Analysis and application of prediction model for formation fluid sampling time while drilling

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Abstract. Formation sampling while drilling (FSWD) is one of the most advanced formation sampling techniques in the world. It is characterized by short operation time, shallow mud invasion, and the obtained formation data is closer to the real situation of the reservoir. During the sampling process, the first fluid that the suction probe on the borehole wall inhales is basically drilling mud filtrate. With the increase of suction time, it gradually mixes into the formation fluid, and finally the formation fluid is infinitely close to 100%. At this time, it is very important to judge the starting time of sampling. If the sampling time is too early, the percentage of samples contaminated by drilling filtrate will be higher, which can not meet the requirement of fidelity. If the sampling time is too late, the drilling fluid will stop circulating for too long, which will cause sticking. In this paper, the prediction method of sampling time is to simulate the permeability of drilling fluid to formation under certain formation parameters and drilling conditions. Based on the simulated permeability results, the suction model of sampling tool is established to simulate the pumping situation, and the variation of the content of drilling filtrate in the pumped fluid with the suction time is obtained, that is, the relationship between the contamination rate of formation fluid and the suction time. This method is of great significance to the field application of fluid sampling tools while drilling.

1 Introduction

It is very important to obtain geological parameters such as fluid type and property by collecting representative formation fluid samples, which is of great significance to accurately determine the oil-gas situation of reservoir and reasonably formulate medium and long-term development plan of oil and gas field [1-2]. At present, there are two main ways to obtain formation fluid: wireline formation sampling and formation sampling while drilling (FSWD).

Wireline formation sampling technology has been developed for a long time and the technology is mature now. However, in the process of sampling, the instrument is easy to stick because the drilling fluid stops circulating for too long. Moreover, due to the sampling after drilling, the formation is opened for a long time, and the formation near the wellbore is seriously polluted by mud filtrate, so it is difficult to obtain the real composition data of formation fluid [3]. FSWD is developed on the basis of wireline formation sampling, formation pressure testing while drilling, and formation fluid analysis technology. It can quickly collect low pollution or non pollution formation fluid when the oil and gas reservoir is just opened. The operation time is short, the mud invasion is shallow, and the formation data obtained are closer to the real situation of the formation [4-6].

In the formation of fluid sampling while drilling, foreign research has a history of more than 20 years. In recent years, Schlumberger, Halliburton and Baker Hughes have launched their own characteristic products [7-8]. Among them, there are many literatures about mud infiltration or sampling and pumping formation fluid. Zazovsky(2008) proposed a model which is a combination of practical experience and simulation calculation. Its fundamental basis is to monitor the fluid composition sucked by downhole probe through optical fluid analyzer (OFA), analyze the optical density difference between formation fluid and drilling filtrate invading formation, reflect the progress of formation fluid displacement drilling filtrate through optical density change, and judge the beginning of sampling time [9-13].

In China, CNOOC oilfield services [14-15] and PetroChina Daqing drilling engineering company [16] have made corresponding attempts in pressure and temperature measurement while drilling, but generally speaking, they are still in the stage of importing and imitating corresponding foreign instruments, and there are still some deficiencies in technical level, technical indicators and field application, especially in the absence of downhole opto-fluid analyzers, sampling time prediction is blank.

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2 Design and research of related parameters

In the process of drilling, the water column pressure of drilling fluid is slightly higher than that of the original formation, which leads to the penetration of drilling fluid into the original formation. The part of drilling fluid that intrudes into the formation is called drilling filtrate. Generally speaking, according to the saturation of the invasion into the formation, it can be divided into three areas: flushed zone, transition zone and original formation, as shown in Figure1. In fact, the radius and saturation of the invasion of drilling filtrate are gradually changing with the invasion time, pressure difference, filtrate viscosity, reservoir permeability and cake permeability. When sampling while drilling under such permeation conditions, the content of drilling filtrate in the pumped formation fluid, that is, when the contamination rate of the pumped formation fluid reaches the sampling requirement, also varies with the filtrate infiltration time, pressure difference, filtrate viscosity, reservoir permeability, pumping capacity and cake permeability.

