Hydraulic extension ability of radial jet drilling with multi-nozzles jet bit

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Abstract. Radial jet drilling technology, which utilizes hydraulic energy of jet to create multiple radial micro-laterals in different layers from the main borehole, has been used widely as an effective approach to enhance the oil recovery, and the extreme extension length of radial micro-laterals affects the effect of simulation directly. However, the prediction model for hydraulic extreme extension ability of RJD has been rarely studied. In this study, a modified model for hydraulic extreme extension ability is proposed based on the force analysis of RJD system and related calculation models for frictions are developed by theoretical and experimental methods. In order to obtain the maximum extension length, the influential factors including flow rate of drilling fluid, specifications of flexible hose, and structure parameters of jet bit are investigated. The results indicate that the hydraulic extension ability of RJD presents a significant positive correlation with the flow rate of drilling fluid and the inner diameter of flexible hose. Although an increase of the number of backward nozzles or its diameter can improve the extreme extension ability of RJD, there is still an optimal value for both the number and diameter of backward nozzles. Without sacrificing the rock-breaking and expanding ability of jet bit, the number of forward nozzles and the angle of backward nozzles should be minimized. Furthermore, a field case of RJD proves the prediction model is favourable for drilling engineering, with a model error of less than 8.5%.

1. Introduction
Radial jet drilling (RJD) technology is employed to provide multiple radial micro-laterals in different layers from the main borehole by utilizing hydraulic energy of jet, which has been used worldwide as a viable technique to enhance the oil recovery and obtained significant improvement in productivity [1-2].

The key components of RJD system consist of a multi-nozzle jet bit, a high-pressure flexible hose, a deflector and coiled tubing (CT) system, as shown in figure 1. High pressure water jet is generated from the multi-nozzle jet bit, and the forward jet is employed to crush the formation rock and create the lateral borehole while the backward one is used to drive the jet bit and widen the micro-lateral. That is, the diameter and the length of micro-laterals which are the key factors to oil and gas simulation are mainly determined by the forward and backward jet. The diameter of the micro-hole could not be adjusted arbitrarily due to the constraint of downhole space. Consequently, the extreme extension length of RJD becomes the only parameter that affects the effect of simulation. Therefore, the extreme extension ability of RJD should be studied in order to design the drilling operation and predict the simulation effect of RJD.
The extreme extension ability of RJD is restricted by many factors, such as formation characteristics, the capacity of drilling pump, hydraulic parameters and friction factors. And the hydraulic extension ability of RJD refers to the maximum length that micro-laterals reaches under restrict of hydraulic parameters such as the capacity of hydraulic equipment, pressure gradient of annulus pressure loss.

Numerous researchers have investigated the RJD technology, and significant achievements have been obtained on equipment, procedures, and applications of RJD [3-6]. However, the research on extreme extension ability of RJD especially the hydraulic extension ability has seldom been published. Buset analyzed the mechanisms of penetration and the pull force of self-induced nozzle [7]. However, the flow rate employed in experiment is unpractical in field application. Guo proposed a mechanical model of multi-nozzle jet bit, but the pulling force calculated by the model which exceeded 8000N was too huge to correspond to reality [8]. Ma proposed a calculation model for pressure loss in RJD [9]. However, the pressure loss in jet bit was not been studied. Wang et al proposed an extending force and hydraulics calculation model of RJD [10]. However, the extension ability of RJD was not been studied. A prediction model for maximum drillable ability of RJD was proposed by Chi [11]. The force analysis of flexible hose and jet bit in horizontal lateral was modeled and the jetting force of the jet bit was equal to the difference of the recoil force which was induced by water jets from the forward and backward directions. However, the prediction maximum length of the horizontal lateral is much less than that of the field application presented by Jain [12].Based on the preliminary research [7, 13, 14], the initial momentum of drilling fluid in jet bit was not been considered in the Chi’s calculation model of jetting force.

In this study, a modified model to predict the hydraulic maximum extension ability of RJD is proposed based on the research of Chi. The calculation model of recoil force is improved and the related computing models of resistance forces are developed by theoretical and experimental methods. In order to obtain the maximum hydraulic extension length of RJD, the influential factors of extreme extension ability are studied. Furthermore, the prediction model has been proved favorable for drilling engineering in field.

2. Calculation model of the hydraulic extension ability

2.1 Fundamental assumptions of calculation model
The hydraulic extreme extension ability of RJD is the maximum length that the horizontal lateral can reach by employing the energy of hydraulic jet. In RJD operation, fresh water is usually employed as drilling fluid and the flow rate of drilling fluid is relatively low compared with the conditional drilling. The calculation model of hydraulic extreme extension model is used in engineering applications, so the calculation model can be simplified based on the following assumptions:

(1) As shown in figure 1 the lateral is assumed to be horizontal and the high pressure flexible hose advances along the micro-lateral with no buckling. That is, the external forces on flexible hose in the vertical direction are balanced.

