Although the above mentioned research are aimed at the submarine pipeline leakage problem, it provides a basis for the feasibility of the study on the diffusion law of the seabed shallow gas layer. This paper will adopt the above method to evaluate the harmfulness of the shallow gas diffusion of the exploration well in a sea area.

2. Theoretical model of gas diffusion in shallow seabed

2.1 Fundamental equations of fluid dynamics

In the process of fluid flow, fluid needs to satisfy the three basic requirements of conservation of mass and conservation of momentum, so the basic equation of fluid is expressed as:

$$\frac{\partial}{\partial t}(\rho\varphi)+\mathrm{div}(\rho\bar{u}\varphi)=\mathrm{div}(\Gamma\,\mathrm{grad}\,\varphi)+S \tag{1}$$

Where, ρ is the density of the fluid, φ represents the general variable of fluid, Γ express the diffusion coefficient of the fluid, S is the source term.

2.2 κ-ε model

The diffusion of shallow gas in seawater is unsteady turbulent motion. In the calculation process, κ-ε turbulence model is used to predict the dynamic diffusion process of shallow gas, and the motion equation can be expressed as:

$$\frac{\partial(\rho\kappa)}{\partial t}+\frac{\partial(\rho\kappa u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[(\mu+\frac{\mu_1}{\sigma_k})\frac{\partial\kappa}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{2}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[(\mu+\frac{\mu_1}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa}+S\varepsilon \tag{3}$$

where, κ express the turbulent kinetic energy of shallow gas, ε express the energy dissipation rate of shallow gas, $\sigma_\kappa,\sigma_\varepsilon$ represent the prandtl Numbers of shallow aerodynamic energy κ and energy dissipation rate ε, respectively. μ represents the dynamic viscosity of the shallow gas, μ_t represents the turbulent viscosity of shallow gas, G_k is turbulent kinetic energy induced by velocity gradient. G_b is the turbulent kinetic energy induced by buoyancy. Y_M is the effect of turbulent fluctuation expansion on energy dissipation rate. $C_{1\varepsilon},C_{2\varepsilon},C_{3\varepsilon}$ express the empirical parameter. S_k and S_ε are custom source item.

2.3 VOF model

The VOF model is used to realize the dynamic characteristics of gas-liquid coupling. a_q is adopted to represent the volume fraction of the q phase. There is no q phase substance in the cell when $a_q=0$. When $0<a_q<1$, the substance in phase q shares a same unit with other substances. $a_q=1$ express that there is only phase q in the cell. The coupling motion of methane and seawater is considered in the process of gas diffusion in the shallow seabed, a_q satisfies the following equation, i.e.,

$$\frac{\partial a_q}{\partial t}+\frac{\partial(ua_q)}{\partial x}+\frac{\partial(va_q)}{\partial y}=0,q=1,2 \tag{4}$$

$$\sum_{q=1}^{2} a_q = 1 \tag{5}$$

2.4 Shallow gas jet rate

When shallow gas leakage occurs at the bottom wellhead, the instantaneous leakage rate of shallow gas at the wellhead with critical flow can be determined by the following equation

$$Q = 4.571 \times 10^{-6} D^2 p[M/(T+273)]^{1/2} \tag{6}$$

where, Q [Kg/s] express jet rate of shallow gas, D[mm] express the size of the hole, P[Kpa] represent formation pressure, M is the molecular weight of the medium, T[°C] is the medium transport temperature. The daily production of shallow gas can be determined by Eq. (6), i.e.,

$$C = \frac{Q \times 60 \times 60 \times 24}{\rho} \tag{7}$$

where, ρ [g/mm^3] express the density of shallow gas.