Figure 1. Profile of drilling filtrate invasion zone

According to the data and analysis, the formation property and fluid property parameters of an oil area in Shengli are as follows^[17]:

1) For medium and high permeability reservoir ($K_1 > 50\text{mD}$), the average formation permeability is 89.6mD , and the porosity of this kind of reservoir Φ_1 is 21.9% . For general low permeability reservoir ($10.2\text{mD} < K_1 < 42.3\text{mD}$), the average formation permeability is 12.5mD , and the porosity of this kind of reservoir Φ_1 is 12.4% .

2) Generally, the permeability of mud cake is 1-3 orders of magnitude smaller than that of formation. Assuming that mud cake is well formed, in medium and high permeability reservoirs, the formation permeability is three orders of magnitude of mud cake permeability; in general low permeability reservoirs, the formation permeability is two orders of magnitude of mud cake permeability, and the unified porosity of mud cake Φ_2 is 3% .

3) The over balanced pressure difference range of drilling fluid during drilling cycle P is $1\text{-}4\text{MPa}$.

4) The viscosity of drilling fluid μ_1 is $25\text{-}35 \text{ mPa} \cdot \text{s}$.

5) The viscosity range of crude oil μ_2 is $25\text{-}100 \text{ mPa} \cdot \text{s}$.

6) The unified drilling fluid density ρ_1 is $1100 \text{ kg} / \text{m}^3$ and the crude oil density ρ_2 is $850 \text{ kg} / \text{m}^3$.

During the analysis and calculation, the formation permeability K_1 is divided into 8 grades: 90mD , 75mD , 60mD , 45mD , 40mD , 30mD , 20mD and 10mD , the overbalance pressure difference P is divided into 4 grades: 1MPa , 2MPa , 3MPa and 4MPa , the crude oil viscosity μ_2 is divided into 4 grades: $25\text{mPa} \cdot \text{s}$, $50\text{mPa} \cdot \text{s}$, $75\text{mPa} \cdot \text{s}$ and $100\text{mPa} \cdot \text{s}$, the invasion time t is divided into 6 grades: 30min , 60min , 90min , 120min , 150min and 180min , the viscosity of drilling fluid μ_1 is selected as $30 \text{ mPa} \cdot \text{s}$ (In discussion 2, the simulation shows that the viscosity of drilling fluid changes in the range of $25\text{-}35 \text{ mPa} \cdot \text{s}$, which has little effect on the sampling time and can be ignored), and other parameters remain unchanged. Among them, a total of 768 different working conditions were established through the combination of different parameters and multi working conditions, and the calculation models of filtrate invasion into the formation and fluid sampling time were established. Through the results of these examples, a data table which can envelope and radiate to various geological conditions and drilling conditions is summarized to determine the sampling time, so as to guide the actual operation of sampling time.

3 Simulation of infiltration process

In order to simplify the modeling and analysis of drilling fluid invasion process, the following assumptions are made: there is oil-water two-phase flow in the reservoir, all fluids in the reservoir conform to Darcy's law and mass conservation equation., the compressibility of crude oil and filtrate is ignored, the density, temperature and viscosity of formation fluid are constant, the rock in the reservoir is isotropic and homogeneous, all the flow in the process of drilling fluid invasion is radial flow.

The seepage between oil-water phases in reservoirs is not considered by capillary force, and the seepage satisfies the following equation.

