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DESIGN AND ROCK BREAKING CHARACTERISTIC ANALYSIS OF MULTI-JET BIT ON RADIAL HORIZONTAL DRILLING

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A multi-jet bit is a kind of high efficiency jet bit mainly applied in radial horizontal drilling technology. The design method for a multi-jet bit is described in this paper, and the influence of its structural parameters (hole number, lateral orifice diffusion angle) and hydraulic parameters (erosion time, jet pressure, standoff distance, confining pressure) on rock breaking efficiency are studied using specially developed experimental apparatus. From the experimental results, a larger number of holes in the jet bit result in a more circular form of borehole. The rock breaking efficiency declines with an increase of hole number when the equivalent diameter of the jet bit is constant. As the lateral orifice diffusion angle increases, the rock breaking efficiency firstly increases and then decreases. The rock breaking efficiency increases linearly during increase of the jet pressure. The optimal standoff distance is 5 to 6 times the nozzle equivalent diameter so that a multi-jet bit can obtain the largest rock breaking volume and borehole depth under zero confining pressure. The rock breaking efficiency of the multi-jet bit declines dramatically with the increase of confining pressure under confining pressure conditions. The conclusions above can provide guidance for design of multi-jet bits for radial horizontal drilling.

Keywords: radial horizontal drilling, multi-jet bit, design of jet bit, rock breaking

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1. Introduction

Hydraulic jet radial horizontal drilling technique can drill multiple horizontal branch holes along the radial direction in the reservoir. Being an important method of enhancing oil and gas recovery, this technique can increase the reservoir contact area substantially so as to improve single well production and control water and sand production, which is suitable for the development of coal bed methane, thin oil formation, fractured and low permeable oil reservoir [1-3]. With the rapid development of coiled tubing, new breakthroughs have been made in water jet radial horizontal drilling. According to the literatures [4,5], foreign companies have drilled horizontal boreholes with a diameter of 50 mm and length of 100 m in sandstone reservoir. There are two key factors for the technique: one is how to drill horizontal boreholes with a certain diameter to allow the following jet bit and soft pipe to go through. The other is how to use hydraulic energy to guarantee the rock breaking borehole diameter and drilling velocity under the conditions that the soft pipe connected to the jet bit must be with a diameter less than 10 mm and the pressure less than 50 MPa. The jet bits used for radial horizontal drilling now available mainly adopt multi-jet bit and combined round straight jet with swirling jet nozzle. Buset P et al. [6-8] proposed to adopt multi-jet bit to sidetrack drilling radial branch holes. Song Jian et al. [9-10] studied the relationship between the double jet flow structure which combines circular hole with a swirl vane with straight hole and the rock breaking characteristics. The variation of moving velocity with rock breaking depth and width by 7 holes jet bit under the pressure of 42 MPa had been analyzed by experiments by K.M.Kalumuck et al. [11]. The parameter design of multiple jets bit with uniform borehole distribution was suggested by Yue Guijie et al. [12] and the experiment on abrasive jet rock breaking characteristic of multi-jet bit was also conducted. Yang Weihua et al. [13] used numerical simulation method to analyze the rock breaking mechanism of combined jet by five-jets bit. The experimental study on rock breaking parameters of combined round straight jet with swirling jet nozzle was performed by Wu Wei et al. [14]. The studies above involve little experiments on rock breaking characteristics of multi-jet bit and its influence factors, especially the impact of confining pressure on rock breaking efficiency. In this paper, four kinds of multi-jet bits are designed to ensure the shape and size of drilling hole and the rock breaking efficiency of the jet bit. The effect of structural parameters (hole number, lateral orifice diffusion angle) and hydraulic parameters (erosion time, jet pressure, standoff distance, confining pressure) on the rock breaking efficiency of multi-jet bit was studied by experimental method, which can provide guidance for design of multi-jet bit in radial horizontal drilling.