3. CFD simulation model of shallow gas diffusion

3.1 Fluid computing model

Taking the seabed shallow gas of an exploration well in a certain sea area as the research object, the borehole diameter was 66cm, the distance from the wellhead to the sea level was 2021m, the length of the seabed was 800m, and the seabed topography and sea wind factors were ignored to establish the computational fluid simulation model. The formation pressure gradient is assumed to be 1.0, the average seawater temperature is 5°C. (200, 0) express the well head coordinates. Meanwhile, 2 million cubic meters per day. 1.5 million cubic meters per day, 1 million cubic meters per day and 500,000 cubic meters per day were selected as shallow gas production. The influence of gas diffusion in seawater was analyzed. As shown in figure 1, the two-dimensional plane model was established to simulate the diffusion behavior of shallow gas in seawater. In the model, the shallow jet velocity of wellhead can be determined according to gas production conversion. $\bar{v}_{0-50}$ represents the average velocity of ocean current of surface current (0-50m), $\bar{v}_{50-150}$ represents the average velocity of subsurface current (50-150m), $\bar{v}_{150-350}$ represents the average velocity of ocean current of the deep layer (150-350m), v_h express the average velocity of the current above 350m depth.

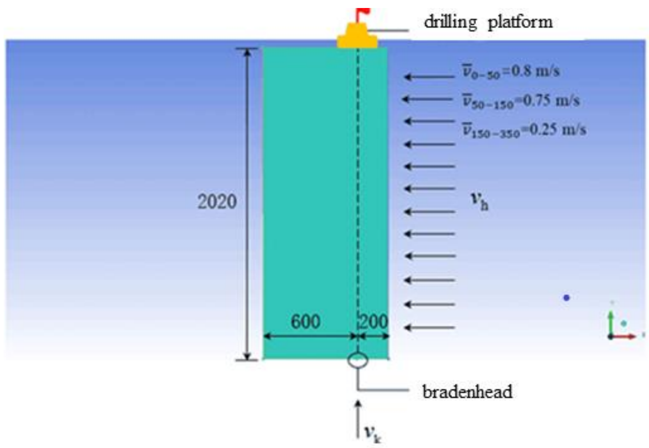

Fig. 1 CFD simulation model of shallow gas diffusion

3.2 Boundary condition

The variable gradient value at the upper end of the fluid calculation domain is zero, and the velocity inlet is adopted at the seabed wellhead with symmetric boundary conditions. The velocity value is set according to the gas production capacity of shallow gas. Meanwhile, when consider the influence of current, no slip boundary condition is adopted at the lower end of the fluid computing domain, the velocity inlet is adopted at the left side of the computational domain, and the free outflow boundary condition is adopted at the right side of the computational domain.

4. Analysis of gas diffusion process

4.1 Current speed 0m/s, gas production 2 million square meters per day

Consider the velocity of ocean current $v_h = 0\text{m/s}$, and the movement behavior and diffusion rule of shallow gas is studied when the gas output was 2 million cubic meters per day. As shown in fig. 2, the blue area represents seawater, the red area represents shallow gas, and the rest are mixtures of shallow gas and seawater. The redder the color, the higher the gas integral in the shallow layer. According to the diffusion process of shallow gas in water with a time interval of 8s, it can be seen that under the action of formation pressure, the shallow gas flows into the seawater in the form of jet flow. Besides, the diffusion behavior of the shallow gas in the seawater experiences the initial stage of evolution and diffusion of the three forms of air mass, namely large bubbles and small bubbles, and the movement track of the gas mass continues to spread to the left. The diffusion radius of air mass gradually increases with the change of time, and shallow gas and seawater flow field coupling action, forming local turbulence. In the final diffusion stage, the direction of wellhead airflow diffusion changes to the right under the action of seawater resistance partial turbulence and gas-liquid coupling. In the steady-state diffusion phase of shallow gas, the maximum volume fraction of gas reaching the vicinity of the drilling platform is 10%, which express the combustion and explosion limit of methane mixed with air. At this moment, the diffusion of shallow gas threatens the operation safety of the offshore drilling platform.

