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Multiphase Flow Law and Well Control Risk Analysis in Deep Water Gas Hydrate Horizontal Well While Drilling

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Abstract. Natural gas hydrate is an important clean energy in the future because of its high energy density, clean and pollution-free, large amount of resources and wide distribution. However, the gas hydrate reservoir in the sea area has the characteristics of deep water depth and shallow reservoir buried depth. It is difficult to develop, and the development cost is high, so it is difficult to meet the needs of commercial exploitation. Horizontal well drilling can ensure reservoir drilling rate, increase reservoir drainage area and improve development efficiency. During the drilling process of deep water gas hydrate horizontal wells, the gas hydrate is decomposed into gaseous gas due to the change of temperature and pressure environment. The multiphase transient flow of gas in the wellbore will affect the wellbore temperature and pressure environment and cause well control risk. The calculation model of multiphase transient flow and temperature field in drilling wellbore of deepwater gas hydrate horizontal well and the model of gas hydrate formation were established. The gas distribution, migration law and temperature and pressure distribution in wellbore were analyzed, and the variation of wellbore pressure, surface flow law and temperature and pressure range of gas hydrate formation were grasped, which will provide theoretical basis and construction reference for deep water gas hydrate horizontal well drilling.

1. Introduction

In order to maintain the rapid economic development and meet the strict requirements of environmental protection, it is imperative to find clean energy. Natural gas hydrate, as an important clean energy source, has the characteristics of high energy density (1 m^3 flammable ice contains 195 m^3 standard natural gas), clean, pollution-free, large resources and wide distribution [1]. In May 2017, the Guangzhou Marine Geological Survey of the Ministry of Land and Resources of China successfully implemented the test production of natural gas hydrate in the Shenhu Sea area of the northern South China Sea [2]. However, the gas hydrate reservoir in the sea area has the characteristics of deep-water depth (more than 1000 m) and shallow reservoir depth (about 200 m below the seabed) [3]. It is difficult to develop and the cost of development is high, so it is difficult to meet the needs of commercial exploitation. Horizontal wells can ensure reservoir drilling rate, increase reservoir drainage area and improve development efficiency [4]. However, in the process of drilling hydrate reservoir, because of the change of temperature and pressure environment, the stability of hydrate will be affected, resulting in the decomposition of gas hydrate into gaseous gas. Gas migration upward affects the stability of bottom hole pressure, which may lead to serious well control problems [5]. For this reason, this paper through establishes the calculation model of multiphase flow and the temperature field and the decomposition model of gas hydrate formation, analyses the gas migration and distribution law in wellbore, wellbore pressure, surface fluid flow law, and the temperature distribution in drilling wellbore of deep-water natural gas hydrate horizontal well.

2. Mathematical modelling

2.1. Multiphase flow model for deep water gas hydrate horizontal well drilling

When formation gas enters the wellbore annulus, the law of fluid flow in the wellbore annulus will change from liquid flow of drilling fluid to complex multi-phase flow of gas, liquid and solid [6]. In order to analyze the gas invasion characteristics after hydrate decomposition during coiled tubing drilling in hydrate reservoir, calculate the annular flow parameters and related surface parameters after gas invasion, and establish a mathematical model of gas-liquid two-phase flow in wellbore. The mathematical model of two-phase flow in wellbore includes the governing equations and auxiliary equations of annular air-liquid two-phase flow in wellbore.

(1) Governing equations of air-liquid two-phase flow in wellbore annulus

The governing equations of multiphase flow in wellbore annulus include continuity equations and motion equations:

$$\begin{cases} \text{Gas continuity equation:} \dfrac{\partial}{\partial z}\left(A\rho_g E_g v_g\right)+\dfrac{\partial}{\partial t}\left(A\rho_g E_g\right)=\Gamma_g \\ \text{Liquid continuity equation :} \dfrac{\partial}{\partial z}\left(A\rho_l E_l v_l\right)+\dfrac{\partial}{\partial t}\left(A\rho_l E_l\right)=0 \\ \text{Motion equation :} \quad \dfrac{\partial}{\partial t}\left(A\rho_l E_l v_l + A\rho_g E_g v_g\right)+\dfrac{\partial}{\partial z}\left(A\rho_l E_l v_l^2 + A\rho_g E_g v_g^2\right)+A\dfrac{\partial P}{\partial z}+A\rho_m g+A\left(\dfrac{\partial P}{\partial z}\right)_{fr}=0 \end{cases} \tag{1}$$