The equation of motion of oil-water two-phase seepage:

Oil phase:

$$\bar{v}_o = -\frac{K_o(s)}{\mu_o} \text{grad}P \quad (1)$$

Water phase:

$$\bar{v}_w = -\frac{K_w(s)}{\mu_o} \text{grad}P \quad (2)$$

The continuity equation of oil-water two-phase flow is as follows:

Oil phase:

$$-\left(\frac{\partial v_{ox}}{\partial x} + \frac{\partial v_{oy}}{\partial y} + \frac{\partial v_{oz}}{\partial z}\right) = \phi \frac{\partial S_o}{\partial t} \quad (3)$$

Water phase:

$$-\left(\frac{\partial v_{wx}}{\partial x} + \frac{\partial v_{wy}}{\partial y} + \frac{\partial v_{wz}}{\partial z}\right) = \phi \frac{\partial S_w}{\partial t} \quad (4)$$

If there is no mass transfer between oil and filtrate, and the pore space is filled together, the oil saturation S_o and filtrate saturation S_w are as follows:

$$S_o + S_w = 1 \quad (5)$$

Where:

$K_o(s)$, $K_w(s)$ are the phase permeability of oil and water respectively.

S_o , S_w are oil phase saturation and filtrate saturation respectively.

The phase conduction of porous media in the fluid flow module of Darcy Two-phase flow are used to solve the simulation. Two phase flow is also used to simulate the process of fluid invasion by drilling filtrate.

A two-dimensional geometric model is established in the plane perpendicular to the drill pipe axis at the sampling formation position. Due to the geometric symmetry of the model, a quarter circle is established to

simulate the formation for solution. The geometric model is shown in Figure 2. Its radius is half of the wellbore diameter of 215.9mm, the reservoir radius is 5m, and the thickness of mud cake is 2mm. Set the boundary conditions, boundary 1 and 2 can not flow, boundary 3 is set at the inlet, boundary 4 is set at the outlet, the saturation of filtrate at the wellhead boundary is set as $S_1 = 1$, and the saturation of remaining oil is set as $S_2 = 0$.

The structural grid is used for the grid generation, and the transient solution is carried out to find out the law of intrusion radius changing with time under a certain saturation.

Figure 2. Reservoir geometry model and grid generation

Example 1: The overbalance pressure difference P is 3MPa, the formation permeability K_1 is 45mD, which belongs to the medium high permeability reservoir, the formation porosity Φ_1 is 21.9%, the drilling fluid viscosity μ_1 is 30mPa · s, and the crude oil viscosity μ_2 is 25 mPa · s. according to the above 2 (2), the medium high permeability formation permeability is three orders of magnitude of the mud cake permeability, so the mud cake permeability K_2 is 0.045 mD, the porosity of mud cake Φ_2 is 3%, the drilling fluid density ρ_1 is 1100 kg / m³, the crude oil density ρ_2 is 850 kg / m³, and the invasion time t is 120min. The parameter in example 1 is one of the

above 768 working conditions, and the permeability nephogram is shown in Figure 3. The color of radial saturation changes from red to blue with the increase of permeability radius, and the change gradient is completely consistent in circumferential direction, which means that the saturation of drilling fluid changes from 100% to 0 with the increase of permeability radius in formation outside wellbore. In this example, the curve of permeability time corresponding to formation saturation changing with permeability radius is shown in Figure 4.

Figure 3. Example 1 cloud image of formation permeability for 120min

Figure 4. Variation of formation saturation with permeability radius after 120min permeability

4 Simulation of suction process

The suction function of the sampling tool is to press a

miniature probe with cushion on the well wall, then reduce the pressure in the probe to enough to destroy the mud cake near the probe and extract the fluid from the formation.

Figure 5. Suction process calculation model

During the simulation, a three-dimensional hollow cylinder is used to simulate the formation. The axis of the cylinder is in the same direction as the axis of the drill pipe. Due to the geometric symmetry of the model, a half cylinder is established to simulate the suction process. The inner diameter of the cylinder is 215.9mm, and the outer diameter is 290mm. The wall thickness is 37mm, which is the maximum thickness of 1h invasion in example 1. The height of the cylinder is 500mm. A tube with an inner diameter of 30mm is set in the middle of the cylinder to simulate the suction probe, as shown in Figure 5(a), Figure 5 (b) shows its meshing model. This model is based on the fact that the pressure in the probe is reduced enough to destroy the mud cake near the probe, so the mud cake modeling can be ignored.