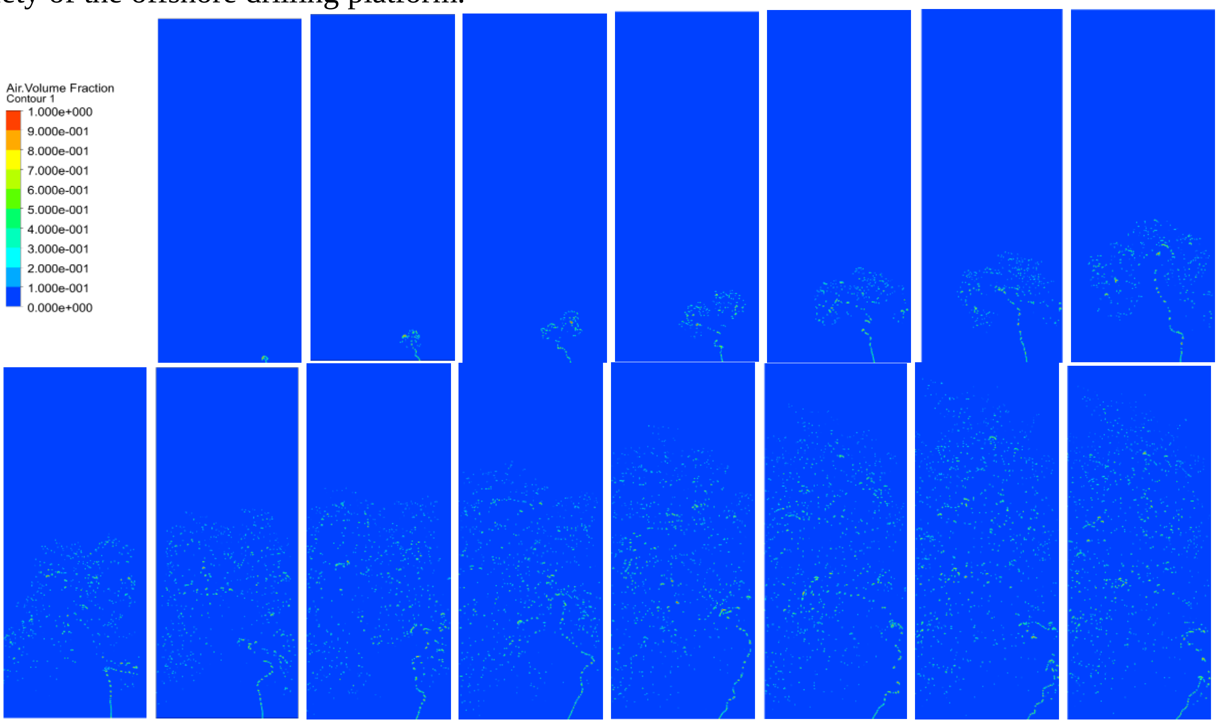

Fig. 2 Gas diffusion rule when v_h =0m/s

4.2 Current speed 0.1m/s, gas production 2 million square meters per day

Consider the velocity of ocean current $v_h = 0.1\text{m/s}$, and the movement behavior and diffusion rule of shallow gas are studied when the gas output was 2 million cubic meters per day, and the results are shown in Fig.3. According to the diffusion process of shallow gas in water at a time interval of 12s, it is observed from Fig.3 that under the continuous action of shallow gas formation pressure, the shallow gas flows into the seawater in a jet state. As the seawater speed increases to 0.1m/s, the direction of the shallow gas jet is consistent with the direction of the ocean current throughout the process. The diffusion behavior of shallow seabed gas in seawater experienced the evolution of three types of gas bubbles: large bubbles and small bubbles. The diffusion radius of air mass increases gradually, and the shallow gas and seawater flow field coupling action, forming local turbulence. In the final diffusion stage, the shallow air mass diffuses in the whole calculation domain under the action of the seawater resistance partial turbulence and gas-liquid coupling. In the steady-state diffusion stage of shallow gas, the maximum volume fraction of gas reaching the vicinity of the drilling platform is 6.3%. The diffusion of shallow gas poses a threat to the safety of the offshore drilling platform with the combustion and explosion limit of methane mixed with air.

