Prediction and Analysis of ECD for Deep Water Hydrate Formation Drilling with Riser

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Abstract. Natural gas hydrate reservoirs in the South China Sea are shallow buried and weakly cemented, making it difficult to drill horizontal well. The accurate prediction of equivalent circulation density (ECD) is the key to the safe drilling of horizontal well in hydrate reservoirs. Therefore, in this study, the ECD prediction model of hydrate formation drilling was established considering the influence of annulus hydrate cuttings decomposition. The influence of key hydraulic parameters such as drilling fluid density, displacement and rate of penetration on ECD was calculated and analyzed, and the leakage risk of hydrate layer was also analyzed. The calculation results show that the hydrate cuttings decomposition area is mainly in the upper annulus of the riser section, which is above 620m in the upper annulus of the riser section under the calculated condition. The ECD whether hydrate cuttings decomposition is considered under calculating conditions is 1060 kg/m^3 and 1068 kg/m^3, respectively. When the initial drilling fluid density is greater than 1064 kg/m^3 and the drilling fluid displacement is greater than 23L/s, there is leakage risk in the reservoir. This study can provide reference for prediction of ECD in deepwater hydrate formation drilling.

Keywords: deep water · hydrate formation · riser drilling · ECD prediction

1 Introduction

Natural gas hydrates are cage shaped complexes formed by water and gas molecules under high pressure and low temperature environments [1, 2]. Due to its huge reserves and clean combustion characteristics, it has attracted widespread attention from scholars both domestically and internationally. Data shows that the total global natural gas hydrate resources exceed 1.5×10^{16} m^3 [3, 4]. Among them, the reserves of marine natural gas hydrates account for about 99% of the total reserves, so the exploration and development of marine natural gas hydrates is a strategic highland for energy competition among countries [5, 6]. At present, the existing methods for extracting natural gas hydrates mainly include depressurization, heat injection, and gas replacement. However, all of these extraction methods require the establishment of flow channels through drilling. Therefore, safe drilling in hydrate formations is the foundation for efficient extraction.

In terms of hydrate formation drilling and ECD prediction, some scholars have carried out relevant studies. Gao et al. [7, 8], considering the coupling of wellbore pipe flow

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and reservoir seepage, constructed a wellbore reservoir coupling model for hydrate formation drilling, and analyzed the characteristics of reservoir temperature variation and hydrate decomposition risk in Wells drilled with and without risers. Ma et al. [9], aiming at the characteristics of horizontal well drilling in conventional oil and gas reservoirs, established a horizontal well drilling ECD calculation model that comprehensively considered factors such as wellbore heat transfer, drill string eccentricity, drill string rotation and cutting-bed, and analyzed the sensitivity of ECD to drilling parameters. Cheng et al. [10] established a transient heat transfer model between wellbore and sediment of natural gas hydrate reservoir to simulate the temperature field in the drill string and annulus, and established a pore thermoelastic model of the whole formation temperature field and pore pressure field in the process of drilling without riser, and analyzed the thermodynamic stability of natural gas hydrate and wellbore stability. Based on wellbore heat transfer theory and drilling engineering parameters, Wang et al. [11] studied the wellbore heat transfer process in the drilling process of natural gas hydrate horizontal Wells in Marine areas, and established the wellbore temperature profile calculation model in the drilling process of natural gas hydrate horizontal Wells in Marine areas, considering the direct frictional heat generation effect between drilling string, well wall and casing. The effect of horizontal section length on bottom hole temperature is also analyzed. Zhang et al. [12] established a prediction model of ECD for offshore high-temperature and high-pressure well by considering the influence of drilling fluid density and rheological parameters, and calculated and analyzed the influence law of drilling fluid consistency coefficient, density and displacement on ECD. Chen et al. [13] built a cuttings migration model in extended reach Wells and analyzed the variation rule of ECD under different borehole cleanliness degrees. The results showed that the influence of borehole cleanliness on ECD increased significantly with the increase of horizontal section length. Liao et al. [14] has built an annular multiphase flow model for hydrate formation drilling considering factors such as annular phase change, and simulated and analyzed the effects of drilling fluid displacement, rate of penetration and annular phase change on multiphase flow. Dong et al. [15] built a calculation model for the drilling temperature field of hydrate formation, and studied the influence of hydraulic parameters on the drilling temperature field of hydrate formation based on reservoir parameters of hydrate trial production in the South China Sea. The results showed that drilling fluid displacement and density had a great influence on the wellbore temperature field. The above studies are mainly related to the temperature and pressure field of hydrate formation drilling and the ECD prediction of conventional oil and gas reservoir drilling. However, the research on ECD prediction of riser drilling in hydrate reservoir is still very weak, and there are no relevant reports at present. Therefore, in this study, the ECD prediction model of riser drilling was established considering the factors of hydrate debris migration and decomposition, and the influence rule of key hydraulic parameters such as drilling fluid density, displacement and rate of penetration on ECD was calculated and analyzed, providing reference for the subsequent ECD prediction analysis of natural gas hydrate reservoir drilling.