Where A is annular cross section,m^2; ρ_g is gas density,kg/m^3; E_g is gas holdup,dimensionless; v_g is gas velocity,m/s; Γ_g is gas source term in continuity equation,kg/m/s; ρ_l is drilling fluid density,kg/m^3; E_l is liquid holdup, $E_l+E_g=1$,dimensionless; v_l is drilling fluid velocity,m/s; P is pressure,Pa; ρ_m is mixture density, $\rho_m=\rho_l E_l+\rho_g E_g$,kg/m^3; $\left(\partial P/\partial z\right)_{fr}$ is frictional pressure drop,Pa.

(2) Solution of multiphase flow model in annulus

1）Initial condition

The initial condition is that the hydrate in annulus just decomposes and there is no gas intrusion:

$$\begin{cases} E_g(0,j)=0, E_l(0,j)=1 \\ v_g(0,j)=0, v_l(0,j)=q_l/A \\ P(0,j)=\rho g j+P_f \end{cases} \tag{2}$$

Where j is depth,m; P_f is annular pressure loss,MPa.

2）Boundary condition

The boundary conditions include bottom hole boundary and wellhead boundary in the process of hydrate decomposition, which are used to judge the convergence of the equation:

$$\begin{cases} E_g(t,H)=\dfrac{q_g}{C_0(q_g+q_l)+Av_\infty}, E_l(t,H)=1-E_g(t,H) \\ v_g(t,H)=\dfrac{C_0(q_g+q_l)}{A}+v_\infty, v_l(t,H)=\dfrac{q_l}{AE_l(t,H)},\ \ P(t,0)=0.1 \end{cases} \tag{3}$$

Where H is Well depth of hydrate decomposition,m; t is time,s.

3）Solving method

Implicit difference method is used to solve the established multiphase flow model, meshing in space and time domain, and discretizing continuity equation, auxiliary equation and boundary condition [7].

2.2. Temperature field calculation model for drilling wellbore of deep-water gas hydrate horizontal well

Compared with land drilling, the law of temperature variation in deepwater drilling is more complex. The temperature of terrestrial formation increases continuously along well depth, while in deepwater drilling, the temperature of seawater section decreases along well depth and the temperature of mud line section increases along well depth. The temperature field calculation models of riser section above mud line and formation section below mud line are established respectively [8].

(1) Calculation model of wellbore temperature field in riser section above submarine mud line

The mud flow in riser can be simplified to one-dimensional axial flow. Based on the energy conservation theory and thermodynamic theory, the calculation model of wellbore temperature field in riser section above the mud line is established.

$$\begin{cases} \dfrac{dT_a}{dz}=-\dfrac{\pi d_{ro}U_{sa}\left(T_s-T_a\right)}{c_mQ_a}-\dfrac{\pi d_{po}U_{pa}\left(T_p-T_a\right)}{c_mQ_a}+\dfrac{1}{c_m}\left(-\dfrac{2fv_a^2}{d_{ri}-d_{po}}-v_a\dfrac{dv_a}{dz}+C_oc_m\dfrac{dP_a}{dz}+g\right) \\ \dfrac{dT_p}{dz}=-\dfrac{\pi d_{po}U_{pa}\left(T_p-T_a\right)}{c_mQ_p}+\dfrac{1}{c_m}\left(-\dfrac{2fv_p^2}{d_{pi}}-v_p\dfrac{dv_p}{dz}+C_oc_m\dfrac{dP_p}{dz}+g\right) \end{cases} \tag{4}$$

Where T_a , T_s , T_p are mud temperature in annulus, seawater and drill string respectively, ℃ ; d_{ro} , d_{ri} , d_{po} , d_{pi} are are riser, drill string outer diameter and inner diameter respectively.,m; U_{sa} , U_{pa} are comprehensive heat transfer coefficients of seawater to annulus and drill string to annulus respectively,W/(m.℃); c_m is specific heat capacity of mud,J/(kg.℃); f is friction coefficient of mud; C_o is Joule-Thomson coefficient,℃/Pa; P_a , P_p are pressure in annulus and pipe respectively,MPa.

