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Study on the Factors Affecting the Annulus Pressure of Riserless Mud Recovery System

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Abstract:

The precise control of the annulus pressure involves the problems of drilling safety and drilling cost, which have always been the focus of drilling engineering. In this paper, combined with the characteristics of the riserless mud recovery (RMR) system, the calculation method of equivalent circulating density (ECD) and annulus pressure of RMR system is proposed. According to the characteristics of the heat exchange of the RMR system, a mathematical model of the thermal field in the annulus is established. The variation law of thermal field in the annulus of some well sections was simulated by computational fluid dynamics (CFD) software. Comparing the CFD analysis results with the calculation results of mathematical models, the feasibility of the mathematical model is verified, and the temperature variation curve in the annulus is obtained. Based on the drilling data of a vertical well in the South China Sea, this paper analyzes the effects of seawater depth, equivalent static density (ESD) of drilling fluid, cuttings concentration and discharge capacity on the annulus pressure and ECD of the RMR system.

Keywords: RMR, annulus pressure, ECD, thermal field, influencing factors

1. Introduction

The limit water depth of riser used in offshore drilling engineering is 3047m [1]. However, due to the impact force of seawater, the riser will vibrate at different frequencies, which makes it impossible for riser to be used perfectly in deep water environment [2,3]. And the manufacturing cost of riser is very expensive. Based on the above problems, and in order to effectively solve the impact of narrow safety pressure window, shallow gas and shallow flow on offshore drilling engineering, Norwegian AGR company invented RMR system [4,5].

As shown in Figure 1, the RMR system is mainly composed of three modules: Suction Module, Subsea Pump and Mud Return Line. The main function of the suction module is to collect the mud returned from the annulus [6,7]. The main function of the subsea pump is to adjust the pump speed so that the pressure exerted on the wellhead by the subsea pump is equal to the static pressure of the seawater at the depth, thereby achieving a dual-gradient drilling (DGD) and achieving precise control of the annulus pressure [8,9]. Another function of the subsea pump is to provide power for the return of mud in the annulus [10,11]. As the only channel for mud in annulus to return to the platform, the selection and deployment of the mud return line will affect the lifting efficiency of mud. In shallow water environment, hose is usually used as return line, because the impact force of seawater in shallow water environment is small, and hose winding on drill pipe will not occur, and using hose can reduce the manufacturing cost of return line [12,13]. However, in deep water environment, due to the increased impact force of seawater, the hose is easily wound around the drill pipe [14,15]. In order to ensure the safety of the drilling, it is necessary to use steel pipe as the mud return line in deep water environment.

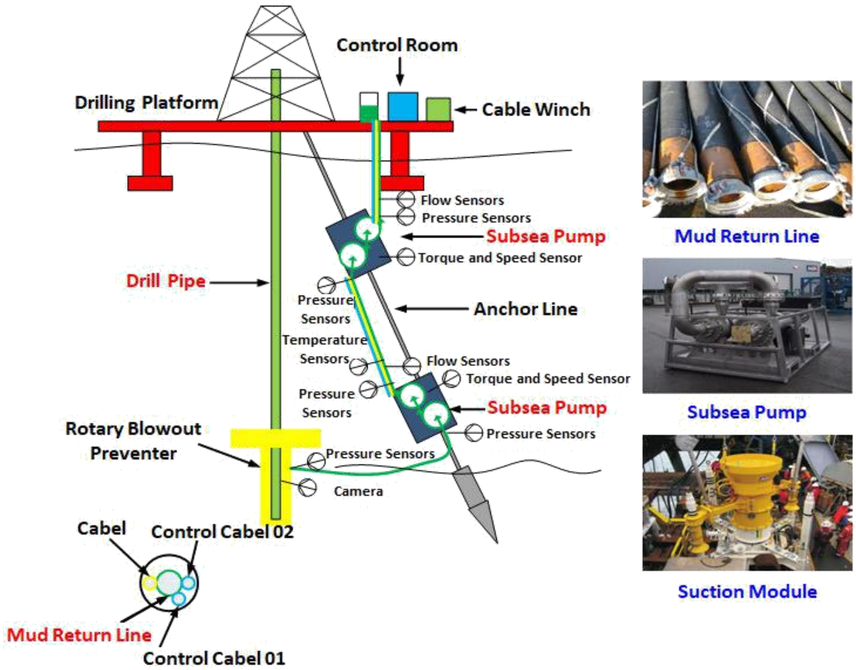


Fig. 1. Composition of the RMR system

In 2003, BP America implemented commercial applications of the RMR system in the Caspian Sea [16]. It is currently the most widely used and most successful DGD technology in the world. Compared with conventional offshore drilling, RMR system has the following advantages:

(1)The RMR system abandons the riser used in conventional offshore drilling, so it can reduce drilling costs and requirements for drilling platforms, and enable the smaller drilling platforms to have the potential to drill in deep water [17,18]. (2) As shown in Figure 2, compared to conventional offshore drilling, the RMR system enables the annulus pressure to be more within the safe pressure window, thus enabling the number of casings to be reduced [19,20]. (3) The RMR system reduces the volume of mud used in the drilling process and reduces drilling costs [21,22]. (4) The RMR system enables the cuttings at the bottom of the well to be lifted along the drilling fluid to the platform through the mud return line instead of being directly discharged to the seabed, thus meeting environmental requirements [23,24]. (5) Because the RMR system uses a small diameter mud return line instead of a large diameter riser, the drilling fluid has a faster return flow rate, so RMR system has higher cuttings lifting efficiency than conventional offshore drilling [25,26].

