Bottom Hole Pressure Calculation of Fractured Carbonate Formation

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Abstract: Carbonate formation is widely distributed in China, mainly showing the sensitivity of the target formation and the development of fracture and cavity types and narrow pressure window. Drilling complicated conditions such as formation leakage or bottom hole pressure less than formation pressure due to gas entering wellbore occur from time to time. To solve these problems, calculating the bottom hole pressure accurately and conducting managed pressure drilling (MPD) for fractured carbonate formation are necessary. In this study, the single-phase hydraulic model based on H-B rheological model is calculated. According to the characteristics of fractured carbonate formation, the drilling fluid leakage model is obtained. By coupling the leakage model with the single-phase wellbore hydraulic model, the bottom hole pressure calculation method is suitable for fractured carbonate formation, which can provide reference for managed pressure control drilling technology. Such a technology is verified by Bozhong X well through the above calculation method of bottom hole pressure. The model is used to simulate the leakage behavior of transverse and longitudinal fractures. Moreover, the variation characteristics of the leakage rate and cumulative leakage amount of the drilling fluid in the fracture are investigated. By comparing the loss control with conventional drilling and MPD, the advantages of controlled pressure drilling operation in the loss control are described.

Keywords: carbonate formation, bottom hole pressure, managed pressure drilling, fracture leakage

1. Introduction

With the deepening of exploration in recent years, the engineering geological conditions of oil and gas reservoir exploitation are becoming increasingly complex. Oil reserves are abundant in the Bozhong area of China, but the exploration and development are difficult. Among them, the fractured carbonate formation is the typical one. Fractured carbonate formation is mainly manifested in the sensitivity of the target formation and in the development of fracture and cavity types and narrow pressure window. In the process of drilling operation, leakage accidents occur, resulting in the loss of drilling fluid, damage to the reservoir, and extension of non-production time of the project. Jin Yan, Chen Mian et al. [1] established the corresponding fracture pressure model by analyzing the leakage rate and corresponding leakage pressure difference of the Ordovician system, providing theoretical guidance for the prediction of the leakage pressure of such a system. Kang Yili (2010) discussed the leakage characteristics of fractured formation according to the geological characteristics of Tahe Oilfield.
Lavrov and Tronvoll [3] analyzed the influence of fracture dip angle and fracture positive compressibility on leakage. Mehrabi [4] analyzed the influence of fracture radius, wellbore radius, normal stress of fracture surface, and fracture opening and closing time on leakage. Serious accidents, such as well kick and cement slurry loss, may also be caused. The safety of drilling operation is restricted. By controlling the annular pressure profile, managed pressure drilling (MPD) can keep the bottom hole pressure at a constant or near constant state and keep the bottom hole equivalent circulating density in the safe density window all the time. MPD can also effectively avoid overflow, leakage, and other complex conditions when drilling in fractured carbonate formation. In all kinds of complex accidents, the loss of drilling fluid in fractured carbonate formation is the most common and typical accident type. Shi Xitian [5] introduced the application and promotion of pressure control drilling and its unique flexible well-killing methods combined with the field application examples of pressure control drilling in Tarim Oilfield. Gomez et al. [6] of Schlumberger company described the safe development of high-temperature depleted oil and gas reservoirs through gas injection and pressure control drilling technology and conducted a risk assessment on pressure control drilling technology. According to the current situation of the development of pressure control drilling technology at home and abroad, although the MPD technology has made great progress and wide application, theoretical research on pressure control drilling in fractured formation is limited. Therefore, the fracture dynamics coupled with wellbore are investigated, and the bottom hole pressure calculation model suitable for pressure control drilling in fractured carbonate formation is established.

2. Fracture Dynamics Coupled with Wellbore

2.1 Hydraulic calculation of the single-phase flow of wellbore

Due to the change of annular flow rate when the leakage occurs in carbonate formation, the annular pressure loss changes, and the bottom hole pressure changes under the influence of annular pressure loss. Therefore, the accurate hydraulic calculation of wellbore pressure is of great significance to determine the bottom hole pressure and whether complex accidents occur underground. In the process of calculating the rheological model of drilling fluid, this study selects the H-B model as the rheological model of drilling fluid for wellbore hydraulic calculation:

\[ \tau = \tau_0 + K\gamma^n, \]

where \( \tau \) is the shear stress, Pa; \( \tau_0 \) is the dynamic shear stress, Pa; \( K \) is the consistency coefficient, \( \text{Pa}\cdot\text{s}^n \), where \( n \) is the liquidity index; \( \gamma \) is the shear rate, \( \text{s}^{-1} \).