(2) Calculation model of wellbore temperature field in the formation section below the submarine mud line

Similarly, according to the law of conservation of energy and thermodynamic theory, the temperature distribution model of annulus and continuous pipe in the stratum below submarine mud line is obtained [9] :

$$\begin{cases} \dfrac{dT_a}{dz}=-\dfrac{\pi d_{ro}U_{fa}\left(T_f-T_a\right)}{c_mQ_a}-\dfrac{\pi d_{po}U_{pa}\left(T_p-T_a\right)}{c_mQ_a}+\dfrac{1}{c_m}\left(-\dfrac{2fv_a^2}{d_f-d_{po}}-v_a\dfrac{dv_a}{dz}+C_oc_m\dfrac{dP_a}{dz}+g\right) \\ \dfrac{dT_p}{dz}=-\dfrac{\pi d_{po}U_{pa}\left(T_p-T_a\right)}{c_mQ_p}+\dfrac{1}{c_m}\left(-\dfrac{2fv_p^2}{d_{pi}}-v_p\dfrac{dv_p}{dz}+C_oc_m\dfrac{dP_p}{dz}+g\right) \end{cases} \tag{5}$$

Where T_f is formation temperature, ℃; d_f is Borehole diameter,m.

(3) Model solution

The wellhead boundary and bottom hole boundary of the calculation model for wellbore temperature field in deepwater gas hydrate horizontal wells are shown in Formula 6. The annular wellhead temperature is equal to the pumping temperature of drilling fluid and the annular bottom hole temperature is equal to the temperature of drilling fluid flowing out from the continuous pipe. Because the governing equations are complex differential equations, it is impossible to get the analytic solution directly. In this paper, the finite difference method in numerical calculation is used to solve the governing equations iteratively, and then the temperature distribution in the borehole annulus and drill string of deepwater gas hydrate horizontal well is obtained.

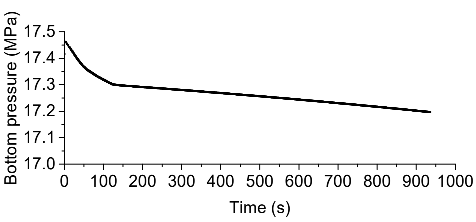
$$\begin{cases} T_a(t,0) = T_{wellhead} \\ T_a(t,H) = T_p(t,H) \end{cases} \tag{6}$$

3. Case study

The parameters of the example well are as follows: water depth is 1300m, well depth is 1745m, vertical depth is 1600m, deviation point is 1528m, horizontal displacement is 200m, dogleg foot is 25 degrees/30m, ground temperature is 20 C, geothermal gradient is 0.02 degrees/m, riser size is 19in, pipe depth is 1380m, bit size is 8-1/2"in, drillpipe size is 5in, drilling fluid density is 1.05g/cm^3.

3.1. Calculation and analysis of multiphase flow in deep water gas hydrate horizontal well drilling

It can be seen from Fig. 1 that when drilling in hydrate reservoir, the bottom hole pressure decreases gradually along time with the decomposition of hydrate into gas. The earlier change is obviously due to the decrease of hydrostatic column pressure in the slim hole within 100 seconds, and the smaller decrease of hydrostatic column pressure when the gas enters the large diameter riser. In addition, the decrease of wellbore pressure will lead to more hydrate generation. Bio-decomposition leads to more serious risk of well control, and the reduction of wellbore pressure will further aggravate the risk of well control. From Figure 3, it can be seen that the gas has been transported to 1000 m deep at 900s and reached the riser at this time. Due to the lower temperature of the riser, the secondary formation temperature of hydrate may occur, which may block the wellbore or throttle manifold. Gas holdup in casing and riser is smaller than that in coiled slim hole, because the diameter of riser and casing is larger than that of coiled slim hole. Figures 2 and 4 show that when drilling into hydrate reservoirs, the increase of outlet displacement and mud pool increment is caused by the decomposition of hydrate. We can observe whether drilling into hydrate reservoirs and judge whether hydrate is decomposed in hydrate reservoirs by monitoring the increment of mud pool and outlet displacement. Therefore, in order to prevent the occurrence of well control risk, measures should be taken to prevent hydrate decomposition, such as controlling wellbore pressure and adding hydrate decomposition inhibitors. Real-time monitoring of mud tank increment and outlet discharge, hydrate decomposition early warning.