The RMR system is still not widely used in the deepwater field, the main reasons are: (1) The technical principle of the subsea pump is complex, and it is not currently possible to manufacture a subsea pump suitable for using in deepwater field [27,28]. (2) There are some difficulties in detecting and handling the kick, and the well control operation is complicated

[29,30]. (3) Because the drill pipe is directly exposed to seawater, the drill pipe needs to have higher corrosion resistance and fatigue strength [31,32].

Well control has always been a major concern of offshore drilling engineering. Based on the drilling data of a vertical well in the South China Sea [33], this paper analyzes the factors affecting the annulus pressure of the RMR system by combining the dual-gradient pressure principle of the RMR system. The main influencing factors include: seawater depth, ESD of drilling fluid, cuttings concentration and discharge capacity.

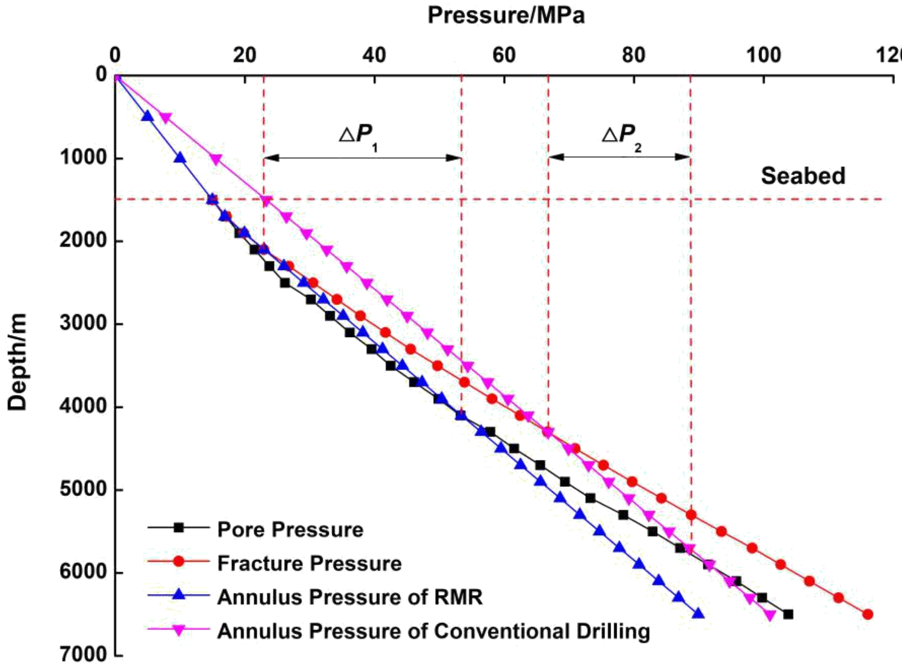


Fig. 2. The RMR system enables the annulus pressure to be more within the safe pressure window

As the seasons and working waters change, the operating water depth will change accordingly. According to the dual-gradient pressure principle of RMR system, the subsea pump adjusts the pump speed so that the pressure acting on the wellhead is equal to the subsea static pressure at that depth [34,35]. Therefore, when the operating water depth changes, the pressure exerted by the subsea pump on the wellhead will also change accordingly, thereby affecting the annulus pressure. This is the biggest difference compared to conventional offshore drilling when analyzing the annulus pressure of the RMR system.

The volume of the drilling fluid in the annulus will change with the change of temperature difference and pressure difference [36,37]. The change of drilling fluid volume will change the ESD of drilling fluid. The change of ESD of drilling fluid will change the ECD in the annulus. Change in the ECD can cause change in the circulating liquid column pressure of the drilling fluid. Therefore, the effect of ESD of drilling fluid on annulus pressure is essentially caused by temperature difference and pressure difference.

From the results of literature research, the influence of cuttings concentration on annular pressure is often neglected, but the reasons for the neglect are not explained [38-41]. The cuttings concentration is a function related to the rate of penetration [42,43]. In this paper, the influence of different cuttings concentration on the annulus pressure is obtained through calculation. Through the calculation results, it is observed whether the cuttings concentration can be neglected in the calculation of the annulus pressure.

The flow rate of drilling fluid in annulus varies with the change of discharge capacity, which results in different annulus pressure loss of drilling fluid in annulus [44,45]. Annulus pressure loss is an indispensable part of annulus pressure analysis. Based on the characteristics of RMR system, the influence of different discharge capacity on annular pressure is analyzed in this paper.

2. Calculation method

The annulus pressure of the RMR system consists of three kinds of pressure: (1) The pressure exerted by the subsea pump on the wellhead and it is also the inlet pressure of the subsea pump. (2) The circulating liquid column pressure generated when the drilling fluid circulates in annulus. (3) The pressure loss caused by drilling fluid circulating in annulus. The annulus pressure of the RMR system can be obtained as:

$$P_{\mathrm{ann}} = P_{\mathrm{inlet}} + P_{\mathrm{m}} + \Delta P_{\mathrm{f}} \tag{1}$$

where P_{ann} is the annulus pressure, MPa; P_{inlet} is the inlet pressure of subesea pump, MPa;P_{m} is the circulating liquid column pressure; P_{f} is the annulus pressure loss, MPa.

The inlet pressure of subesea pump can be written as:

$$P_{\mathrm{inlet}} = 0.00981 \rho_{\mathrm{w}} h_{\mathrm{w}} \tag{2}$$

where ρ_{w} is the density of seawater, g/cm3;h_{w} is the seawater depth, m.

The circulating liquid column pressure can be written as:

$$P_{\mathrm{m}} = 0.00981 \left[\rho_{\mathrm{m}} \left(1 - C_{\mathrm{a}} \right) + \rho_{\mathrm{c}} C_{\mathrm{a}} \right] h_{\mathrm{f}} \tag{3}$$

where ρ_{m} is the density of drilling fluid, g/cm^3; ρ_{c} is the density of cuttings, g/cm^3; C_{a} is the cuttings concentration, dimensionless; h_{f} is the formation depth, m.