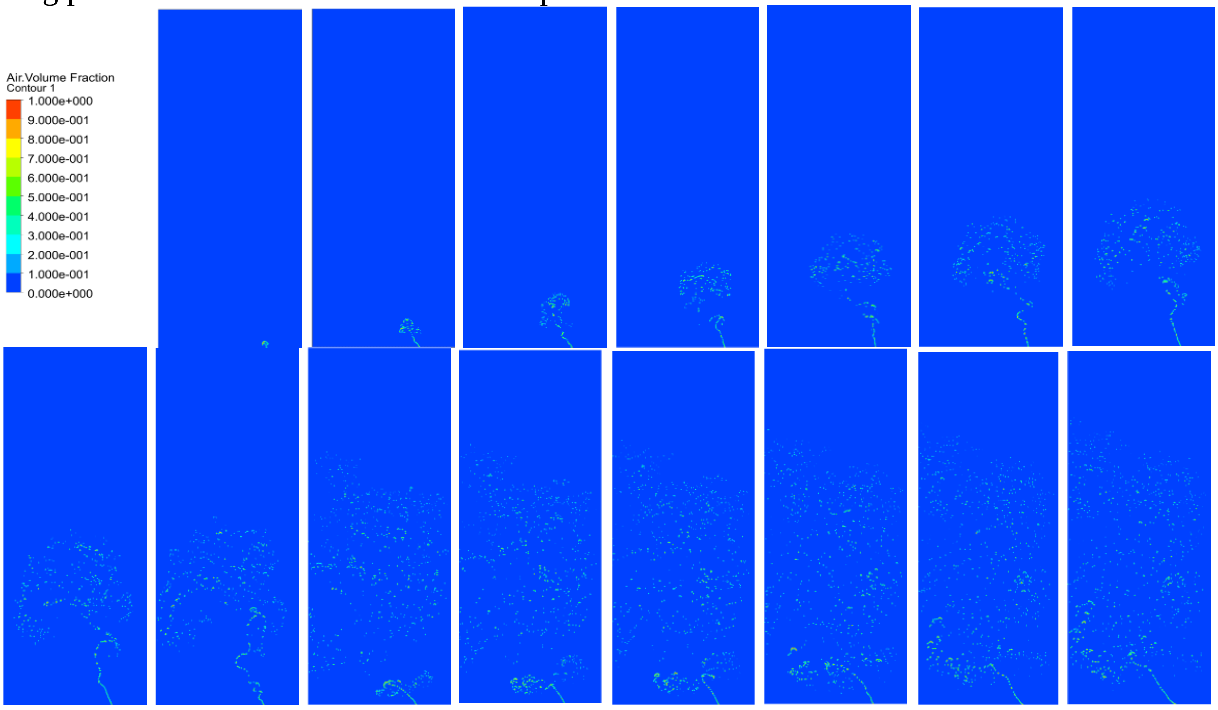

Fig. 3 Gas diffusion rule when $v_h = 0.1\text{m/s}$

5. Gas flammability assessment

Considering that methane is the main component of the shallow gas, and pose a threat to the safety of the platform during the diffusion of the shallow gas. According to GB/T 12474-1990, in room temperature and standard atmospheric pressure, the explosion limit of methane volume fraction is 5.3-14%. When the volume fraction of methane near the offshore platform is lower than its explosion limit or higher than the explosion limit, methane will neither explode nor catch fire. Figure 4 shows the volume fraction of the shallow gas near the rig. As shown in Fig. 4, when the production of shallow gas is 5×10^5 cubic meters per day and the velocity of ocean current is 0m/s, 0.1m/s, 0.2m/s, 0.3m/s, the volume fraction of methane is 0, 0, 1.5%, 2.1%, respectively. When the shallow gas production is 1 million cubic meters per day and the velocity of ocean current is 0m/s, 0.1m/s, 0.2m/s, 0.3m/s, the volume fraction of methane is 0, 0.9%, 2.9%, 4.1%, respectively. When the shallow gas production was 1.5 million cubic meters per day and the velocity of ocean current is 0m/s, 0.1m/s, 0.2m/s, 0.3m/s, the volume fraction of methane is 1.5%, 2%, 4.3% and 6.3%, respectively. When the shallow gas production is 2 million cubic meters per day and the velocity of ocean current is 0m/s, 0.1m/s, 0.2m/s, 0.3m/s, the volume fraction of methane is 1.2%, 3.8%, 6.7% and 10.27%, respectively. It can be known from the explosion limit of methane in the air that when the ocean velocity is 0m/s and the shallow gas production is 1.5 million cubic meters per day and 2 million cubic meters per day, the volume fraction of the shallow gas exceeds the explosion limit of methane in the air. When the velocity of ocean current is 0.1m/s, the shallow gas production is 2 million cubic meters per day, and the volume fraction of the shallow gas exceeds the explosion limit of methane in the air. Therefore, when the velocity of ocean current is 0m/s, 0.1m/s and the shallow gas production is 2 million cubic meters per day, the diffusion of the shallow gas can pose a threat to the safety of the offshore drilling platform. When the velocity of ocean current is 0.1m/s and the shallow gas production is 1.5 million cubic meters per day, the diffusion of the shallow gas can pose a threat to the safety of the offshore drilling platform.