The H-B model can describe the rheological properties of drilling fluid accurately in a wide range of shear rates. Specifically, the rheological model includes the following situations:

- \( \tau_0 = 0 \), the fluid is Newtonian fluid.
- \( \tau_0 \neq 0 \) and \( n = 1 \), the liquid is plastic liquid.
- \( \tau_0 = 0 \) and \( n < 1 \), the liquid is pseudoplastic liquid; \( n > 1 \), the liquid is dilatant liquid.

The H-B model can well simulate the rheological properties of drilling fluid, especially for drilling fluid with high density and high temperature–high pressure formation. Specifically, the accuracy of the H-B model is high [7]. The experiment also shows that the goodness of fit of parameters is large, and the overall error is small.

After the flow pattern is determined, the circulating pressure loss is calculated. In the process of calculating the bottom hole pressure, the drilling fluid is assumed to be incompressible fluid. In the calculation process, Reynolds number is used to determine whether the fluid is laminar flow or turbulent flow, and then the annular fluid and the fluid in the pipe are calculated.

The circulation pressure loss of the laminar flow pattern is estimated by Fan Honghai [8].

Pipe flow:
\[
P_n = 4K \sum_{i=1}^{n} (L_i - L_{i-1}) \left( \frac{6n+2}{n} \right)^n \frac{V^n}{D_i^{n+1}} + \frac{3n+1}{2n+1} \left( \frac{4\tau_0}{D_i} \right)^n.
\]

Annular flow:

\[
P_N = 4K \sum_{i=1}^{n} (L_i - L_{i-1}) \left( \frac{8n+4}{n} \right)^n \frac{V^n}{(D_o - D_i)^{n+1}} + \frac{8n+4}{n+1} \left( \frac{\tau_0}{D_o - D_i} \right)^n.
\]

The circulation pressure loss of the turbulent flow pattern is as follows:

Pipe flow:

\[
P_m = \frac{2f \rho \sum_{i=1}^{n} (L_i - L_{i-1}) V^2}{D_i},
\]

Annular flow:

\[
P_m = \frac{2f \rho \sum_{i=1}^{n} (L_i - L_{i-1}) V^2}{D_e},
\]

\[
D_e = \frac{4D_o^4 - D_i^4}{\ln \left( \frac{D_o}{D_i} \right)} + \sqrt{D_o^2 - D_i^2}.
\]

where \( Re \) is the Reynolds number, dimensionless; \( \rho \) is the density of drilling fluid, g/cm\(^3\); \( D_i \) is the drill string inner diameter, cm; \( V \) is the flow rate of the drilling fluid, cm/s; \( D_h \) is the diameter of the borehole; \( D_o \) is the drill string outer diameter, cm; \( L \) is the pipeline length, cm.

2.2 Theoretical model of fracture leakage

The fracture roughness in the formation has an important impact on drilling fluid loss. The influence of fracture roughness should be considered when studying fracture leakage. Therefore, the deformation degree of fracture has an important influence on drilling fluid leakage, and the assumptions of the fracture leakage model established in this study are as follows: the fracture is a single fracture and cannot be expanded; the sealing effect of drilling fluid material on the fracture is not considered; the fracture wall has no permeability; the formation fluid and drilling fluid have the same properties and are incompressible, which is the H-B rheological model.

According to the above assumptions, the continuity equation of incompressible fluid is estimated by Hou Bing [9]:

\[
-\frac{\partial}{\partial x}(w_i v_i) = \frac{\partial w_i}{\partial t},
\]

where \( w \) is the width of fracture, m; \( v_i \) is the flow rate of drilling fluid in the fracture, m/s;

Momentum equation:

\[
\frac{\partial \tau}{\partial x} = -\frac{\partial P}{\partial x},
\]

where \( \tau \) is the dynamic shear stress, Pa; \( P \) is the pressure, Pa.

According to the momentum equation and the H-B model, the leakage rate model can be obtained as follows:

\[
v_i = -\left( \frac{dP}{dx} \right)^{-1} \left( \frac{n}{n+1} \right) \left( \frac{1^n}{K} \right) \left( -\tau_0 - \frac{dP}{dx} y \right)^{n+1}.
\]
2.3 Coupling study of fracture leakage and wellbore
Under normal drilling conditions, drilling fluid leaks from the wellbore to the fracture when drilling in fractured formation. When the displacement of drilling pump is constant, the annular velocity of drilling fluid in the wellbore is reduced due to the leakage of drilling fluid. At this time, the annular pressure consumption and the bottom hole pressure are also reduced, thus affecting the leakage of drilling fluid into fractures. Moreover, the leakage of drilling fluid in fractures and the flow state of wellbore affect and couple each other and jointly affect the bottom hole pressure in the drilling process. Therefore, the coupling calculation of fracture leakage and wellbore flow should be conducted. The process of coupling calculation is a double verification. After the known bottom hole pressure is brought into the fracture leakage rate formula, the leakage rate can be obtained, and then the obtained value is brought into the circulating pressure loss of annulus and pipe flow to calculate the bottom hole pressure. The linear regression analysis is conducted between the calculated bottom hole pressure and the known bottom hole pressure. If the accuracy requirements are met, then the calculated leakage rate is correct; otherwise, the leakage rate obtained at another time should be replaced until the accuracy requirements are met.