When the fluid flow in the annulus is laminar, the annulus pressure loss can be written as:

$$\Delta P_{\mathrm{f}} = \frac{4h_{\mathrm{f}}K}{\left(d_{\mathrm{h}} - d_{\mathrm{po}}\right)}\left[\frac{4\left(2n+1\right)v_{\mathrm{m,ann}}}{n\left(d_{\mathrm{h}} - d_{\mathrm{po}}\right)}\right] \tag{4}$$

When the fluid flow in the annulus is turbulent, the annulus pressure loss can be written as:

$$\Delta P_{\mathrm{f}} = \frac{2f\rho_{\mathrm{m}}h_{\mathrm{f}}v_{\mathrm{m,ann}}^{2}}{\left(d_{\mathrm{h}} - d_{\mathrm{po}}\right)} \tag{5}$$

where K is the consistency coefficient of drilling fluid, Pa·s^n; n is the fluidity index of drilling fluid, dimensionless; $v_{\mathrm{m,ann}}$ is the flow rate of drilling fluid in the annulus, m/s; d_{h} is the diameter of wellbore, cm; d_{po} is the outer diameter of drill pipe, cm; f is the friction coefficient, dimensionless.

ECD can be written for annulus as:

$$ECD = \frac{\rho_{\mathrm{w}}h_{\mathrm{w}}}{h_{\mathrm{f}}} + \left[\rho_{\mathrm{m}}\left(1 - C_{\mathrm{a}}\right) + \rho_{\mathrm{c}}C_{\mathrm{a}}\right] + \frac{\Delta P_{\mathrm{f}}}{h_{\mathrm{f}}} \tag{6}$$

ESD can be expressed with the following equation [46,47]:

$$ESD = \frac{\left[\rho_{\mathrm{m}}\left(1 - C_{\mathrm{a}}\right) + \rho_{\mathrm{c}}C_{\mathrm{a}}\right]}{1 + C_{\mathrm{T}}\Delta T - C_{P}\Delta P} \tag{7}$$

$$C_{\mathrm{T}} = \frac{5.4907\times10^{-4}\left[\rho_{\mathrm{m}}\left(1 - C_{\mathrm{a}}\right) + \rho_{\mathrm{c}}C_{\mathrm{a}}\right]}{1 + 4.8351\times10^{-3}\Delta T} \tag{8}$$

$$C_{\mathrm{P}} = 0.5636\times10^{-3}\left[\rho_{\mathrm{m}}\left(1 - C_{\mathrm{a}}\right) + \rho_{\mathrm{c}}C_{\mathrm{a}}\right]\Delta P^{-0.1394} \tag{9}$$

where C_{T} is the thermal expansion coefficient, dimensionless; C_{P} is the elastic compression coefficient, dimensionless; T is the temperature difference between the drilling fluid at a certain depth and the platform, °C; P is the pressure difference between the drilling fluid at a certain depth and the platform, MPa.

Cuttings concentration can be calculated via [48]:

$$C_{\mathrm{a}} = \frac{ROP}{3600\left(v_{\mathrm{m,ann}} - v_{\mathrm{s}}\right)\left(1 - d_{\mathrm{po}}^{2} / d_{\mathrm{h}}^{2}\right)} \tag{10}$$

$$v_{\mathrm{m,ann}}=\frac{40Q}{\pi\left(d_{\mathrm{h}}^{2}-d_{\mathrm{po}}^{2}\right)}$$

(11)

$$v_{\mathrm{s}}=\mathrm{A}\sqrt{\frac{d_{\mathrm{s}}\left(\rho_{\mathrm{s}}-\rho_{\mathrm{m}}\right)}{\rho_{\mathrm{m}}}}$$

(12)

where *ROP* is the rate of penetration, m/h; v_s is the setting velocity of cuttings in annulus, m/s; Q is the discharge capacity, L/s; A is conversion coefficient, dimensionless; d_s is the cutting diameter, cm.

3. Thermal field

Since the drill pipe in the RMR system is directly exposed to seawater, the thermal field of RMR system is quite different from that of conventional offshore drilling. Since the temperature change affects the ECD, it is necessary to analyze the thermal field in the annulus. Because the main research content of this paper is to analyze the factors affecting the annulus pressure, only the mathematical model of the annulus thermal field is given in this section. The establishment of a mathematical model of the thermal field of other parts can also refer to this method.

3.1 Assumed conditions

A drilling fluid control volume of length dx is taken in the annulus, and the flow direction of drilling fluid is set to positive direction, and the following assumed conditions are made:

(1) The temperature in any section of annulus perpendicular to the flow direction is uniform;

(2) Ignore the heat conduction along the flow direction;

(3) All physical properties are constants;

(4) No heating measures were taken in the wellbore.

3.2 Mathematical model

The physical model of heat transfer process of annulus is shown in Figure 3.