2 Model Development

2.1 ECD Calculation Model for Hydrate Formation Drilling

When riser drilling is used in deep water hydrate formation, the temperature and pressure of hydrate cuttings in the annulus constantly change with the upwelling process of drilling fluid. When the temperature and pressure conditions in the annulus can no longer maintain the equilibrium of hydrate phase, the hydrate stored in the cuttings decomposes into gas and water, and the annulus changes from liquid-solid two-phase flow to gas-liquid-solid three-phase flow. Hydrate phase transition behavior poses challenges to the accurate prediction of ECD. In order to properly establish ECD prediction model for hydrate formation drilling, reasonable assumptions are as follows:

(1) hydrates in cuttings are regarded as methane hydrates.
(2) The hydrates in the cuttings are evenly distributed.

ECD is the sum of drilling fluid equivalent static density (ESD) and additional equivalent circulating density (AECD) [16].

$$ECD = ESD + AECD \tag{1}$$

Equivalent static density is the equivalent drilling fluid density value converted by hydrostatic column pressure at any depth in the hole, which can be calculated by the following formula:

$$ESD = \frac{P(H, \rho)}{gH} = \frac{P_0 + \int_{H_0}^{H} \rho g dH}{gH} \tag{2}$$

where, ESD is the equivalent static density of drilling fluid, g/cm^3. P_0 is the wellhead pressure, MPa. $\int_{H_0}^{H} \rho g dH$ is the hydrostatic column pressure at vertical depth H, MPa.

The additional equivalent circulation density is the added value of drilling fluid density corresponding to the total annular pressure consumption. The calculation formula is as follow:

$$AECD = \frac{P_a}{gH} \tag{3}$$

where, $AECD$ is the additional equivalent circulation density, g/cm^3. P_a is the total annular pressure loss from the wellhead to the calculated depth, MPa.

The calculation of annular pressure loss in drilling with a riser can be divided into horizontal section, inclined section, and riser section. The calculation formula for annular pressure loss varies among different well sections. The calculation formula for annular pressure loss in vertical well sections is:

$$P_a = \frac{2fL_v \rho_m}{D_o - D_p} v_a^2 \tag{4}$$

where, f is the Fanning friction coefficient without dimensionality. L_v is the well depth, m. ρ_m is drilling fluid density, kg/m^3. v_a is drilling fluid flow rate, m/s. D_o is the hole diameter, m. D_p is the outside diameter of the drill pipe, m.

The calculation of annular pressure loss of horizontal well drilling in hydrate formation also needs to consider the influence of hydrate cuttings decomposition and hydrate decomposition around the well. When methane gas is produced by the decomposition of hydrate debris, the vertical annulus changes from liquid-solid two-phase flow to gas-liquid-solid three-phase flow, and the influence of gas intrusion on friction coefficient and flow rate increment should be considered. Therefore, the fluid flow rate is replaced by the gas phase and liquid phase conversion velocity, and the Fanning friction coefficient is replaced by the Joss friction coefficient. The calculation formula of annular pressure consumption of hydrate cuttings decomposition stage is as follows:

$$P_a = \frac{2f_D L_v \rho_m}{D_o - D_p}(v_{sl} + v_{sg})^2 \tag{5}$$

where, f_D is the friction coefficient of Joss, without dimensionality. v_{sl} is the liquid phase conversion velocity, m/s. v_{sg} is the gas conversion velocity, m/s.

