Optimization Analysis of Suction Probe for Formation Sampling While Drilling

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Abstract. Formation sampling while drilling (FSWD) is one of the most advanced formation sampling technologies in the world. During the operation, a small probe with a cushion is pressed against the wellbore to reduce the pressure in the probe enough to break the cake seal and extract the fluid from the formation. The content of drilling mud filtrate (drilling filtrate or filtrate) in the extracted formation fluid is determined by pollution rate. When the pollution rate of the extracted formation fluid drops to the specified index, the valve in the sample chamber is opened for sampling. When the sampling volume is reached, the pump and valve are closed. The time from the pump opening to the pump closing is called sampling time. The shorter the sampling time is, the shorter the circulation time of drilling fluid will be, so as to reduce the sticking accidents. Due to the influence of wellbore radial space, the size of the suction probe is limited. In order to avoid phase change of the pumped formation fluid during the operation process, the suction pressure difference should not be too large, etc. In this paper, the finite element simulation method is used to analyze the relationship between the above changes of the suction probe and the sampling time in the simulation results from the aspects of changing the size, shape, structure and arrangement of the suction probe in the formation fluid sampling tool while drilling, so as to realize the optimal selection of the suction probe. The research results of this method have important guiding significance to the design of fluid sampling tool while drilling.

1. Introduction

Sampling while drilling technology can quickly collect low pollution or non-pollution formation fluid when the oil and gas reservoir is just opened [1]. The operation time is short, the drilling mud invasion is shallow, the obtained formation data is closer to the real situation of the formation, and can reduce sticking and sticking accidents [2]. Therefore, it has become a research hotspot of oil service companies at home and abroad [3]. At present, the technology has been studied abroad for more than 20 years. In recent years, Schlumberger, Halliburton and Baker Hughes have launched their own characteristic products [4-5]. CNOOC and PetroChina Daqing drilling engineering company have made corresponding attempts in pressure and temperature measurement while drilling [6-7], but generally speaking, they are still in the stage of importing and imitating corresponding foreign instruments.

The suction probe studied in this paper is based on the background of formation fluid sampling while drilling, which has its special environmental requirements. For example, the suction rate should not be
too large, otherwise it will cause too large local pressure fluctuation, which will cause the phase change of the obtained formation fluid sample; moreover, due to the limitation of the wellbore inner diameter space and the force of the suction probe pressing into the wellbore, a single suction probe port can be used. The diameter cannot be designed too large and so on, and these aspects of foreign research started earlier and have been more mature. The single probe first appeared in the 1950s, and was initially used for cable formation testing [8]. In 2006, zefzaf proposed an elliptical probe structure and introduced its application in Bakr oilfield in Egypt [9]. Compared with the standard probe, it can effectively reduce the sampling time from the perspective of sealing. In 2007, akkurt (Schlumberger) proposed a focused suction probe, which can separate the mud filtrate from the formation fluid, ensure the sampling quality, and minimize the pollution of the collected fluid samples [10]. In 2014, CIG K and others proposed a kind of Saturn probe, which can quickly seal and obtain formation fluid in tight formation, reducing the risk of sticking [11]. For the domestic, the research on the specific optimization of the probe structure is shallow, and the research is not deep enough.

In the process of sampling, the pump in the tool sucks through the suction probe on the wellbore. The fluid that first sucks the suction probe is basically drilling filtrate. With the increase of suction time, there is gradually formation fluid mixed in, and the final formation fluid is nearly 100%. The contamination rate of drilling filtrate in the formation fluid is expressed as the contamination rate. When the contamination rate of the extracted formation fluid is less than or equal to the specified index, the valve in the sample chamber is opened for sampling, and the pump and valve are closed when the sampling quantity is reached. The time interval from the beginning of pumping to the completion of sampling is called sampling time. On the premise that the phase change of the pumped formation fluid does not occur, the shorter the sampling time is, which is what the designers of the tool strive to pursue.

In this paper, the Comsol Multiphysics software is used to simulate, from the aspects of changing the size, shape, structure and layout of the suction probe, the relationship between the time when the pollution rate of the formation fluid is reduced to the specified index in the simulation results and these changes of the suction probe is analyzed, and the optimal probe form is selected.

2. Establishment and Simulation of suction foundation model

The suction function of the sampling tool is realized by pressing a micro probe with cushion on the well wall, and then reducing the pressure in the probe enough to destroy the mud cake near the probe and extract the fluid from the formation, as shown in Figure 1.