Example 2. Input the parameters of the corresponding reservoir infiltration model in example 1, and import the relationship curve between the saturation and the radius of the wellbore in example 1 to define the saturation of the filtrate in the reservoir, which is known as the known pollution situation of the stratum as shown in Figure 6. At this point, the radial color gradient is consistent.

(a) Circumferential flow field of reservoir

(b) Axial flow field of reservoir
Figure 6. In example 2, the saturation distribution of reservoir drilling filtrate at 0 min suction process

In the case of unknown formation fluid bubble point, in order to make the outlet pressure of the suction probe and the formation pressure of the sample have little difference, the suction pressure difference should be maintained at 3MPa, so as to prevent the phase transformation of the sample during the suction process. Figure 7 shows the saturation distribution of the drilling filtrate in the reservoir model at 121min during the pumping process of example 2, which shows that the radial color gradient is no longer consistent. During the pumping process, a cone-shaped flow field distribution is formed at the entrance of the probe, and the formation fluid flows towards the probe head. With the continuous pumping, the flow field velocity near the pipe wall of the probe suction inlet decreases. Because of the difference between the direction of suction and that of suction, the degree of contamination is always higher than that of the area with the same direction of suction, which leads to the contamination rate at the wall of the probe always higher than that at the center of the probe. Figure 8 shows the curve of the average pollution rate of the filtrate at a certain cross section of the probe with time. It shows that with the increase of the suction time, the pollution rate of the drilling filtrate rapidly decreases from 100% to 15% within 20 minutes of the sampling time. After 20 minutes, the pollution rate decreases slowly and finally infinitely approaches but is not equal to 0%. When the sampling time is 121 minutes, the pollution rate is 5%, and the qualified samples can be obtained (the pollution rate of drilling filtrate in the design fluid sample is less than 5%).

(b) Axial flow field of reservoir
Figure 7. In example 2, the saturation distribution of reservoir drilling filtrate at 121 min suction process

Figure 8. In example 2, the variation curve of the percentage of drilling filtrate (contamination rate) in the fluid pumped by the probe with time

5 List and application of each example

The relevant condition parameters and simulation results of example 1 and example 2 are listed in the parameter group number 400 in Table 1 in combination order. According to the seepage simulation calculation method in case 1 and the suction simulation calculation method in example 2, the seepage and simulation calculation of 768

working conditions mentioned in example 1 are completed, and the results are summarized in Table 1, as shown in Table 1. In practical application, two methods can be adopted.

(1) If the relevant parameters of the sampling formation and drilling are exactly consistent with the gear in the serial number of a parameter group in Table 1, the sampling time can be directly checked for reference, if it is very close to a parameter gear in Table 1, about 20% above and below the gear value, it can be similar to that gear to look up the table. For example, when $K_1=47\text{mD}$, $\mu_2=26\text{mPa}\cdot\text{s}$, $P=2.8\text{MPa}$, $t=120\text{min}$, It can be approximated to $K_1=45\text{mD}$, $\mu_2=25\text{mPa}\cdot\text{s}$, $P=3\text{MPa}$, $t=120\text{min}$, that is, 400 serial number parameter group in Table 1, then sampling time of 121min can be obtained directly. Compared with the actual simulation calculation, the error is + 16%. Under the condition of sacrificing sampling time, the pollution rate of the retrieved sample can be less than 5%, which can meet the sampling requirements.