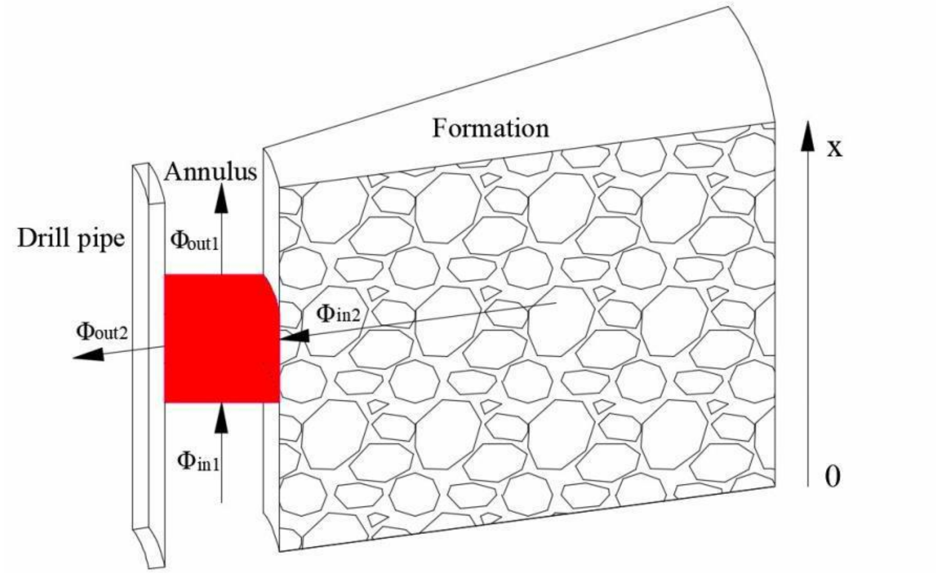


Fig. 3. Heat transfer model of annulus

The heat injected from the lower surface of the control volume:

$$\Phi_{in1} = q_m C_p t_x \tag{13}$$

The heat transfer from the formation to the drilling fluid in the annulus:

$$\Phi_{in2} = U_{fa}\pi\left(d_h - d_{po}\right)\left(t_{for} - t_x\right)dx \tag{14}$$

The temperature of the formation at depth x:

$$t_{for} = t_s + m\left(L - x\right) \tag{15}$$

The heat that flows from the upper surface of the control volume:

$$\Phi_{out1} = q_m C_p t_{x+dx} \tag{16}$$

The heat transfer from the drilling fluid in annulus to the drilling fluid in drill pipe:

$$\Phi_{out2} = U_{ap}\pi\left(d_h - d_{po}\right)\left(t_x - t_e\right)dx \tag{17}$$

Combined with the boundary condition $t_{x=0}=t_i$, the calculation equation of the temperature of drilling fluid in annulus can be obtained:

$$t = Ax + Be^{cx} + D \tag{18}$$

$$A = -\frac{mU_{fa}}{U_{fa} + U_{ap}} \tag{19}$$

$$B = -\frac{U_{fa}t_i + U_{ap}t_e}{U_{fa} + U_{ap}} - \frac{mU_{fa}q_m C_p}{\pi\left(d_h - d_{po}\right)\left(U_{fa} + U_{ap}\right)^2} \tag{20}$$

$$C = -\frac{\left(U_{fa} + U_{ap}\right)\pi}{q_m C_p}\left(d_h - d_{po}\right) \tag{21}$$

$$D = B \tag{22}$$

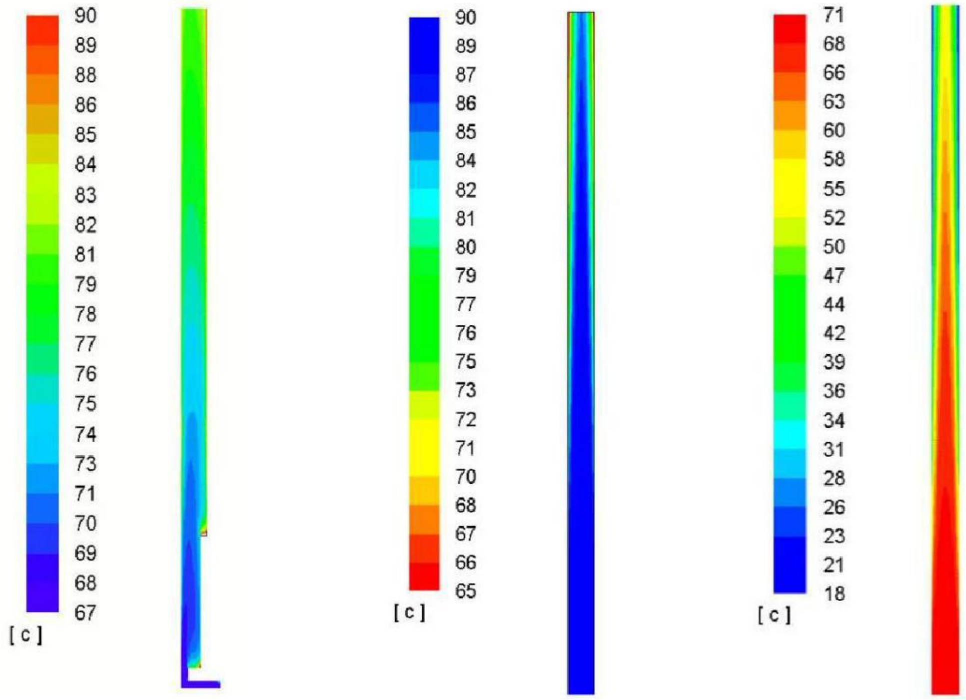
where U_{fa} is the heat transfer coefficient between the formation and the drilling fluid in annulus,W/(m^2·°C); U_{ap} is the heat transfer coefficient between the drilling fluid in annulus and the drilling fluid in drill pipe, W/(m^2·°C); t_i is the temperature of the drilling fluid at the bottom of well, °C; t_e is the temperature of the drilling fluid in drill pipe, °C; t_s is the surface temperature of formation, °C; m is geothermal gradient, °C/100m; q_m is the mass flow of drilling fluid through control volume, kg/s.

3.3 CFD analysis

The temperature changing of the drilling fluid in annulus at formation depth 500-1000m, 2500-3000m and 4500-5000m were simulated. The basic parameters are shown in Table 1. The results of the CFD analysis are shown in Figure 4.