There is no cuttings bed in the small inclination well section, and the time required to calculate annular pressure does not need to consider the influence of such factors as cuttings bed. The calculation formula is as follow:

$$P_{an} = \frac{32(f_l + f_s)C_e C_r \rho_f Q^2}{\pi^2 (D_o - D_p)^3 (D_o + D_p)^2} + \rho_s g C_s \cos\theta \tag{6}$$

where, C_e is the pressure loss coefficient caused by drill string eccentricity, without dimensionality. C_r is the pressure loss coefficient caused by drilling string rotation, which is dimensionless. C_s is the annulus solid phase concentration. P_{an} is the annular pressure loss without cuttings bed, MPa. Q is drilling fluid displacement, m^3/s. f_l is the fluid friction coefficient. f_s is the friction coefficient of cuttings. ρ_s is the cuttings density, g/cm^3.

In the calculation of annular pressure loss in highly inclined Wells and horizontal sections, the influence of cuttings bed and drill string eccentricity and rotation should be considered. The effect of cuttings bed on annular pressure loss is mainly to reduce the flow section of annular fluid and thus increase AECD. The calculation formula of the cuttings bed height is as follows [17]:

$$\begin{aligned} H_{ca} = {} & 6.489\rho_f^{-2.45}\rho_s^{-0.51}(-v_a^{1.567} + 0.16v_a^{0.57} + 1.62v_a^{-0.433}) \\ & (-0.003\theta^2 + 0.3744\theta - 1.27)(1 + 0.5E)(1 + N)^{-0.185} \\ & [10d_s/(D - d_0)]^{-0.15} R_p^{0.276}(\mu_e^2 + 0.711\mu_e + 0.0692) \end{aligned} \tag{7}$$

$$H_c = \frac{H_{ca}}{D_o - D_p} \tag{8}$$

$$\mu_e = S\left(\frac{D - d_0}{12000v_a}\right)^{1-n}\left(\frac{2n+1}{3n}\right)^n \tag{9}$$

$$E = \frac{2e}{D - d_0} \tag{10}$$

$$d_s = \frac{R_p}{0.6N} \tag{11}$$

$$v_a = \frac{Q_m}{A_a} \tag{12}$$

where, H_{ca} is the cuttings bed height, mm. μ_e is the effective viscosity of drilling fluid, Pa·s. θ is the well inclination Angle, degree. E is the eccentricity of the drill string, without dimension. d_s is the diameter of cuttings, mm. R_p is the rate of penetration, m/s. v_a is the annular return velocity of drilling fluid, m/s. N is the drill string speed, r/min. k is the drilling fluid consistency coefficient, Pa·sn. n is the drilling fluid flow index without dimensionality. e is the eccentric distance, mm. A_a is the cross-sectional area of the horizontal annulus, m^2. Q_m is the horizontal annular drilling fluid displacement, m^3/s.

2.2 Drilling Temperature Field Model of Hydrate Formation

Due to the significant impact of wellbore temperature on hydrate phase equilibrium and the fact that multiphase flow in the annulus involves phase to phase heat and mass transfer, the ECD model needs to be solved together with the temperature field model.

The inside of drill pipe is single-phase flow, and its temperature field model can be expressed as:

$$C_l \pi R_{pi}^2 \rho_l \frac{\partial T_p}{\partial t} + C_l \rho_l q_l \frac{\partial T_p}{\partial z} = 2\pi R_{pi} U_t (T_a - T_p) \tag{13}$$

where, C_l is the specific heat capacity of drilling fluid in the drill pipe, J/(kg·K). R_{pi} is the inner radius of the drill pipe, m. ρ_l is the drilling fluid density in the drill pipe, kg/m^3. T_p is the temperature inside the drill pipe, K. q_l is drilling fluid displacement, m^3/s. U_t is the total heat transfer coefficient between the annulus and inside the drill pipe, W/(m·K). T_a is the annular temperature, K.