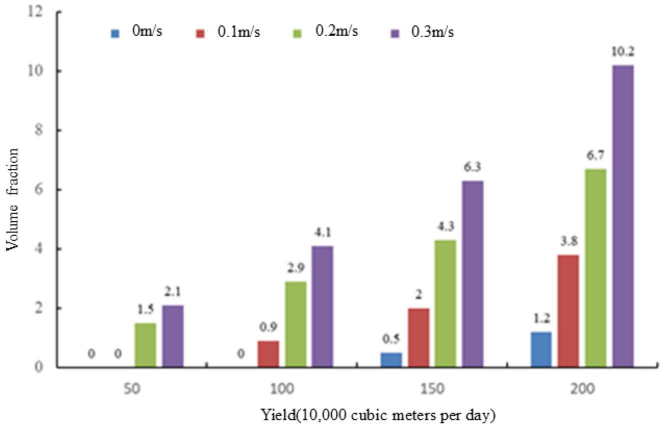

Fig. 4 Volume fraction of shallow gas (methane) on the rig

6. The time of shallow gas to rise to sea level

Fig. 5 shows the time required for shallow gas to rise to the sea surface in the fluid model. It can be seen from Fig. 5 that the time is mainly determined by the gas production capacity of shallow gas and the velocity of ocean current. When the velocity of ocean current is constant and the gas production volume is larger, the time required for the shallow gas to move up to the sea surface is shorter. When the production of shallow gas is $5x10^5$ cubic meters per day and the velocity of ocean current is 0.3m/s, 0.2m/s, 0.1m/s and 0m/s, respectively. The time for the shallow gas to rise to the surface is 610s, 573s, 502s, and 470s, respectively. When the production of shallow gas is 1 million cubic meters per day and the velocity of ocean current is 0.3m/s, 0.2m/s, 0.1m/s and 0m/s, the time for the shallow gas to rise to the surface is 327s, 286s, 243s, and 216s, respectively. When the production of shallow gas is 1.5 million cubic meters per day and the velocity of ocean current is 0.3m/s, 0.2m/s, 0.1m/s and 0m/s, respectively, the time for the shallow gas to rise to the surface is 230s, 182s, 157s and 136s, respectively. When the production of shallow gas is 2 million cubic meters per day, and the velocity of ocean current is 0.3m/s 0.2m/s, 0.1m/s, and 0m/s, the time for the shallow gas to rise to the surface is 173s, 137s ,114s and 98s, respectively.