(2) The RJD is employed in shallow zone, soft formation or coal bed methane reservoirs. The pressure drop of jet bit in field work is able to satisfy the requirement of the rock-breaking threshold pressure. Some factors such as lithology, heterogeneity, fracture, fault, etc. are ignored in the calculation. That is the penetration of formation rock is not influenced by jet velocity.

(3) The CT with diameter of 25.4 or 38.1mm is usually employed in RJD and the Reynolds number of drilling fluid always exceeds 2000 in field work. So the drilling fluid flow in CT, flexible hose is assumed to be turbulent.

(4) Based on the laboratory test, diameter of micro-lateral induced by a chosen jet bit is fixed. To simplify the calculation, the distance to the rock is assumed to have no influence on the recoil force exerted by the forward and backward facing jets.

2.2 Force analysis of RJD system
According to the working principle of RJD, there are five external forces acting on the RJD system in horizontal direction: recoil force generated by water jet from forward nozzles and backward nozzles, \( F_r \); ambient pressure of drilling fluid, \( F_o \); friction between flexible hose and horizontal wellbore, \( F_{fw} \); friction between flexible hose and deflector, \( F_{fd} \); viscous force acting on RJD system due to drilling fluid flowing in the annulus between wellbore and high pressure hose, \( F_{fa} \). Where, the \( F_r \) is the driving force of jet bit and the others are the resistance. The analysis of forces on RJD system is shown in figure 2.

![Figure 2. Forces on RJD system.](image)

The resultant force on the RJD system along the horizontal direction can be expressed as:

\[
F = F_r - F_o - F_{fw} - F_{fa} - F_{fd}
\]

Resultant force \( F \) is the only power to drive the RJD system. When \( F \) is above 0, RJD system advances continuously and the friction acted on RJD increases consequentially until the value of \( F \) is equivalent to the friction. Then the length of lateral is the extreme extension ability of RJD system.

2.3 Calculation models of different forces

2.3.1 Recoil force of water jet
Based on the theorem of momentum, the sum of the external forces acting on the research object is equal to the rate of momentum change of that research object. As shown in figure 2 and figure 3, the
high pressure fluid in jet bit is considered to be the research object. Based on the preliminary model assumptions, the momentum equation of research object in x-axis is required and can be written as:

$$\int \rho_f v_x v_x dA = \sum F_x$$

(2)

Where, \( \rho_f \) is the density of drilling fluid; \( v_x \) is the velocity component of research object in x-axis; \( v_n \) is the flow velocity of drilling fluid; \( A \) is the cross sectional area of research object; \( F_x \) is the total external force acting on the research object in x-axis, which is induced by the wall of jet bit.

Figure 3. Sketch of the jet bit.

By integrating, equation (2) can be derived as follows:

$$F_x = \rho_f v_i Q_f - \rho_f v_f Q_f - (m-1)\rho_f v_f Q_f \cos \beta + n \rho_f v_b Q_b \cos \theta$$

(3)

Where, \( v_i \) is the velocity of drilling fluid in jet bit; \( Q \) is the flow rate of drilling fluid in jet bit; \( v_f \) and \( Q_f \) are the velocity and flow rate of the forward jets and backward jets respectively; \( m \) is the number of forward nozzles of jet bit; \( \beta \) is the angle between the axis of forward nozzle and jet bit; \( n \) is the number of backward nozzles of jet bit; and \( v_b \) and \( Q_b \) is the velocity and flow rate of forward jets and backward jets respectively; \( \theta \) is the angle between the axis of backward nozzle and jet bit.

Based on the Newton’s Third Law, the external force acting on the high pressure fluid by the wall of jet bit is equal to the force applied to jet bit by high pressure fluid, that is:

$$F_r = F_x$$

(4)

The velocity of drilling fluid in jet bit \( v_i \) can be obtained as:

$$v_i = \frac{Q}{A_i} = \frac{4Q}{\pi d_i^2}$$

(5)

Where, \( A_i \) is the inner sectional area of the jet bit, \( d_i \) is the inner diameter (ID) of the jet bit.

Based on the Bernoulli Equation, the flow rate and velocity of the forward and backward jets can be obtained as:

$$\begin{cases}
  v_f = v_b = \frac{4Q}{\pi (m d_f^2 + n d_f^2)} \\
  Q_f = \frac{CQ d_f^2}{md_f^2 + nd_f^2} \\
  Q_b = \frac{CQ d_b^2}{md_b^2 + nd_b^2}
\end{cases}$$

(6)

Where, \( C \) is the discharge coefficient of jet bit nozzles.