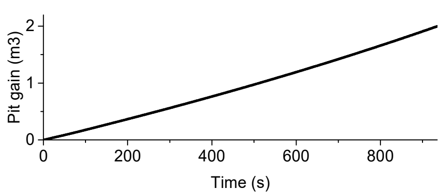
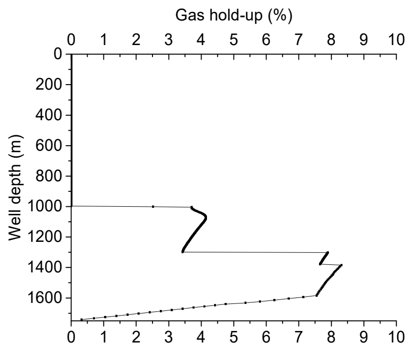


Figure 1. Bottom-hole pressure variation over time **Figure 2**. Pit gain over time



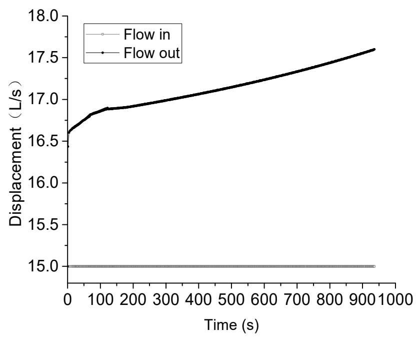


Figure 3. Gas hold-up variation over depth **Figure 4**. Flow out and flow in variation over time

3.2. Wellbore pressure and temperature distribution

Fig. 5 is the result of temperature distribution in annulus and drillpipe under different displacement. It can be seen from the figure that with the increase of displacement, the temperature in annulus and drillpipe increases gradually. When the displacement is 5, 10 and 15L/s, the temperature in drill string is higher than that in annulus, and the difference in seawater section is much greater than that in formation section. When the displacement is 20 and 25 L/s, the temperature in the continuous pipe is lower than that in the annulus. With the increase of displacement, the intersection point of annulus temperature and temperature line in the drill string gradually moves up. In the range of 5-25L/s, the lowest temperature is 6.5 C and the highest temperature is 39 C. Annulus pressure increases with the increase of well depth, and the pressure in drill string increases first and then decreases, and the pressure in bottom hole is the same as annulus pressure. The reason for the decrease of pressure in drill string is that the vertical depth does not increase, but the friction resistance in pipe increases, which results in the decrease of pressure in drill string. The pressure distribution range in annulus is 0-17.8 MPa.

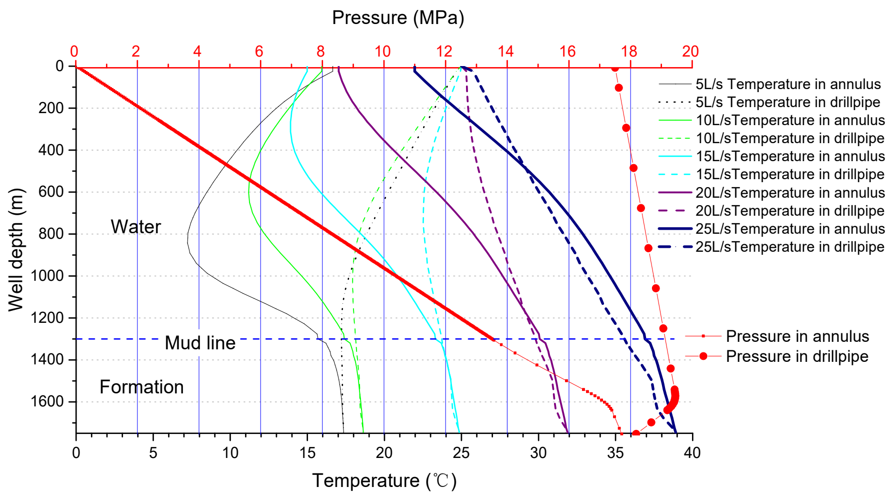


Figure 5. Temperature and pressure distribution variation over depth in wellbore annulus and drill string