Table 1. Input parameters for CFD

Parameter	Data	Parameter	Data
Minimum annular velocity, m/s	3.7	Annulus width, m	0.12
Geothermal gradient, °C /100m	4.2	Formation density, kg/m^3	3.1
Heat transfer coefficient U_{fa}, W/(m^2• °C)	430.3	Heat transfer coefficient U_{ap}, W/(m^2• °C)	152.7



(a)4500m~5000m **(b) 2500m~3000m** **(c) 500m~1000m**

Fig. 4. CFD analysis results of annulus temperature

The temperature of drilling fluid at the bottom of well is 67 °C. According to the result of CFD analysis, the temperature of drilling fluid at 4500m is about 80 °C, 90 °C at 3000m, 85 °C at 2500m, 70 °C at 1000m and 50 °C at 500m. From the results of CFD analysis, the temperature of drilling fluid in the annulus first increased and then decreased.

3.4 Calculation results

The temperature distribution of drilling fluid in annulus is calculated by using the established mathematical model. The calculation results are shown in Figure 5.

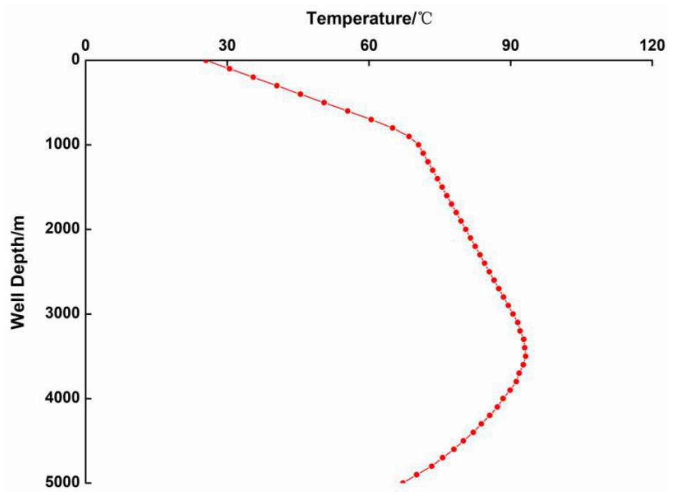


Fig. 5. The calculation result of temperature distribution in annulus

The calculation results are basically consistent with CFD analysis results, which show that the mathematical model established in this paper has certain accuracy.

From the calculation results, there is a tendency for the temperature of the drilling fluid in the annulus to rise first and then decrease. This is because when the drilling fluid just begins to return in the annulus, $\Phi_{in2} > \Phi_{out2}$, the temperature of the drilling fluid will rise. As the drilling fluid continues to flow in the annulus, $\Phi_{in2} < \Phi_{out2}$, the temperature of the drilling fluid will drop.

4. Case study

All the calculations and analysis in this paper are based on drilling data from a vertical well in the South China Sea. Based on the drilling data of this well, the effects of seawater depth, ESD of drilling fluid, cuttings concentration and discharge capacity on ECD and annulus pressure are analyzed in this section. The key parameters of the well are shown in Table 2. The casing program of the well is shown in Figure 6. The calculation of this section is based on the size of intermediate casing.

Table 2. Key parameters of the vertical well in the South China Sea

Parameter	Data	Parameter	Data
Well depth, m	6300	Seawater depth, m	1500
Diameter of surface casing, m	0.34	Diameter of intermediate casing, m	0.24
Diameter of production casing, m	0.18	Diameter of drill pipe, m	0.13
Density of drilling fluid, kg/m^3	1500	Density of seawater, kg/m^3	1020
Density of cuttings, kg/m^3	2500	Surface temperature of seawater, ^{o}C	20
Geothermal gradient,^{o}C/100m	4.2	Circulation time, h	8
Rate of penetration, m/h	7	Discharge capacity, L/s	45

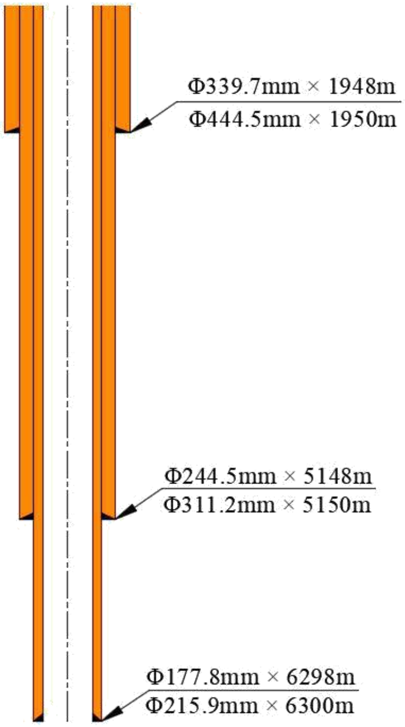


Fig.6. Casing program of the vertical well in the South China Sea

4.1 Effect of seawater depth

According to the dual-gradient pressure principle of the RMR system, the pressure exerted by the subsea pump on the wellhead is equal to the static pressure of the seawater at that depth. Therefore, the change in seawater depth mainly affects the pressure exerted by the subsea pump on the wellhead. By combining Eq.(1) and Eq.(6), the variation trend of ECD and annular pressure at seawater depths of 1500m, 2000m, 2500m and 3000m is analyzed. The calculation results are shown in Figure 7 and Figure 8.