Since the migration and decomposition behavior of annulus hydrate debris involves heat transfer, hydrate phase transition heat needs to be considered. In addition, the heat transfer medium outside the annulus of riser section and formation section is different, so the temperature field model needs to be established in different sections. The temperature field model of annulus of riser section and formation section is as follows:

$$\begin{gathered} \frac{\partial T_a}{\partial t} \pi (R_{ri}^2 - R_{po}^2) C_m \rho_m + C_m \rho_m \frac{\partial T_a}{\partial z} = \\ 2\pi R_{po} U_t (T_p - T_a) + 2\pi R_{ri} U_e (T_{sea} - T_a) + r_h \Delta H \end{gathered} \tag{14}$$

$$\begin{gathered} \pi (R_w^2 - R_{po}^2) C_m \rho_m \frac{\partial T_a}{\partial t} + \rho_m q_m C_m \frac{\partial T_a}{\partial z} - r_h \Delta H = \\ 2\pi R_{po} U_t (T_p - T_a) + \frac{2\pi \lambda_f U_f R_w}{U_f R_w f(t) + 2\lambda_f} (T_f - T_a) \end{gathered} \tag{15}$$

where, R_{ri} is the inner diameter of the riser, m. R_{po} is the outer diameter of the drill pipe, m. C_m is the specific heat capacity of drilling fluid in annulus, J/(kg·K). ρ_m is the density of drilling fluid in annulus, kg/m^3. U_e is the total heat transfer coefficient of seawater and annular drilling fluid, W/(m·K). T_{sea} is sea water temperature, K. r_h is the rate of hydrate decomposition in cuttings, mol/s. ΔH is the heat of hydrate decomposition, kJ/mol. R_w is the radius of the hole, m. λ_f is the formation thermal conductivity, W/(m·K). U_f is the total heat transfer coefficient between the annulus and the formation, W/(m·K). $f(t)$ is a dimensionless time function. T_f is the formation temperature, K.

2.3 Hydrate Phase Equilibrium and Decomposition Rate Model

Based on the hydrate phase model and the water rich phase model, combined with the phase equilibrium theory, the phase equilibrium model for natural gas hydrates can be obtained as follow:

$$\ln a_w - \sum_{i=2}^{2} \gamma_i \ln(1 - \sum_{j}^{N_c} \theta_{ij}) = \frac{\Delta\mu_w^0}{RT_0} - \int_{T_0}^{T} \frac{\Delta h_w^0 + \Delta C_p^0 (T_a - T_0)}{RT_a^2} + \int_0^P \frac{\Delta V}{RT_a} dP_a \tag{16}$$

where, a_w is the activity of water in the water-rich phase, without dimension. γ_i is the characteristic constant of hydrate and has no dimension. N_c is the number of components in the complex that can form hydrate and has no dimension. θ_{ij} is the occupancy of guest molecule j in hole i. R is the gas constant, J/mol. $\Delta\mu_w^0$ is the chemical potential difference between the empty hydrate lattice and pure water under the conditions of T_0 and zero pressure, J/mol. Δh_w^0 is the molar enthalpy difference between the empty hydrate lattice and pure water under the conditions of T_0 and zero pressure, J/mol. ΔC_p^0 is the specific heat capacity difference between the empty hydrate lattice and pure water under the conditions of a and zero pressure, J/(mol·K). ΔV is the molar volume difference between the empty hydrate lattice and pure water, m^3/mol.

Previous studies have shown that the hydrate decomposition rate is mainly related to factors such as temperature, pressure, dissolution surface area and fugacity difference. Kim et al. [18] proposed a kinetic model of hydrate decomposition considering the above factors:

$$-\frac{dn_h}{dt} = K_d A_h (f_e - f_g) \tag{17}$$

where, n_h is the number of moles of hydrate, mol. f_g and f_e are current gas fugacity and phase equilibrium gas fugacity respectively, Pa. A_h is the dissolution surface area of natural gas hydrate, m^2. K_d is the decomposition rate constant, mol/(m^2·Pa·s).