3.3. Temperature distribution of gas hydrate formation pressure

By calculating the model of gas hydrate formation and decomposition, the chart of gas hydrate formation pressure and temperature distribution shown in Figure 6 is established. When the pressure and temperature are in the lower right area of the graph, the gas hydrate is easy to form in the wellbore. When the displacement is 5L/s, the pressure is 8MPa and the temperature is 7C at 800m depth. The temperature and pressure conditions are in the temperature and pressure region of hydrate formation. Natural gas hydrate may be formed here. When the displacement is greater than 10L/s, the wellbore temperature and pressure are distributed outside the temperature and pressure region of hydrate formation, and the risk of hydrate formation is small. Therefore, displacement affects hydrate formation by affecting annular temperature during drilling, so attention should be paid to displacement control during drilling.

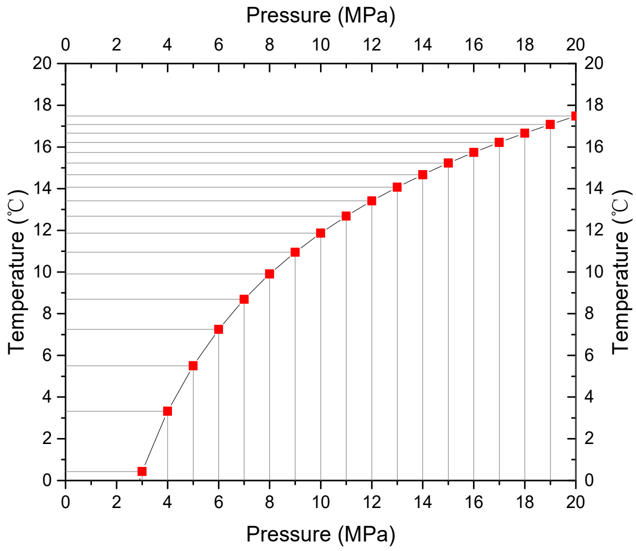


Figure 6. Temperature and pressure distribution plate for natural gas hydrate formation

4. Conclusion

(1) When drilling in hydrate reservoir, with hydrate decomposition into gas, the bottom hole pressure gradually decreases along time, and the pressure of hydrostatic column decreases greatly in the early stage. In the later stage, when gas enters large diameter riser, the pressure of hydrostatic column decreases slightly, and the decrease of bottom hole pressure will lead to more hydrate decomposition, resulting in further deterioration of well control risk. Internal transport to riser may cause secondary hydrate formation, blockage of wellbore or throttle line. With the increase of outlet discharge and mud tank increment, hydrate decomposition warning can be carried out by real-time monitoring of mud tank increment and outlet discharge.
(2) When the displacement is small, the temperature in the continuous pipe is higher than that in annulus, and the difference in seawater section is much larger than that in formation section. When the displacement is large, the temperature in drill string is lower than that in annulus section. With the increase of displacement, the intersection point between annulus section temperature and temperature line in drill string gradually moves up. Annulus pressure increases with the increase of well depth, and the pressure in drill string increases first and then decreases, and the pressure in bottom hole is the same as annulus pressure. The reason for the decrease of pressure in drill string is that the section is horizontal, the vertical depth does not increase, and the friction in pipe circulation increases.
(3) Temperature and pressure distribution chart of gas hydrate formation is established, and temperature and pressure conditions of gas hydrate formation are given intuitively. By calculating the temperature and pressure of wellbore under different displacement and combining with the temperature and pressure chart of gas hydrate formation, drilling displacement can be optimized to avoid the formation of gas hydrate in wellbore and reduce the risk of well control.

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