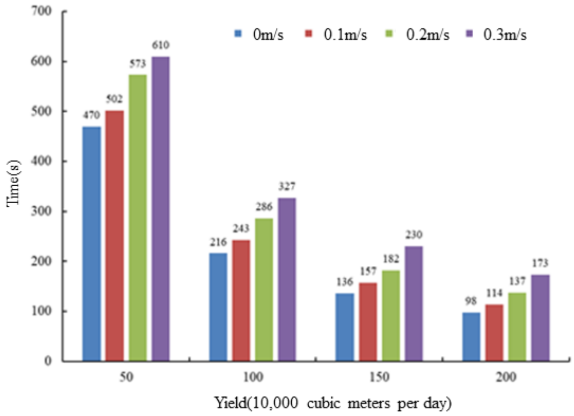

Fig. 5 The time of shallow gas to rise to sea level

7. Gas diffusion region

Fig. 6 shows the diffusion range of shallow gas in the steady state phase of gas diffusion in the fluid model (the white boundary indicates the area where the gas volume fraction is greater than 3% when the shallow gas is diffused). It can be seen from Fig.6 that 200-0, 200-0.1, 200-0.2 and 200-0.3 represent the diffusion range of shallow gas when the production of the gas is 2 million cubic meters per day and the velocity of ocean current is 0m/s, 0.1m/s, 0.2m/s and 0.3m/s, respectively. As shown in Fig.6, when the velocity of ocean current is 0 m/s and 0.1 m/s, and a certain volume fraction of shallow gas near the platform. The volume fraction is 10.2% and 6.3%, both exceeding the explosion limit of methane mixed air, and the production safety of the platform is seriously threatened. With the velocity of ocean current continues to increase to 0.2m /s and 0.3m /s, the gas integral number in the inner shallow layers 200m and 400m in the center of the platform is zero, and the gas diffusion cannot affect the safe production of the platform. In Fig. 6, 150-0, 150-0.1, 50-0.2 and 150-0.3 represent the shallow gas production of 1.5 million cubic meters per day, respectively. When the velocity of ocean current is 0m/s, 0.1m/s, 0.2m/s, and 0.3m/s, the diffusion range of the shallow gas can be seen from the Fig.6. When the velocity of ocean current is 0m/s and 0.1m/s, the volume fraction of the shallow gas near the platform is 6.7% and 4.3%. Hence, When the shallow gas production is 1.5 million cubic meters per day and the velocity of ocean current is 0m/s, the gas volume fraction on the platform exceeds the explosion limit of methane mixed air, and the production safety of the platform is seriously threatened. When the shallow gas production is 1.5 million cubic meters per day and the velocity of ocean current is 0.1m/s, the gas volume fraction on the platform does not exceed the explosion limit of methane mixed air, and the gas diffusion does not affect the safe production of the platform. As the velocity of ocean current continues to increase to 0.2m/s and 0.3m/s, the integral number of shallow gas with 100m and 600m in the center of the platform is zero. The gas diffusion unable affect the production safety of the platform. As shown in Fig.6, 100-0, 100-0.1, 100-0.2 and 150-0.3 represent the shallow gas production of 1 million cubic meters per day, respectively. It can be seen from the Fig.6, when the velocity of ocean current is 0m/s and 0.1m/s, there is a certain volume fraction of shallow gas near the platform, and the volume fraction are 3.8% and 2%. When the velocity of ocean current continues to increase to 0.2m /s and 0.3m /s, the gas integral number in the shallow layer of 280m and 600m in the center of the platform is zero. Therefore, when the shallow gas production is 1 million cubic meters per day, the gas diffusion unable affect the safe production of the platform. In the Fig.6, 50-0, 50-0.1, 50-0.2 and 50-0.3 represent the diffusion range of the shallow gas when the production of the gas is $5x10^5$ cubic meters per day and the velocity of ocean current are 0m/s, 0.1m/s, 0.2m/s and 0.3m/s, respectively. As shown in Fig.6, when the velocity of ocean current is 0 m/s, there is a certain volume fraction of shallow gas near the platform, and the volume fraction is 1.5%. As the current speed continues to increase to 0.1m/s, 0.2m /s, and 0.3m /s, the gas volume fraction near the drilling platform is zero. Therefore, when the shallow gas production is 1 million cubic meters per day, the gas diffusion cannot affect the safe production of the platform.