2. Structure design of multi-jet bit

2.1. Working principles of multi-jet bit

The front and back jet produced by self-propelled multi-jet bit are both multiple jets. The main function of front jet is to break the rocks in order to open a borehole with certain diameter while the back jet is mainly to enhance the pulling force of the hydraulic jet bit. Meanwhile, the back jet can erode the well wall and remove cuttings to enlarge the hole. Multiple jets spray into the bottom hole with a big area, generating a discontinuous annular high impact area at the
bottom hole. The central nozzle plays a predominant role in rock breaking and other nozzles assisted to enlarge the borehole to form a maximum borehole diameter while ensuring the rock breaking depth. Rear lateral jet generates reverse thrust in the radial direction and the reverse thrust keeps self-balancing if the jet bit is centered since the uniform distribution of the back nozzle. While the jet bit is close to the bottom hole, the resistance of the back jet near the bottom side increases, leading to the increase of the reverse thrust which pushes the jet bit to the center until the reverse thrust of back jet is counterbalanced by the weight of jet bit. It can overcome the problem that the hose may be unstable at radial feeding if propelled by traditional external force [15-16]. Therefore, multi-jet bit always suspends in the drilled borehole that guarantees the borehole horizontal and straight and reduces the difficulty of well trajectory control.

2.2. The structure of multi-jet bit

Self-propelled multi-jet bit is a critical component of radial horizontal drilling, which not only has to break the rocks but also produce forward self-propelled force to the high-pressure hose. According to the hole number of forward jet, the jet bit can be divided into three types: five-holes, six-holes and seven-holes jet bit. They usually have six back nozzles. The main structural parameters are summarized here: backward orifice diameter \( d_b \), backward orifice diffusion angle \( \theta_b \), jet inlet taper angle \( \alpha \) and forward orifice diffusion angle \( \theta_f \), as shown in figure 1.

2.3. Diameter of the nozzle

According to the basic theory of fluid mechanics, the fluid flowed through the nozzle meets the law of energy conservation, assuming that the pressure near the internal and external area of the jet bit is evenly distributed respectively. As the distance between inlet and outlet crossed section of the nozzle is quite short, the pressure loss can be neglected. Based on Bernoulli equation:

\[
\frac{P_{in}}{\rho g} + \frac{v_0^2}{2g} = \frac{P_{out}}{\rho g} + \frac{v^2}{2g} + h_f
\]  

If the local head loss is expressed in the form of velocity head loss [17], the following can be obtained:

\[
h_f = \frac{\xi}{2} \frac{v^2}{2g}
\]  

Substitution equation (2) into equation (1) results in,

\[
(1 + \xi) \frac{v^2}{2g} = \frac{P_{in}}{\rho g} - \frac{P_{out}}{\rho g}
\]  

For all kinds of the nozzle, the value of Pin, Pout and \( v_0 \) is equal, thus the jet outlet velocity of each nozzle can be expressed by the central jet outlet velocity. It is assumed that the outlet velocities of central jet, lateral jet and back jet are \( v_1 \), \( v_2 \) and \( v_3 \) respectively, then:

\[
v_1 = \sqrt{\frac{1 + \xi_1}{1 + \xi_2}} v_i
\]  

\[
v_3 = \sqrt{\frac{1 + \xi_3}{1 + \xi_1}} v_i
\]  

The local head loss coefficient of the central vertical nozzle can be obtained according to the table in reference:

\[
\xi_1 = 0.5 \left( \frac{d_l^2}{d_i^2} - 1 \right)
\]  

The local head loss coefficient of central jet nozzle, \( \xi_1 \), is approximately equal to 0.5. Since there is a certain angle between the axis of lateral and back nozzle and the axis of jet bit, the local head loss coefficient will increase. Thus assuming that \( \xi_2 = 3 \xi_1 \), \( \xi_3 = 8 \xi_1 \).

The outlet diameters of central, lateral and back nozzle are \( d_c \), \( d_l \), and \( d_b \). Based on the mass conservation principle:

\[
\frac{\pi}{4} (n_1 d_c^2 + n_2 d_l^2 + n_3 d_b^2) = Q
\]  

Where \( n_1 \), \( n_2 \), \( n_3 \) are the hole number of central, lateral and back nozzle.