2.3.2 Ambient pressure of drilling fluid on the RJD system

The ambient pressures acting on the RJD system are balanced in the vertical direction, so its action area is the sectional area of the forward surface of jet bit \( A_o \). The ambient pressure can be expressed as:
\[ F_o = p_{out} A_o = \frac{\pi}{4} p_{out} d_o^2 \]  

(7)

Where, \( p_{out} \) is the ambient pressure of drilling fluid; \( d_o \) is the outer diameter (OD) of jet bit.

2.3.3 Friction between high pressure hose and horizontal wellbore

According to the classical friction law, resistance due to flexible hose moving in rough wellbore can be expressed as follows:

\[ F_{hw} = \mu q_{hb} L_h \]  

(8)

Where, \( \mu \) is the coefficient of sliding friction; \( L_h \) is the length of horizontal wellbore; \( q_{hb} \), the buoyant weight of flexible hose per unit length, can be defined as:

\[ q_{hb} = \left[ \rho_h + \frac{\pi}{4} \rho_f (d_{hi}^2 - d_{ho}^2) \right] g \]  

(9)

Where, \( \rho_h \) is the liner density of flexible hose; \( d_{hi} \) is the ID of flexible hose; \( d_{ho} \) is the OD of flexible hose; \( g \) is the gravity acceleration.

Based on equation (8) and equation (9), friction between flexible hose and wellbore is related to the sliding friction coefficient and the length of horizontal wellbore under the given flexible hose. Friction coefficient becomes the main factor to affect the friction when the flexible hose has been chosen. However, friction coefficient between polyurethane and concrete is employed as that between high pressure flexiblue hose and well bore in previous researches [10-11], which neglects the roughness of wellbore and differs from the field conditions. Due to the irregularity of borehole wall, it is rather difficult to establish a theoretical model to calculate the sliding friction coefficient.

An experiment is conducted to accurately measure the sliding friction coefficient between flexible hose and horizontal wellbore. The schematic diagram of friction coefficient test is shown in figure 4. The porous cuboid concrete blocks (shown in figure 5) adopted as the formation rock are tied up and placed to a horizontal plane with certain height. Then the mimic formation is drilled horizontally by the RJD on ground. The borehole in the concrete blocks is employed to conduct the sliding friction coefficient measurement experiment.

(a)  
(b)

Figure 4. Schematic diagram of the sliding friction coefficient test. a uniformly accelerated motion stage. b uniformly deceleration motion stage

Figure 5. Structures of mimic formation and borehole
The flexible hose filled with drilling fluid is placed in mimic lateral. Inlet and outlet of the flexible hose are sealed, one of which is connected to a string whose gravity is neglected. The other end of the string is connected to one object with a mass of \( m_1 \) through a fixed pulley. The initial height of the object from ground is \( x \). When the object is released from the height \( x \), the whole system will be in uniformly accelerated motion with the initial velocity of 0. According to the Newton’s second law of motion, the acceleration of this stage can be obtained by following equation:

\[
a_1 = \frac{m_1 g - \mu m_2 g}{m_1 + m_2}
\]  

(10)

Where, \( a_1 \) is the acceleration of the accelerating stage; \( m_2 \) is the mass of flexible hose filled with drilling water.

Let \( v_t \) denote the instantaneous velocity of flexible hose at the moment when the object reaches to the ground. The formula for uniformly accelerated motion of flexible hose can be written as:

\[
v_t^2 = 2a_1x
\]

(11)

The tension of the string on the flexible hose disappears after the heavy object lands on the ground, and then the flexible hose will be in uniformly decelerated motion under the sliding friction which is opposite to its movement direction. The acceleration of this stage \( a_2 \) can be expressed as:

\[
-\mu m_2 g = m_2 a_2
\]

(12)

Where, \( a_2 \) is the acceleration of the decelerating stage.

Let \( y \) denote the total sliding distance of high pressure hose in simulated wellbore, the formula for uniformly decelerated motion of flexible hose can be written as

\[
0 = v_t^2 + 2a_2(y - x)
\]

(13)

Combining equation (11) and equation (13) yields the following equation:

\[
-a_1x = a_2(y - x)
\]

(14)

The sliding friction coefficient can be obtained by combining equation (10), equation (12) and equation (14):

\[
\mu = \frac{m_1 x}{(m_1 + m_2)(y - x) + m_2 x}
\]

(15)

The results of tests with varied \( x \) and \( m_1 \) are listed in table 1. The arithmetic average value of experimental data is 0.209 and the maximum error of the sliding friction coefficient is 1.75%, so the arithmetic average value of experimental data 0.209 can be employed to the sliding friction coefficient between the high pressure flexible hose and horizontal wellbore. Accordingly, the friction between high pressure hose and horizontal wellbore can be expressed as:

\[
F_{fs} = 0.209 \times \left[ \rho_h + \frac{\pi}{4} \rho_f (d_{hi}^2 - d_{ho}^2) \right] L_h g
\]