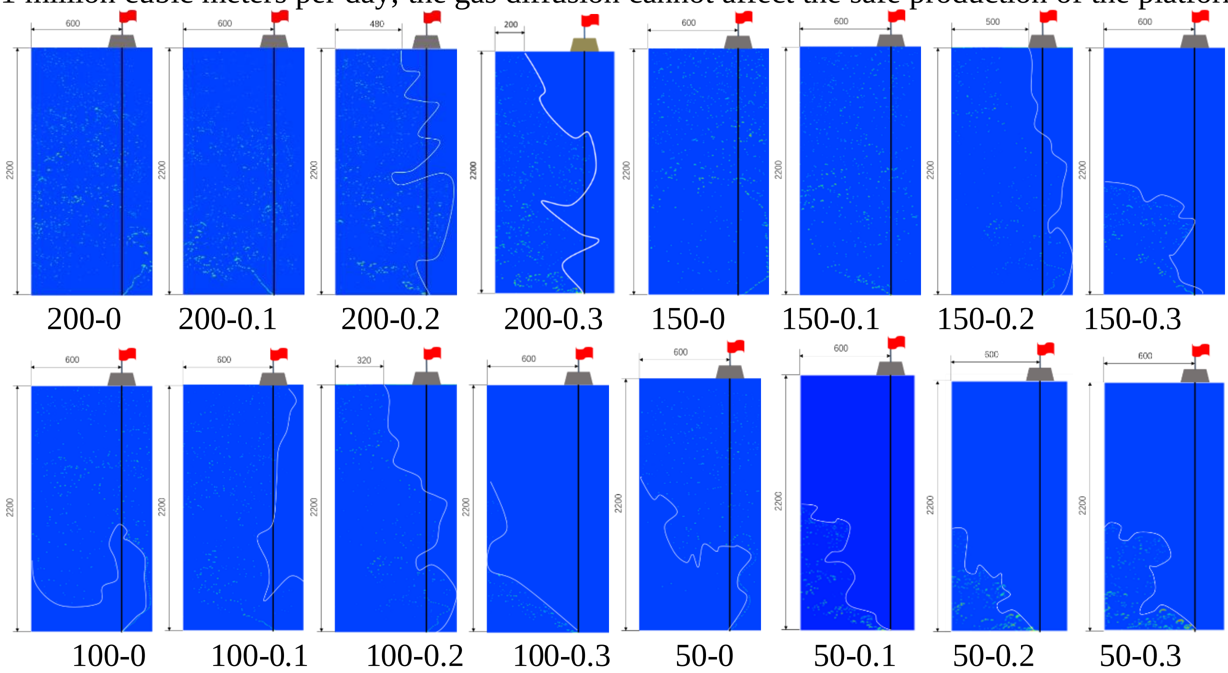

Fig.6 Gas diffusion region

8. Conclusion

(1) During the diffusion process of shallow air in seawater, it experiences the evolution of three forms of air mass: large bubbles and small bubbles. The higher the velocity of shallow air jet, the smaller the gas diffusion radius, the larger the volume fraction of gas reaching the sea surface, and the shorter the time to reach the sea surface. Meanwhile, the higher the velocity of ocean current, the larger the gas diffusion radius, and the smaller the volume fraction of the gas reaching the sea surface, and the longer the time to reach the sea surface.

(2) The influence of shallow gas on the safety of the drilling platform was evaluated with the production of 2 million cubic meters per day, 1.5 million cubic meters per day, 1 million cubic meters per day and $5x10^5$ cubic meters per day as well as the velocity of ocean current of 0m/s, 0.1m/s, 0.2m/s and 0.3m/s taken into account, respectively. The study found that the higher the production of shallow gas and the lower the velocity of current, the greater the harm to the safety of drilling platform.

(3) When the production of shallow gas is 2 million cubic meters per day and the velocity of ocean current is 0 m/s and 0.1 m/s, and a certain volume fraction of shallow gas existed near the platform, the volume fraction is 10.2% and 6.3%, both exceeding the explosion limit of methane mixed air, and the production safety of the platform is threatened. When the shallow gas production is 1.5 million cubic meters per day and the velocity of ocean current is 0m/s, the gas volume fraction near the platform exceeds the explosion limit of methane mixed air, and the production safety of the platform is seriously threatened.

Acknowledgments

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