In order to better study the flow law of formation fluid pumped while drilling, the following assumptions are made in the modeling analysis of the pumping process of the suction probe:

● There is oil-water two-phase flow in the reservoir;
● All the fluids in the reservoir conform to Darcy’s law;
● The compressibility of crude oil and filtrate is ignored;
● The density, Temperature and viscosity of the formation fluid are constant;
● The rocks in the reservoir are isotropic and homogeneous;
● The capillary force is not considered in the flow between oil and water in the reservoir;

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

Oil phase:
\[
\vec{v}_o = - \frac{K_o(s)}{\mu_o} \text{grad}P
\]  
(1)

Water phase:
\[
\vec{v}_w = - \frac{K_w(s)}{\mu_w} \text{grad}P
\]  
(2)

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

Oil phase:
\[
- \left( \frac{\partial v_{ox}}{\partial x} + \frac{\partial v_{oy}}{\partial y} + \frac{\partial v_{oz}}{\partial z} \right) = \frac{\partial \delta_{so}}{\partial t}
\]  
(3)

Water phase:
\[-\left( \frac{\partial v_{wx}}{\partial x} + \frac{\partial v_{wy}}{\partial y} + \frac{\partial v_{wz}}{\partial z} \right) = \phi \frac{\partial s_{w}}{\partial t} \]  

(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:

\[
S_o + S_w = 1
\]  

(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 suction model is solved by Darcy's law and porous media phase transfer, and a three-dimensional hollow cylinder is used to simulate the formation. The axis of the cylinder is in the same direction as the drill pipe axis. Its inner diameter is 215.9mm, the maximum invasion radius of the reservoir is 268 mm, and the height of the cylinder is 500mm. A pipe with an inner diameter of 30mm is set in the middle of the cylinder to simulate the suction probe. Since the pressure in the probe is reduced enough to destroy the mud cake near the probe, the mud cake modeling can be ignored. The mesh generation is shown in Figure 2.

In example 1, the formation permeability is 89.6mD, the formation porosity is 21.9%, the drilling fluid viscosity is 25mPa·s, the formation original fluid viscosity is 50mPa·s, the probe diameter is 30mm, and the suction pressure difference is 3MPa, the relation curve between initial saturation and distance from wellbore radius in pumping model be as follows:

\[
S_w = 78.46e^{-39.7x} - 0.148
\]  

(6)

Where $S_w$ is filtrate saturation and $X$ is radius from wellbore. Equation (6) it is introduced into the model to simulate the invasion process of mud filtrate in the initial infiltration process.

As shown in Figure 3, the known contamination of the formation is shown. At this time, the radial color change gradient is consistent. Keep the difference between the outlet pressure of the suction probe and the formation pressure at the sampling place small, otherwise it will affect the phase transition of the sampling. Set the suction pressure difference as 3MPa to solve the suction model.

Figure 4 shows the saturation distribution of drilling filtrate in the reservoir model at 50 min during the pumping process of example 1, which shows that the radial color gradient is no longer consistent. In the process of suction, a cone-shaped flow field is formed at the entrance of the probe, and the formation fluid flows towards the probe. With the continuous process of suction, the velocity direction of the flow field near the pipe wall of the probe inlet is different from that of the suction direction, which leads to the pollution degree always higher than that of the area with the same suction direction as the probe, and the pollution rate at the pipe wall of the probe is always higher than that of the central part of the probe. Therefore, the ultimate contamination rate depends on the fluid in the wall area of the suction inlet. Figure 5 shows the curve of the average contamination rate of the fluid at a certain cross section of the probe with time. The Figure shows that with the increase of the suction time, the contamination rate
decreases rapidly from 100% to nearly 0%. In 90 min, the sample with 5% contamination rate can be obtained.

Figure 3. In example 1, the saturation distribution of reservoir drilling filtrate at 0min pumping process

Figure 4. In example 1, the saturation distribution of reservoir drilling filtrate at 50min pumping process

3. The influence of the diameter change of the suction probe on the sampling time
The diameter of the suction probe was changed from 30mm in example 1, to 20mm and 13 mm, which became example 2 and example 3, and other conditions remained unchanged. The results of three examples are compared in Figure 6. It can be seen from the analysis in Figure 6 that when the probe diameter is 30mm, the contamination rate in the fluid pumped by the probe decreases the fastest. Therefore, the diameter of the suction probe should be increased as much as possible under the condition that the internal dimension of the tool and the overall dimension of the suction probe are allowed.

Figure 5. In example 1, Curve of pollution rate with time

Figure 6. Curves of contamination rate with time under different probe diameters
4. The influence of structure change of suction probe on sampling time

It can be seen from Figure 7 that in the cross section of the probe suction port, parallel to the axis of the borehole axis and perpendicular to the shaft on the pollution rate gradient is slightly different. This is because the drilling filtrate in the direction of the wellbore axis is more than that in the direction of the wellbore circumference in the fluid pumped, which enlightens us to increase the size of probe parallel to the axis of the wellbore, and decrease the size of probe perpendicular to the axis of the wellbore. At this time, the cross section is changed from a circle to an ellipse, which can improve the rate of pollution reduction in the pumped fluid.