3. Application of Bottom Hole Pressure Coupling Calculation Model
High angle fractures are well developed in carbonate formation. When drilling straight wells in carbonate formation, axial fractures are easily formed. In the actual drilling process, the premise of forming axial fracture is that the fracture is closed or the leakage is small or the lost circulation is successfully implemented, so that the drilling can continue without serious leakage after encountering the fracture. If the bottom hole pressure is improperly controlled, then it may make the fracture after plugging communicate again and even communicate with the natural large fracture, which can cause serious leakage and lead to complex accidents. When the bottom hole pressure difference increases, the fracture opens, and the drilling fluid leaks into the fracture; when the differential pressure decreases, the fracture closes, and the drilling fluid in the fracture flows into the wellbore and causes kick.

In this study, Bozhong X well, which is drilled into carbonate formation, is selected as the simulated wellbore to simulate the fracture leakage. The bottom hole pressure is calculated by the abovementioned leakage model coupled with the bottom hole. Formulas (7) and (9) are mainly used and applied to pressure control drilling technology. Considering that the influence of fracture roughness on leakage is small, the crack is assumed to be a smooth plate joint to simplify the calculation. The basic parameters of the leakage simulation are presented in Table 1.

| Parameter/unit | Value  | Parameter/unit          | Value  |
|----------------|--------|-------------------------|--------|
| depth/m        | 6350   | Dip angle of fracture/° | 0      |
| vertical depth/m| 6350  | coefficient of fracture compressibility/Pa⁻¹ | 10⁻⁷  |
| length of upper casing/m | 4300 | Step interval dx, dy/m | 6.25  |
| length of lower casing/m | 1925 | Displacement/L/s | 6      |
| inner diameter of upper casing/mm | 155.80 | φ3 | 10 |
| inner diameter of lower casing/mm | 155.80 | φ6 | 15 |
| length of upper drill pipe/m | 4300 | φ100 | 55 |
| outer diameter of upper | 100.6 | φ200 | 80 |
According to the drilling design of Bozhong X well, the bottom hole pressure difference is within 2–6 MPa. Under the condition of keeping other parameters unchanged, the bottom hole pressure difference is taken as 2, 4, and 6 MPa. Through calculation, the leakage rate and cumulative leakage curve of closed fracture under different pressure differences can be obtained, as illustrated in Figure 1.

| Parameter                        | Value          |
|----------------------------------|----------------|
| drill pipe/mm                   | 1600           |
| length of lower drill pipe/m     | 300            |
| outer diameter of lower drill pipe/mm | 600         |
| length of drill collar/m         | 89.10          |
| density of drilling fluid/g/cm³  | 1.8            |
| outer diameter of drill collar/mm| 220            |
| direct stress of fracture surface/MPa | 150    |
| size of fracture/m               | 100 × 100      |
| width of maximum fracture/mm     | 0.5            |
| leakage time/s                   | 600            |
| time step/s                      | 0.05           |

**Figure 1.** Effect of initial pressure difference on the formation leakage rate
Figure 2. Effect of initial pressure difference on the cumulative leakage

The simulation results indicate that the leakage rate and cumulative leakage increase as pressure difference increases. Li Daqi [10] divided the leakage process of closed fractures into early, middle, and late stages. In the early stage of leakage, the curve of leakage rate and cumulative leakage amount is approximately straight line, the leakage rate decreases rapidly, and the cumulative leakage volume increases rapidly; in the middle stage, the slope of the curve of leakage rate and cumulative leakage volume changes with time, and the decrease of leakage rate and the increase rate of cumulative loss amount slow down; in the late stage, the leakage rate gradually decreases to zero with a low slope, whereas the cumulative leakage increases with a low slope until it becomes horizontal.