According to the equation deduction above, substitution equation (4) and (5) into equation (7), the outlet jet velocity of the central nozzle, impact pressure and internal pressure of the jet bit under different flow rates and nozzle diameters can be obtained. By analyzing and comparing these data, the optimized nozzle diameter can be selected.

2.4. The diffusion angle of back nozzle

Back nozzle provides traction force for the jet bit mainly through recoil effect. The smaller of the angle \( \theta_b \) between the axis of back nozzle and the jet bit is, the larger the component of recoil force in the horizontal direction will be. Since the back nozzle should have an effect of enlarging borehole, if \( \theta_b \) is too small, the effect will not be distinct. Meanwhile, the local head loss through the nozzle will increase if the angle becomes larger, which leads to the decrease of flow rate, jet outlet velocity and the recoil force. Considering all the factors above, the value for \( \theta_b \) is generally between 20° and 30°.

2.5. Other parameters

According to the structure size of the diverter in radial horizontal drilling and the result of ground test, the length of Multi-jet bit, \( l \), equals 8 to 10 times of \( d_e \), where \( d_e \) is the equivalent diameter of the jet bit. The forward orifice diffusion angle (lateral orifice diffusion angle), \( \theta_f \), is from 10 to 30°. The forward hole number is from 6 to 7. The forward nozzle diameter, \( d_f \), is from 0.6 to 0.8 mm. The backward hole number is from 5 to 6. The backward nozzle diameter, \( d_b \), is from 0.8 to 1.0mm. These structural parameters will be optimized combining with hydraulic parameters by rock breaking experiment.
3. Experimental set-up
The rock breaking experiments with multi-jet bit were carried out on the standard jet erosion apparatus. The experimental apparatus is mainly composed of water feeder, high-pressure pumps, high-pressure pipelines, pressure gage, and jet rock breaking workbench. The rock breaking experiments under atmosphere submerged conditions were conducted in the tank filled with water, as shown in figure 2. During the experiments with confining pressure, the water tank was replaced by the experimental device illustrated in figure 3, and the confining pressure was adjusted with the choke valve installed in the liquid outlet.

The main performance parameters of the experimental apparatus are described as follows:
1. High Pressure Pump: two piston pumps, with rated pump pressure 50 MPa, delivery capacity 120 L/mm, and power of motor 75 KW.
2. Core Example Holder: the holder is used to hold the core example during the rock breaking experiments. During the atmosphere pressure experiments, it was placed in the water tank. During the confining pressure experiments, it was placed in the experiment device shown in figure 3.
3. Jet Bit: the multi-jet bit nozzles, with the hole number from 3 to 9, were designed and manufactured in this study. From figure 4, the central hole is located in the center of the jet bit, with other holes distributed evenly around it. The overall open area of each multi-jet bit is the same and their equivalent diameter is 3 mm. As a result, the open area of single hole decreases with the growth of hole number.
4. Experiment Steps and Methods

1. Prepare all the rock samples using the construction cement in accordance with the ratio of sand to cement as 2:1. All the samples should be homogeneous. The evaluation indicator of water jet rock breaking efficiency includes: borehole depth, borehole diameter and rock breaking volume. The value of borehole diameter should be the largest diameter of the drilled holes. The borehole depth and diameter are measured by vernier caliper. The measurement of rock breaking volume adopts sand filling method and each sample should be measured three times and take the average.

2. Research on the influence of structural parameters (hole number, lateral orifice diffusion angle) and hydraulic parameters (erosion time, jet pressure, standoff distance) on rock breaking efficiency under zero confining pressure.

3. Study the influence of hole number, jet pressure and standoff distance on rock breaking efficiency under confining pressure. Through the experiments, when confining pressure is larger than 3 MPa and the jet pressure is 25 MPa, the rock breaking capacity is little, so the maximum value of confining pressure should be controlled within 3 MPa.