2.4 Auxiliary Equation

At the same well depth at the initial time of the riser section, the seawater temperature is consistent with the temperature of the drilling fluid in the annulus and drill pipe, which can be expressed as:

$$t = 0, \quad T_p = T_a = T_{sea} \tag{18}$$

At the initial time of the formation section, the formation temperature in the depth of the same well is consistent with the temperature of drilling fluid in the annulus and drill pipe, which can be expressed as:

$$t = 0\,,\ \ T_p = T_a = T_f \tag{19}$$

Drilling fluid inlet temperature:

$$Z = 0\,,\ \ T_t = C \tag{20}$$

Formation temperature boundary:

$$r \to \infty\,,\ \ T_f = T_{f0} \tag{21}$$

where, C is a constant and the inlet temperature of drilling fluid is set, K. T_{f0} is the initial formation temperature, K.

3 Model Calculation Data

Hydrate formation drilling parameters in South China Sea were used to analyze the safety risk of hydrate drilling. The main calculation parameters adopted in this study are shown in Table 1.

Table 1. Related parameters of ECD calculation for horizontal well drilling in hydrate formation.

Parameter	Value
Drilling fluid density /(g·cm^{-3})	1.05
Seabed temperature /°C	2.8
Drilling fluid specific heat capacity /(J·kg^{-1}·°C^{-1})	3930
Drilling fluid inlet temperature /°C	20
Water depth /m	1772
Main wellbore displacement /(L·min^{-1})	900
Inlet viscosity of drilling fluid /(mPa·s)	10
Formation thermal conductivity /(W·m^{-1}·°C^{-1})	2.25
Drill pipe thermal conductivity /(W·m^{-1}·°C^{-1})	43.75
Thermal conductivity of drilling fluid/(W·m^{-1}·°C^{-1})	0.60
Cuttings diameter /mm	8
Bit diameter /m	0.2159
Drill pipe inner diameter /m	0.1080

(*continued*)

Table 1. (*continued*)

Parameter	Value
Rate of penetration /m·h^{-1}	20
Drill pipe outer diameter /m	0.1270
Drill collar outer diameter/m	0.1651
Drill collar inner diameter/m	0.0730
Inner diameter of riser /m	0.4820
Inner diameter of casing /m	0.2245
Casing outside diameter /m	0.2445
Approximate horizontal section length /m	246
geothermal gradient /°C·m^{-1}	0.1
Booster pipeline displacement /L·s^{-1}	70
Drill collar length /m	60

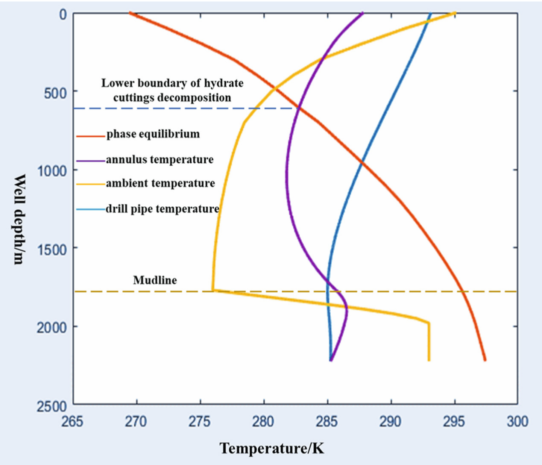

Fig. 1. Temperature field of riser drilling and hydrate debris decomposition area.

4 Results and Discussion

4.1 Decomposition Area of Hydrate Cuttings

As shown in Fig. 1, the calculated wellbore temperature curve is overlaid with the hydrate phase equilibrium curve to obtain the decomposition area of hydrate cuttings. The lower part of the intersection of the red and purple curves represents the hydrate phase equilibrium area, while the upper part represents the hydrate decomposition area. From the comparison of the positions of the two curves, it can be seen that in the deep part of the well below the intersection of the curves, the wellbore temperature is always lower than the minimum temperature at which the hydrate maintains phase stability. Therefore, the hydrate cuttings remain stable until they rise to the intersection position without decomposition. Until the depth of the well reaches around 620m at the intersection point, the decomposition begins, and there is no intersection between the hydrate phase equilibrium curve in the wellbore annulus above the decomposition point and the wellbore temperature curve. Therefore, during the drilling process, only the phase change decomposition of the hydrate cuttings in the upper part of the riser needs to be considered.