Taking Bozhong X well as an example, the predicted formation pressure equivalent density is 1.25 g/cm³. Density is increased to add a part of the original density of drilling fluid for balancing the formation pressure during the drilling process to prevent kick and other accidents. Surface back pressure is added to apply a part of pressure on the wellhead during MPD for ensuring that the bottom hole pressure is in a balanced or nearly balanced state. The comparison between MPD and conventional drilling is presented in Table 2.

|          | Conventional drilling | MPD                                                                 |
|----------|-----------------------|----------------------------------------------------------------------|
| Density of drilling fluid g/cm³ | 1.25                  | 1.22                                                                |
| Circulating pressure loss MPa    | 1.5                   | 1.5                                                                |
| Additional density g/cm³         | 0.05–0.13             | 0–2.6                                                              |
| Bottom hole pressure difference in conventional drilling MPa | 4.35–7.65             | 1–2.5                                                              |

Assuming that no control of leakage exists for pressure control drilling and conventional drilling in case of fracture leakage, the above table data and the data in Table 1 are used to calculate the leakage situation of pressure control drilling and conventional drilling when drilling with single fracture at the maximum and minimum bottom hole pressure differences, as illustrated in Figure 3.
By comparing the leakage of single fracture between MPD and conventional drilling, the leakage rate and cumulative loss of pressure control drilling are found smaller than those of conventional drilling because of its ability to maintain a low bottom hole pressure difference. In case of fracture leakage, MPD can reduce 2.8 MPa pressure by adjusting surface back pressure. If the leakage continues, then the pump displacement can be reduced, which can keep the bottom hole pressure in the near balance state, to achieve the purpose of rapid control of leakage. However, conventional drilling can only reduce the bottom hole pressure by 1.6 MPa by reducing the pump displacement. If the bottom hole pressure difference is to be further reduced, then the drilling fluid density can only be reduced; thus, it cannot meet the requirements of the control of leakage.

4. Conclusion
To explore the leakage characteristics of drilling fractures, the wellbore hydraulic model and fracture leakage model are established in this study. To simulate the leakage characteristics under real wellbore conditions, this research establishes a fracture leakage model coupled with wellbore by coupling the leakage of drilling fluid in fractures with wellbore flow, uses the model to simulate the leakage of drilling fluid in fractures, and carries out application practice by using the pressure control drilling technology in the field. The main conclusions are as follows:

- The fracture leakage model coupled with wellbore can well adapt to complex bottom hole conditions and is suitable for bottom hole pressure calculation in fractured carbonate formation.
- MPD can maintain a low bottom hole pressure difference, which can reduce the degree of leakage when drilling fractures, and can quickly control the bottom hole pressure by adjusting the surface back pressure.
- When adjusting surface back pressure to control leakage, the variation range of surface back pressure should be controlled to reduce the bottom hole pressure fluctuation.

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References:
[1] Jin Yan, Chen Mian, et al. 2007. Statistical Analysis of Leakage Pressure of Ordovician Carbonate Formation in Tazhong. Oil drilling & Production Technology. 29 (5):82-89.
[2] Hao Xining, Wang Zhiming, et al. 2009. Fracture Leakage Law of Mud Cap Pressure Control Drilling. Oil drilling & Production Technology. 31 (5):49-51.
[3] Lavrov, A. and J. Tronvoll. 2006. Numerical Analysis of Radial Flow in a Natural Fracture:Applications in Drilling Performance and Reservoir Characterization. in Abu DhabiInternational Petroleum Exhibition and Conference. Abu Dhabi, UAE: Society of Petroleum Engineers.
[4] Mehrabi, M., M. Zeyghami and M.P. Shahri. 2012. Modeling of Fracture Ballooning in Naturally Fractured Reservoirs: A Sensitivity Analysis. in Nigeria Annual International Conference and Exhibition. Lagos, Nigeria: Society of Petroleum Engineers.
[5] Shi Xitian, Xiao Tie, et al. 2010. Application of Pressure Control Drilling Technology in Ordovician Carbonate Sensitive Reservoir in Tarim Basin. Drilling & Production Technology 33(6): 130-131,140.
[6] Gomez, E.D., et al. 2012. Successful Use of Managed Pressure Drilling (MPD) in Low Pressure, High Pressure, High Temperatre, and Deeper Reservoirs in Mexico South. SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition.
[7] Wang Binbin, Wang Ruihe, Bu Yuhuan. 2010. Numerical Simulation no Cementing Displacement in Different flow Patterns. Drilling Fluid & Completion Fluid. 27(3): 76-78.
[8] Fan Honghai. 2013. Fluid mechanics of practical drilling. Beijing: Petroleum Industry Press.
[9] Hou Bing, Chen Mian, Lu Hu, et al. 2009. Cause analysis of lost circulation and plugging method in Paleogene of Kuqa Piedmont structure. Oil Drilling & Production Technology. 34(1): 40-44.
[10] Li Daqi, Kang Yili, Liu Xiushan, et al. 2013. Progress in Drilling Fluid Loss Dynamics Model for Fractured Formation. International Journal of Geomechaics, 41(8): 42-47.