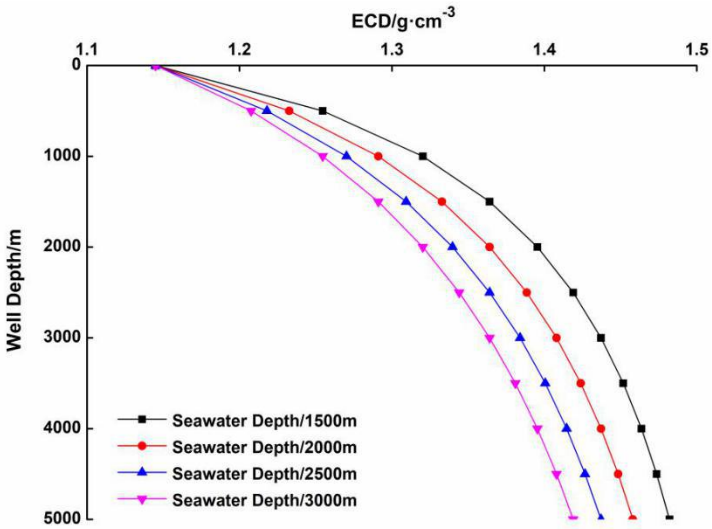


Fig. 7. Influence of seawater depth on ECD

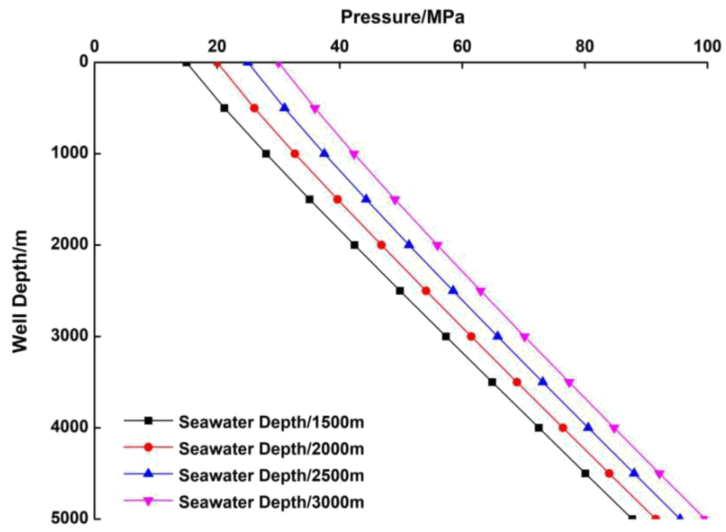


Fig. 8. Influence of seawater depth on annulus pressure

As can be seen from Figure 7 and Figure 8, as the seawater depth of the operating environment of the RMR system increases, the value of the ECD decreases and the value of the annulus pressure increases.

This is because, as the seawater depth increases, the pressure P_{inlet} acting on the wellhead increases, but the circulating liquid column pressure P_{m} and annulus pressure loss P_{f} did not change. As a result, the ECD and annulus pressure increase.

From the above analysis, the inlet pressure of the subsea pump P_{inlet} has an important influence on the change of the annulus pressure. Under the condition that the P_{inlet} is constant, certain measures should be taken to regulate the ECD so that the annulus pressure can pass through the safe pressure window to a greater extent.

4.2 Effect of ESD of drilling fluid

It can be known from Eq.(7) that the ESD of the drilling fluid is affected by the temperature difference and pressure difference of the drilling fluid.

If only the effect of the temperature difference ΔT is considered, combined with the Figure 5, it can be known that the volume of the drilling fluid in the annulus will first expand and then shrink, thereby causing the ESD to decrease first and then increase. Change in ESD will cause the same change in ECD.

If only the effect of the pressure difference ΔP is considered, it can be known that the change in the pressure difference causes the volume of the drilling fluid to continuously expand, causing the ESD to continuously decrease, thereby causing the ECD to continuously decrease.

After the temperature difference and the pressure difference are coupled, the calculation results are shown in Figure. 9 and Figure. 10.