(2) If the relevant parameters of sampling formation and drilling are between two working condition parameter

serial numbers, and deviate more than 20% from the gear in the serial number of a parameter group in Table 1, the average conservative method can be used to determine the sampling time. For example, when $K_1=56\text{mD}$, $\mu_2=32\text{mPa}\cdot\text{s}$, $P=2.8\text{MPa}$, $t=114\text{min}$, The overbalance pressure difference is within the range of 2-3MPa in Table 1, so the larger value of P is 3MPa, and the invasion time is within the range of 90-120min in Table 1, so the value of t is 120min, The formation permeability and viscosity of crude oil can be discussed as follows: ① $K_1=45\text{md}$, $\mu_2=25\text{mPa}\cdot\text{s}$, $P=3\text{MPa}$, $t=120\text{min}$; ② $K_1=45\text{md}$, $\mu_2=50\text{mPa}\cdot\text{s}$, $P=3\text{MPa}$, $t=120\text{min}$ ③ $K_1=60\text{md}$, $\mu_2=25\text{mPa}\cdot\text{s}$, $P=3\text{MPa}$, $t=120\text{min}$ ④ $K_1=60\text{md}$, $\mu_2=50\text{mPa}\cdot\text{s}$, $P=3\text{MPa}$, $t=120\text{min}$, corresponding to 400, 424, 496 and 520 condition numbers respectively. The average sampling time of the four groups is 119.5min, and the error is + 25% compared with the actual simulation value. Under the condition of sacrificing sampling time, the pollution rate of the retrieved samples can be less than 5%, which can also meet the sampling requirements.

Table1. List of sampling time required under different reservoir and drilling parameters under suction pressure drop of 3MPa(Partial display)

Condition parameter serial number	The formation permeability K_1/mD	Viscosity of crude oil $\mu_2/\text{mPa}\cdot\text{s}$	The overbalance pressure difference P/MPa	The invasion time t/min	Sampling time T/min ($C<5\%$)
1				30	...
2				60	...
3				90	...
4				120	...
5				150	...
6			1	180	...
7				30	...
8				60	...
9				90	...
10				120	...
11				150	...
12			2	180	...
13		25			
...			3		
19					
...			4		
25					
	10				
		50			
...					
49					
...		75		...	...
73					

...		100	...		
97					
...	20				
193					
...	30				
289		...			
...	40				
385					
...					
400		25	3	120	121
...					
409			...	...	...
...					
424		50	3	120	88
...	45				
...		...			
481			...	...	...
...					
496		25	3	120	162
...					
504					
...		50			
520			3	120	107
...	60				
...					
577					
...	75		...	...	
673		...			...
...					
768	90	100	4	180	

6 Discussion

(1) The purpose of this paper is to explain how to predict the sampling time by simulation. The gear setting and density of formation permeability and crude oil viscosity in Table 1 are determined according to the situation of an oil area in Shengli. If other oil areas have relevant parameters falling in the middle of the two gears in Table 1, there will be some errors in determining the sampling time by method 2, and the larger the gear spacing is, the greater the error is. Therefore, in order to reduce the error, the corresponding parameters in Table 1 can be divided into more detail, and more combined examples can be added, so that more accurate sampling time can be obtained, and more practical application of field conditions can be convenient.

(2) In the simulation, if the viscosity of drilling fluid μ_1 is 25-35 mPa·s, it can be divided into three grades 25mPa·s, 30mPa·s and 35mPa·s. The other parameters are the same as those in example 1 to simulate the permeability process. Then, based on the permeability results, the suction process is simulated according to example 2. The relationship between the pollution rate and the corresponding suction time is shown in Figure 9. It can be seen that when the viscosity of drilling fluid changes in a small range, it has little effect on the final sampling time. Therefore, the viscosity of drilling fluid in Table 1 is calculated by taking the middle value of 30mPa·s. If the variation range of drilling fluid viscosity is larger than 30MPa·s, it is necessary to add the range of drilling fluid viscosity in Table 1, and the number of parameter groups and the amount of simulation calculation are doubled.

Figure 9. The variation curve of the percentage of drilling filtrate (pollution rate) in the fluid pumped by the probe with time under different drilling fluid viscosities

(3) The sampling time listed in Table 1 is based on the suction pressure drop of 3MPa. If it is known that the sampling formation pressure is far greater than the bubble point pressure of the formation fluid, the suction pressure drop can be increased, and the sampling time will be shortened as a result. In this way, the data in Table 1 needs to be replaced with a large suction pressure drop, and the same simulation method is needed to recalculate.

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