5. Results and Discussion

5.1. Influence of hole number on rock breaking efficiency of multi-jet bit

The effect of hole number on the shape of the erosion hole was studied. As shown in figure 5, under atmosphere submerged condition, the shape of the erosion hole becomes more round with increase of hole number. The erosion hole of each jet cannot connect fully with each other, if the hole number decreases. However, when the hole number is 9, the erosion hole connects fully with each other, and the shape of the erosion hole is very round. This indicates that the energy distribution of the multiple jets has the characteristics of local concentration and overall overlying, which can improve the rock breaking effect.

5.2. Influence of lateral orifice diffusion angle on rock breaking efficiency of multi-jet bit

Figure 6 shows the variation of rock breaking volume with lateral orifice diffusion angle generated by multi-jet bit with 7 holes under atmosphere submerged condition when the erosion time is 3 minutes, the standoff distance is 15 mm and the jet pressure is 20 to 35 MPa. With the increase of lateral orifice diffusion angle, the rock breaking volume first increases and then declines. Thus, an optimal diffusion angle exists and the optimal value of diffusion angle is 15° in this experiment. The main reason is that the axial velocity component of lateral jet is high and the radial velocity component is low when the lateral orifice diffusion angle is small. Consequently the main rock breaking form is impact breaking. The jet radial velocity component increases with the increase of the lateral orifice diffusion angle. And the main rock breaking form of radial velocity component is shear breaking, which is easier to break the rock than impact breaking [18]. Therefore, the borehole depth and rock breaking volume will increase. When lateral orifice diffusion angle is too large, single jet rock breaking will be dominated due to the dispersion of the multiple jets. Therefore, the synergy of each jet on rock breaking capacity is weakened and the borehole depth and rock breaking volume will be decreased.

5.3. Influence of erosion time on rock breaking efficiency of multi-jet bit

The length of erosion time has a direct effect on the feeding speed of the drill pipe in the process of radial horizontal drilling. The hole diameter, borehole depth and rock breaking volume will increase with
prolonging of erosion time under normal conditions. However, the increasing trend will be different with the variation of different jet bits and time periods. The relation curves between hole diameter, borehole depth, rock breaking volume and erosion time is shown in figure 7-9 when the confining pressure is zero, jet inlet pressure is 25 MPa and the standoff distance is 15 mm. With the extension of time, the hole diameter, borehole depth and rock breaking volume first increase sharply then tend to flatten. In former two minutes, they increase quickly and then go on steadily at the third minutes. This indicates that water jet rock breaking is a dynamic process with several stages. Analysis suggests that the impact force plays a major role in rock breaking in the early stage, while in the later stage, rock breaking mainly depends on the combined effect of scouring on the hole wall by returned fluid and hydraulic pressure to increase borehole depth and rock breaking volume. According to the influence of erosion time on rock breaking efficiency, three minutes will be selected as jet erosion time in further experiment. The increasing amplitude of hole diameter is small with the increase of erosion time and this varies a little with different jet bits, which demonstrates that the hole diameter of multi-jet bit is mainly influenced by diameter of the circle formed by center of the holes on the jet bit while is less affected by hole number.

5.4. Influence of jet pressure on rock breaking efficiency of multi-jet bit

Jet pressure represents the capacity of total water jet energy. With the increase of jet pressure, the water jet energy for rock breaking is increasing. The rock breaking capacity is reinforced due to the increase of the flow rate and water-horse power of water jet and the enhancement of the impact, shear and tensile force of water jet. Figure 10 shows the influence of jet pressure on rock breaking volume when confining pressure is zero, erosion time is 3 minutes and standoff distance is 15 mm. The rock breaking volume shows linear increase as the increase of jet pressure. In addition, the maximum rock breaking borehole diameters of multi-jet bit vary a little under the same jet pressure. It indicates that the hole number has little impact on external diameter of drilled hole. The external diameter of drilled hole is mainly influenced by hole distribution scheme on the jet bit. It is similar to other types of jet bit that when jet pressure increases, the jet effective standoff distance becomes larger to form a greater borehole depth. The increase of borehole depth plays a significant role on the enlargement of rock breaking volume.
5.5. Influence of standoff distance on rock breaking efficiency of multi-jet bit