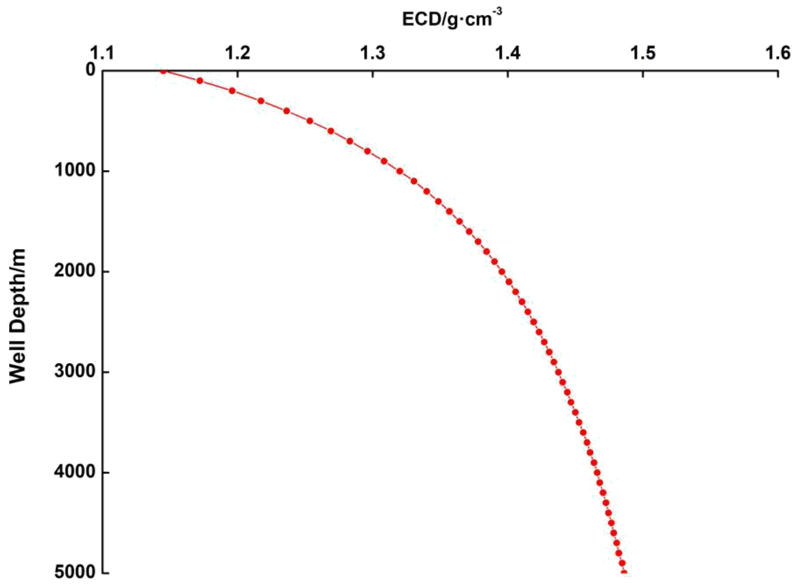


Fig. 9. Influence of ESD of drilling fluid on ECD

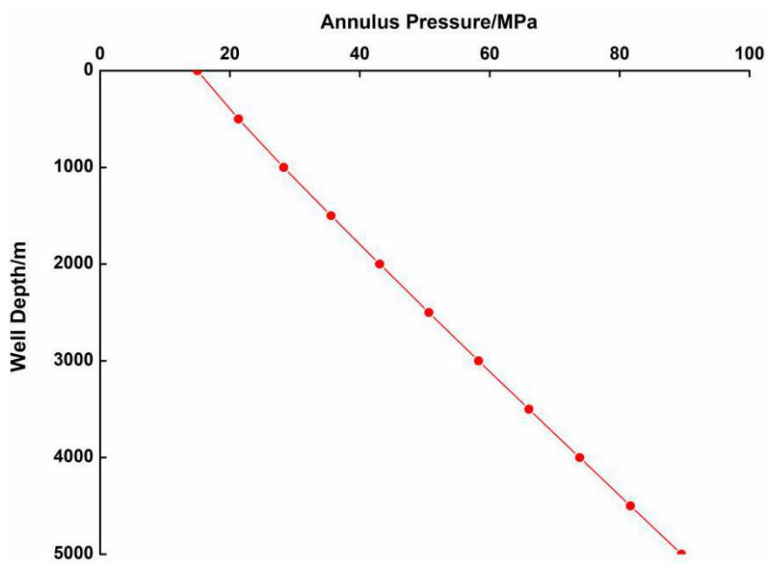


Fig. 10. Influence of ESD of drilling fluid on annulus pressure

From the results of the coupling, the ECD in the annulus continues to decrease, and the annulus pressure continues to decrease. Therefore, for the RMR system, the effect of ΔP on the annulus pressure is greater than the effect of ΔT. However, in the calculation of the annulus pressure, in order to ensure the accuracy of the results, it is necessary to couple the two influencing factors.

4.3 Effect of cuttings concentration

From Eq.(10), it can be seen that the cuttings concentration is a function related to the rate of penetration, and the functional relationship between them is shown in Figure 11.

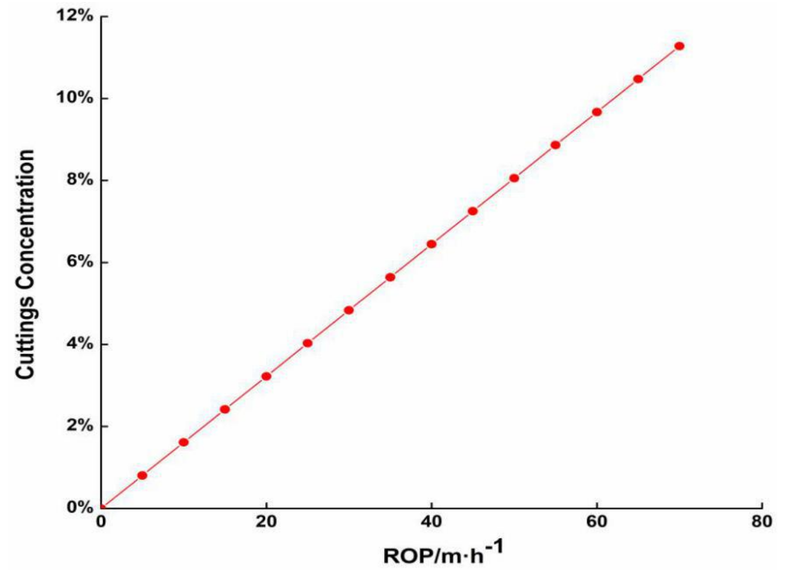


Fig. 11. The functional relationship between the cuttings concentration and the rate of penetration

By combining Eq. (3) and Eq. (6), the effects of different cuttings concentration on ECD and annulus pressure are explored. The cuttings content was set to 5%, 7%, 9% and 11% respectively. The calculation results are shown in Figure 12 and Figure 13.