4.2 ECD in Hydrate Formation Drilling

Considering the influence of hydrate debris migration and decomposition, the ECD of hydrate formation drilling was calculated and analyzed. As shown in Fig. 2, the ECD with hydrate cuttings decomposition considered in hydrate formation drilling was significantly different from that without hydrate cuttings decomposition. At the toe of the wellbore, the ECD with and without hydrate debris decomposition is 1060 kg/m^3 and 1068 kg/m^3 respectively, which translates to a difference of about 0.15MPa in bottom hole pressure. This pressure value has little influence on conventional reservoir drilling, but its influence cannot be ignored due to the narrow safe pressure window of hydrate formation.

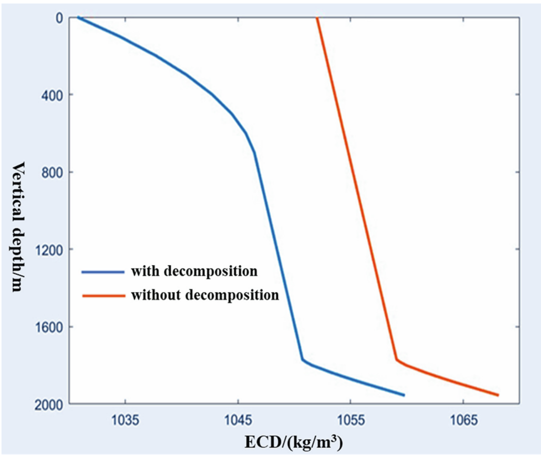

Fig. 2. Variation of ECD with borehole depth in hydrate formation.

4.3 The Impact of Key Drilling Parameters on ECD

The basic parameters used for calculation and analysis are drilling fluid density of 1050 kg/m^3, displacement of 15 L/s, penetration rate of 20 m/h and inlet temperature of 20 °C. Other parameters are based on the relevant data in Table 1. During the drilling process of hydrate formation, drilling fluid density mainly affects ECD by affecting

ESD. Five groups of drilling fluid densities of 1030 kg/m^3, 1040 kg/m^3, 1050 kg/m^3, 1060 kg/m^3 and 1070 kg/m^3 were set to analyze their effects on ECD. As shown in Fig. 3, ECD gradually increased with the increase of drilling fluid density. Under riser drilling conditions, when the initial drilling fluid density is greater than 1064 kg/m^3, the bottom hole circulating pressure equivalent density is greater than 1080 kg/m^3 and the reservoir faces the risk of leakage. Therefore, the drilling fluid density has a small choice range under riser drilling conditions.

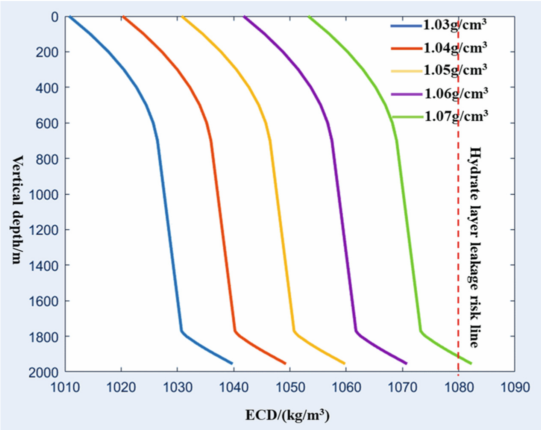

Fig. 3. Influence of different drilling fluid densities on ECD in hydrate formation drilling.