![Figure 7. Different suction time (10 min, 50 min and 80 min), probe cross-section drilling filtrate saturation cloud distribution](image)

In example 4, the cross section of the suction probe is changed into an ellipse, and the flow area remains unchanged. The major axis of the ellipse is parallel to the wellbore axis, and the minor axis is perpendicular to the wellbore axis. Other parameters are the same as those in example 1. In order to optimize the ratio of long axis to short axis of elliptical probe, the suction simulation of elliptical probe with different ratios is carried out, as shown in Table 1.

| Ratio of major axis to minor axis of elliptical probe (a/b) | The pollution rate of the same time (80 min) of suction (%) |
|----------------------------------------------------------|------------------------------------------------------------|
| 0.14                                                     | 6.35                                                       |
| 0.22                                                     | 6.66                                                       |
| 0.36                                                     | 7.04                                                       |
| 0.44                                                     | 7.19                                                       |
| 0.54                                                     | 7.29                                                       |
| 0.56                                                     | 7.41                                                       |
| 0.64                                                     | 7.46                                                       |
| 0.75                                                     | 7.61                                                       |
| 0.93                                                     | 7.70                                                       |
| 1                                                        | 7.82                                                       |

It can be seen from Table 1 that the smaller the ratio of the long axis to the short axis of the elliptical probe, the lower the pollution rate in the same sampling time, that is, the higher the sampling efficiency. In order to improve the sampling efficiency, the smaller the ratio of the long axis to the short axis of the elliptical probe can be adopted under the condition that the tool space is limited and the processing degree is satisfied.

In addition, it can be seen from Figure 7 that the pollution gradient near the pipe wall of the suction probe is greater than that at the center of the pipe, which enlightens the design and manufacture of a concentric double-layer probe (focusing probe). The center layer can inhale the high-purity formation fluid reaching the specified index earlier, and the outer layer can inhale the formation fluid with higher pollution. By diverting the fluid pumped by the center and the outer layer, the sampling can be realized earlier.
The cross-sectional dimensions of the double-layer probe in example 5 are shown in Figure 8, in which the inner diameter of the outer layer $D_1 = 30$mm, the outer diameter of the inner layer $D_2 = 25$mm, and the inner diameter of the inner layer $D_3 = 21$mm. Other parameters are the same as those in example 1. The pollution gradient cloud of the simulation results is shown in Figure 9, and the comparison curve between example 5 and example 1 is shown in Figure 10. It is obvious that the focusing probe can greatly reduce the sampling time.

5. The influence of the layout of the suction probe in the tool on the sampling time
Limited by the space in the tool, the maximum size of a single suction probe is only 30mm, so the speed of reducing the pollution rate can be improved by increasing the number of probes. For this reason, two and four 30mm probes are symmetrically arranged from the same wellbore height, and the simulation calculation of example 6 and 7 are carried out correspondingly. The other conditions are the same as that of example 1, and the results are compared with example 1. Figure 11 is the corresponding cloud chart of pollution rate gradient, and Figure 12 is the corresponding curve comparison chart of pollution rate with time.
The characteristics of example 6 and 7 are that at the same time in the same example, the cloud image of pollution gradient in each probe is the same, and Figure 12 is symmetrical. Inspired by the enlightenment, we adopt the layout method as shown in Figure 13, that is, the probe center group layout method. The purpose is to make the pollution rate of the group leader probe in the center of the probe group reduce faster, that is, it can reach the sampling time faster than the probes around it. There is one "group leader" in the center of Figure 13 and two "group leaders" in the center of Figure 14. Figure 15 is the curve comparison of corresponding pollution rate with time. Figure 16 is the comparison of the time-varying curve of the contamination rate with the change of the angle between the radial and axial probes with the same height in the wellbore of the central group arrangement method (5 probes).
Figure 15. Comparison of time varying curves of contamination rate in "group leader" probe of single probe and central group arrangement method

It can be seen from Figure 15 that the probe center group arrangement method is obviously better than the single probe. In addition, in the probe center group arrangement method, the 8-probe two group leaders is slightly better than the 5-probe one group leader. Therefore, as long as the displacement of the suction pump allows, the number of probes can be appropriately increased by the center group arrangement method, so as to increase the number of group leaders. It can be seen from Figure 16 that in the central group layout method, the radial angle between the probes with the same axial height of the wellbore is 60° and 45°, and the variation of pollution rate with time is very close, both of which are obviously better than the angle of 90°. From the perspective of space, the angle of 60° is more convenient to arrange the probe.

Figure 16. Comparison of the curve of contamination rate with time by changing the angle between the radial and axial probes with the same height in the wellbore

6 Discussion
1) From the above analysis, it can be seen that the sampling time can be shortened by increasing the diameter of the probe, changing the suction port of the probe from round to ellipse with the same area, double-layer probe, increasing the number of probes and probe center group method, among which the double-layer probe and probe center group arrangement method are the most effective.

2) Considering the addition of a filter screen close to the mouth in front of the probe suction end, this will inevitably disarrange the pollution cloud gradient, which is no longer good for the double-layer probe with a small overall diameter on this tool. In addition, the double-layer probe will increase the difficulty of manufacturing the probe, especially when the size is small.

3) The suction effect of the probe center group arrangement method is less affected. Within the allowable range of the displacement of the suction pump, the similar extended arrangement can be continued along the axial length direction of the tool, as shown in Figure 14, which can be increased to 2, 3... "Group leader" and so on.

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