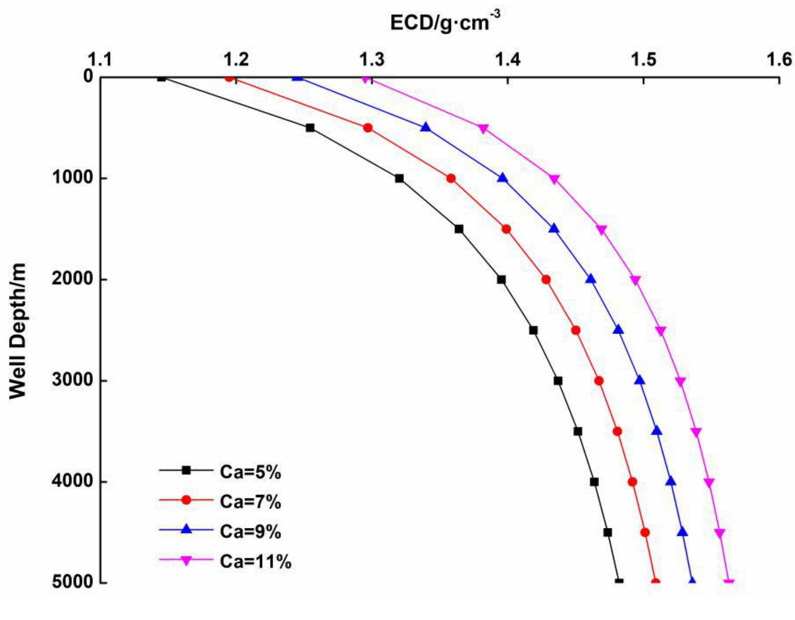


Fig. 12. Influence of cuttings concentration on ECD

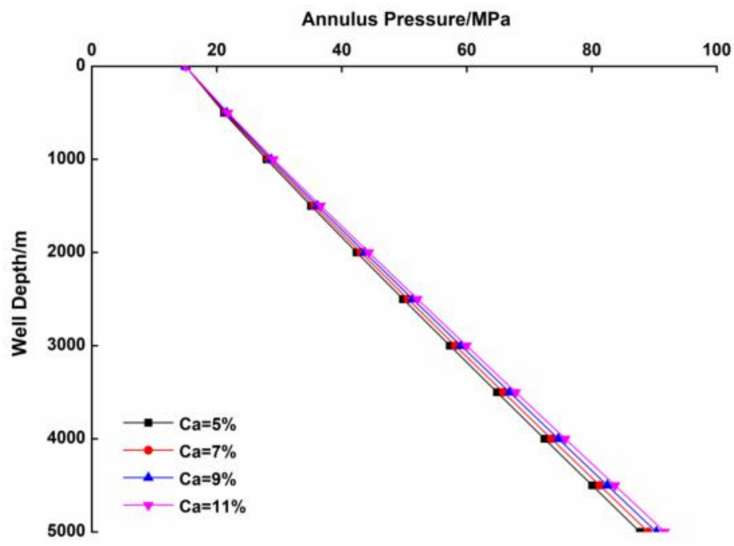


Fig. 13. Influence of cuttings concentration on annulus pressure

As can be seen from Figure 12 and Figure 13, as the cuttings concentration increases, the ECD and annulus pressure also increases. This is because, as the cuttings concentration increases, the circulating liquid column pressure P_m increases, but inlet pressure of subsea pump P_{inlet} and annulus pressure loss P_f did not change. As a result, the ECD and annulus pressure increase.

4.4 Effect of discharge capacity

By combining Eq.(4) and Eq.(5), it can be known that the discharge capacity mainly affects the annlus pressure loss. The discharge capacity is set to 45L/s, 55L/s, 65L/s and 75L/s respectively. The effects of different discharge capacity on ECD and annulus pressure are explored. The calculation results are shown in Figure 14 and Figure 15.

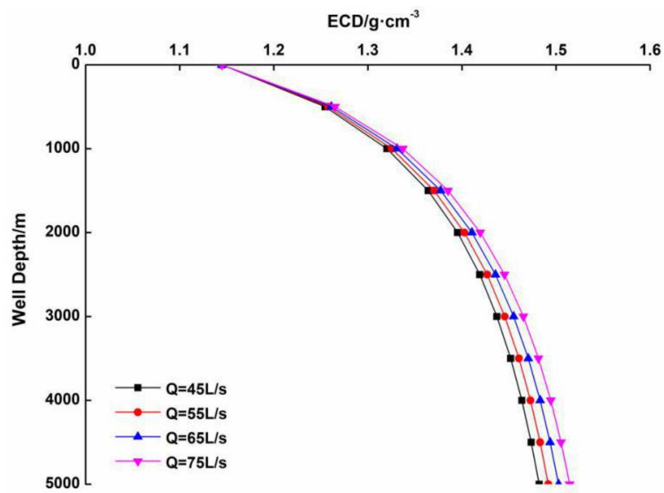


Fig. 14. Influence of discharge capacity on ECD

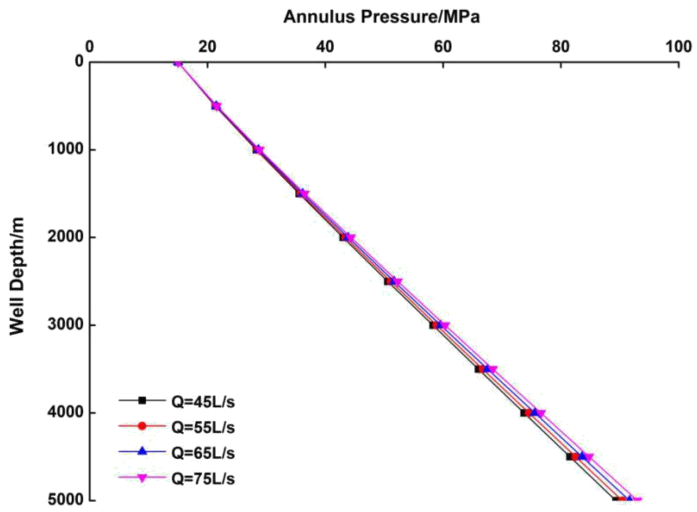


Fig. 15. Influence of discharge capacity on annulus pressure

It can be seen from Figure 14 and Figure 15 that as the discharge capacity increases, the ECD will increase and the annulus pressure will increase slightly.

The main reason is that as the discharge capacity increases, the flow velocity of the drilling fluid in the annulus becomes larger, and the pressure loss becomes larger. Combined with Eq.(1) and Eq.(6), it is obtained that the annulus pressure and the ECD is increased.

5. Conclusion

1. The temperature of the drilling fluid in the annulus is calculated using a mathematical model of the thermal field within the annulus.Through the results of calculation, the temperature of the drilling fluid in the annulus of the RMR system increases first and then decreases.

2. As the seawater depth increases, the pressure P_{inlet} acting on the wellhead increases, but the circulating liquid column pressure P_m and annulus pressure loss P_f did not change. As a result, the ECD and annulus pressure increase.

3. The effect of the ESD of the drilling fluid on the annulus pressure is actually the effect of changes in temperature difference and pressure difference. From the calculation results, the effect of the pressure difference on the annulus pressure in the RMR system is greater than the effect of the temperature difference.

4. The increase in the cuttings concentration in the annulus increases the circulating liquid column pressure, but the increase is small. Therefore, when calculating the annulus pressure of the RMR system, the influence of the cuttings concentration can be neglected, thus simplifying the calculation.

5. As the discharge capacity increases, the flow velocity of the drilling fluid in the annulus becomes larger, and the pressure loss becomes larger, so the annulus pressure and ECD increase

Acknowledgments

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