During the drilling process of hydrate formation, the drilling fluid displacement mainly affects ECD by affecting AECD. Five sets of drilling fluid displacement were set up, including 12 L/s, 15 L/s, 18 L/s, 21 L/s and 24 L/s to analyze the impact on ECD. As shown in Fig. 4, with the increase of drilling fluid displacement, ECD gradually increases, mainly because the annular pressure loss gradually increases with the increase of displacement, especially in the approximate horizontal section. When the drilling fluid displacement is 12 L/s, the ECD of the horizontal section increases rapidly, which is caused by the low rock carrying efficiency of the horizontal section with small displacement. When the drilling fluid displacement is higher than 23 L/s, the ECD at the toe of the horizontal section is higher than 1080 kg/m^3, and there is a high risk of leakage in the formation. Due to the narrow pressure window limitation, the range of drilling fluid displacement options is small, and drilling with a slightly larger critical rock carrying displacement can be used.

The rate of penetration in hydrate formation affects ECD mainly by influencing cuttings bed height and annulus cuttings content. Five sets of penetration rates (16 m/h, 20 m/h, 24 m/h, 28 m/h and 32 m/h) are set to analyze their effects on ECD. As shown in Fig. 5, ECD gradually increases with the increase in ROP, which is due to the increase in the annulus cuttings bed and the increase in solid phase content. ECD in the upper riser segment decreased with cuttings content, mainly because hydrate cuttings content increased with the increase of ROP, and the gas decomposition volume of hydrate cuttings increased accordingly, while gas expansion in the wellhead segment led to an increase in

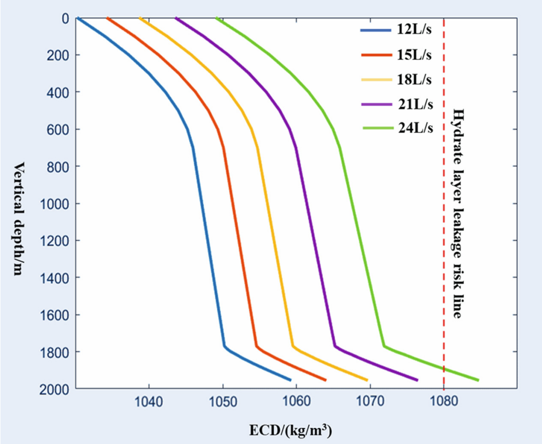

Fig. 4. Influence of different drilling fluid displacement on ECD in hydrate formation drilling.

gas content, so ECD decreased significantly. Due to shallow burial and weak cementation, the formation fracture pressure equivalent density is small, and when the drilling rate is greater than 28 m/h, there is leakage risk of hydrate formation.

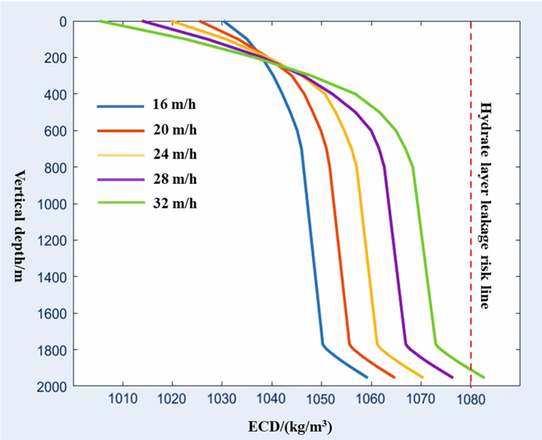

Fig. 5. Influence of different penetration rates on ECD in hydrate formation drilling.

5 Conclusion

In this study, a prediction model of ECD for hydrate riser drilling was established based on factors such as hydrate cuttings migration and decomposition. The influence rules of key hydraulic parameters such as drilling fluid density, displacement and penetration rate on ECD were calculated and analyzed, and the leakage risk of hydrate formation was analyzed. The main conclusions were as follows:

(1) The hydrate cuttings decomposition area is mainly in the upper annulus of the riser section, which is above 620m in the upper annulus of the riser section under calculated working conditions.
(2) Whether to consider hydrate cuttings decomposition at toe end of wellbore under working conditions, ECD is 1060 kg/m^3 and 1068 kg/m^3, respectively.
(3) When the initial drilling fluid density is greater than 1064 kg/m^3 and the drilling fluid displacement is greater than 23L/s under the calculated working conditions, there is a risk of reservoir leakage. In the drilling process, key parameters such as drilling fluid density, displacement and mechanical drilling rate need to be carefully regulated.

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