Standoff distance is the key factor of rock breaking. The adjustment of standoff distance is critical for effective utilization of the jet energy when other conditions are constant. Without an appropriate standoff distance, even the jet pressure is higher than threshold pressure of rock breaking, the rock breaking efficiency cannot be improved. Under submerged and confining pressure condition, the attenuation of jet energy is sharply. Therefore, the standoff distance within the jet potential core cannot ensure the maximum rock breaking effect. Experiment indicates that there is an optimal standoff distance when multi-jet bit breaks rocks.

The variations of borehole depth and rock breaking volume with dimensionless standoff distance (ratio of real standoff distance to nozzle equivalent diameter) are illustrated in figure 11, 12 when the confining pressure is zero and jet pressure is 25 MPa. The borehole depth and rock breaking volume first increase and then decrease respectively with the increase of standoff distance. Thus an optimized standoff distance exists. The optimal standoff distance is 5 to 6 times of nozzle equivalent diameter in this experiment. The main reason is that the jets are independent within small standoff distance and each jet has not fully spread and mixed with each other. Each jet cannot work together to break rocks and the impact area is relatively small. While the standoff distance exceeds a certain scope, jet is severely retarded by medium around so that its energy decreases substantially and the jet pressure may even be lower than the threshold pressure of rock breaking. As a result, the rock breaking efficiency will become lower.

5.6. Influence of confining pressure on rock breaking efficiency of multi-jet bit

The relationship of rock breaking volume with the confining pressure is shown in figure 13 under confining pressure when erosion time is 3 minutes, standoff distance is 15 mm and jet pressure is 25 MPa. The rock breaking volume decreases as the confining pressure increases. The rock breaking capacity of the jet bit with one hole is higher than the jet bit with multiple holes. When the confining pressure is 2 MPa compared with 5 MPa for the jet bit with one hole, the borehole diameter decreases 16% and the rock breaking volume decreases 28%. The attenuation amplitude of multi-jet bit is larger. Taking the multi-jet bit with 9 holes for instance, it has barely any capacity for rock breaking when the confining pressure reaches 2 MPa. The attenuation of rock breaking effect is fast under a small confining pressure, when it reaches to a certain value, the attenuation slows down gradually.

The hole number of multi-jet bit have different influence on rock breaking efficiency under confining pressure. When the hole number increases, the hole diameter, hole depth and rock breaking volume decrease quickly with
the increase of confining pressure. Figure 14 shows the relationship of the reduction rate (evaluation indicator ratio of 2 MPa to 0.5 MPa) of three evaluation indicators for rock breaking efficiency with hole number when the confining pressure is 0.5 and 2 MPa respectively. The figure suggests that the influence of confining pressure on rock breaking efficiency with different hole numbers is distinct. The more hole number of the multi-jet bit is, the larger attenuation amplitude of borehole diameter, hole depth and rock breaking volume will be. The main reason is that hydraulic energy of each jet becomes smaller and the effective distance, which is lower than that of rock breaking threshold pressure, decreases after spraying out from the jet bit with increasing hole number. The rock breaking efficiency is largely influenced by confining pressure. The more hole number is, the smaller effective standoff distance of multi-jet bit will be.

There are two main reasons for the reduced rock breaking efficiency of multi-jet bit with the increase of confining pressure. One is that the presence of confining pressure leads to fast decrease of jet energy, thus the impact force of single jet declines and the energy on jet cross section is small resulting in reduction of impact area [19]. The other is that according to rock mechanics theory, the increase of confining pressure not only increases the rock strength but also increases its plasticity for rock samples with small porosity and permeability, which causes the rock changes from brittle failure into plastic failure. Both of the two changes will increase the threshold pressure of rock breaking.

6. Conclusions

1. Radial horizontal drilling is one of the novel effective methods for reservoir stimulation. One of the key points for improvement of radial horizontal drilling is to increase the borehole enlargement capacity of multi-jet bit and solve the problem of feeding and friction drag of the high pressure hose to improve rock breaking efficiency and enhance the feeding ability of the hose.

2. The rock breaking characteristics of multi-jet bit had been studied by experiments. It can be concluded that the form of drilled hole becomes more round with the increase of hole number on the jet bit. The form of borehole drilled by multi-jet bit with 9 holes is almost circular under experimental condition.

3. There is an optimal standoff distance for the multi-jet bit to obtain the largest rock breaking volume and borehole depth under zero confining pressure. The value is 5 to 6 times of the nozzle equivalent diameter in this experiment.

4. Confining pressure has a significant effect on rock breaking efficiency of multi-jet bit. The rock breaking efficiency declines sharply when confining pressure increases. As the increase of hole number, the rock breaking efficiency decreases under the same nozzle equivalent diameter. While ensuring the borehole diameter, the reduction of hole number contribute to improve rock breaking efficiency of multi-jet bit.

**Nomenclature**

- \( d_1 \) = backward orifice diameter, mm
- \( \theta_1 \) = backward orifice diffusion angle, degree
- \( d_f \) = forward orifice diameter, mm
- \( \alpha \) = jet inlet taper angle, degree
- \( \theta_f \) = forward orifice diffusion angle, degree
- \( P_{in} \) = the internal pressure of jet bit, Pa.
- \( P_{out} \) = the external pressure of jet bit, Pa.
- \( h_\xi \) = the local loss head through the nozzle, Pa.
- \( v_0 \) = the flow velocity inside the jet bit, m/s.
- \( v \) = the flow velocity at the outlet of the nozzle, m/s.
- \( \xi \) = the local head loss coefficient at the outlet of the nozzle.
- \( \xi_1 \) = the local head loss coefficients of central nozzle.
- \( \xi_2 \) = local head loss coefficients of lateral nozzle.
- \( \xi_3 \) = the local head loss coefficients of back nozzle.
- \( d_1 \) = the diameters of inlet of the nozzle.
- \( d_2 \) = the diameters of outlet of the nozzle.

**References**


Проектирование и анализ характерных особенностей многоструйного породоразрушающего долota при радиально-горизонтальном бурении

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Реферат

Многоструйное долото - это своего рода высокоэффективное струйное долото, применяемое главным образом в технологии радиально-горизонтального бурения. В статье описывается метод проектирования многоструйного долота и исследуется влияние его структурных (количество отверстий, угол рассеяния боковых отверстий) и гидравлических (период эрозионной обработки, давление струи, отклонение струй, гранниевые величины давления) параметров на эффективность разрушения пород, используя специально разработанное оборудование. Из экспериментальных результатов видно, что чем больше число отверстий в многоструйном долоте, тем более окруженным будет ствол скважины. Эффективность породоразрушения снижается с увеличением количества отверстий, при постоянном эквивалентном диаметре струйного долота. С увеличением угла рассеяния боковых отверстий эффективность породоразрушения сначала увеличивается, а затем уменьшается. Эффективность породоразрушения линейно растет с увеличением давления струи. Оптимальное отклонение от базы в 5 - 6 раз больше эквивалентного диаметра сопла, так что многоструйное долото может достичь наибольшего объема разрушения горных пород при приближении глубины скважины к нулевой отметке. Эффективность породоразрушения многоструйного долота резко снижается с увеличением горного давления. Вышеприведенные результаты могут служить руководством при проектировании многоструйного долота для радиально-горизонтального бурения.

Radial-horizontal qazıma üçün sükurdağdıcı çoxşırnaqlı baltanın layihələndirilməsi və ona maxsus xüsusiyyətlərin təhəlləsi

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