(16)

| \( x(m) \) | \( m_1=0.5\text{kg} \) | \( m_1=0.6 \) | \( m_1=0.7 \) | \( m_1=0.8 \) | \( m_1=0.9 \) |
|---|---|---|---|---|---|
| 0.1 | 0.211 | 0.207 | 0.210 | 0.208 | 0.209 |
| 0.2 | 0.208 | 0.210 | 0.208 | 0.206 | 0.209 |
| 0.3 | 0.212 | 0.209 | 0.209 | 0.211 | 0.208 |
| 0.4 | 0.210 | 0.208 | 0.209 | 0.210 | 0.209 |
| 0.5 | 0.209 | 0.211 | 0.210 | 0.209 | 0.213 |
| 0.6 | 0.211 | 0.209 | 0.210 | 0.208 | 0.209 |
### 2.3.4 Friction between high pressure hose and deflector

The deflector resistance is tested according to the research of Chi [11], the structure and details of test deflector are shown in figure 6 and table 2. The results indicate that there is significant linear correlation between the resistance and drilling fluid pressure in the flexible hose, as shown in figure 7.

![Figure 6. Structure of the deflector.](image)

**Table 2. Parameters of deflector employed in test**

| Parameter | Length(mm) | Width(mm) | \(d\)(mm) | \(L_1\)(mm) | \(R\)(mm) | \(\alpha\)(deg) | \(\beta\)(deg) |
|-----------|------------|-----------|-----------|-------------|---------|---------------|---------------|
| Value     | 400        | 118       | 30        | 100         | 90      | 160           | 90            |

So the friction between high pressure hose and deflector can be calculated by the following equation:

\[
F_{fd} = a p_{fh} + b
\]  

(17)

Where, \(a\) and \(b\) are the correlation coefficient, related to the slope and intercept of fitting line, \(p_{fh}\) is the drilling fluid pressure in the flexible hose at the deflector, obtained by the hydraulics calculation of RJD system, defined as:

\[
p_{fh} = \Delta p_b + \Delta p_{fh} \frac{L_h}{L_{fh}}
\]  

(18)

Where, \(\Delta p_b\) is the pressure loss of jet bit, \(\Delta p_{fh}\) is the pressure loss in the high pressure flexible hose, \(L_{fh}\) is the length of flexible hose.

![Figure 7. Results of the deflector resistance test.](image)

\[
y = 0.9974x + 5.2671 \\
R^2 = 0.9985
\]
Under present experimental conditions, the values of $a$ and $b$ are 0.9974N/MPa and 5.2671N, respectively. By submitting the value of $a$ and $b$, the friction between high pressure hose and deflector can be obtained as:

$$F_{fd} = 0.9974 \times (\Delta p_b + \Delta p_{fh} \frac{L_{b}}{L_{fh}}) + 5.2671$$

(19)

2.3.5 Viscous force of drilling fluid

Due to the viscosity of drilling fluid, there is viscous force acting on high pressure flexible hose when it advances in the annulus filled with drilling fluid. Based on the theory of boundary layer, the viscous shearing stress $\tau$ can be expressed as:

$$\tau = \begin{cases} 
0.332 \rho_f \frac{v_a^2}{\sqrt{Re}} & \text{Re} \leq 2000 \\
0.0296 \rho_f \frac{v_a^2}{\sqrt{Re}} & \text{Re} > 2000 
\end{cases}$$

(20)

Where, $v_a$ is the flow velocity of drilling fluid in the annulus between horizontal wellbore and flexible hose, $Re$ is the Reynolds number.

So, the viscous force of drilling fluid can be expressed as:

$$F_{fa} = \frac{\pi}{4} d_{ho}^2 L_{ah} \tau$$

(21)

2.4 Extreme horizontal extension ability of RJD

Based on the force analysis of RJD system, the micro-lateral borehole reaches its extreme extension length when the value of resultant force $F$ decreases to zero. On the base of equation (1), that is:

$$F_r - F_o - F_{fa} - F_{fd} = 0$$

(22)

Submitting equations (3), (7), (16), (19), and (21) into equation (22) and formula translation yields:

$$L_{ah} = \frac{0.209 \rho_f \frac{v_a}{g} Q_f - \rho_f \frac{v_a}{g} Q_f - (m-1) \rho_f \frac{v_a}{g} Q_f \cos \beta + n \rho_f \frac{v_a}{g} Q_f \cos \theta - \frac{\pi}{4} p_{out} d_o^2 - 0.9974 \times \Delta p_{b} - 5.2671}{\frac{\pi}{4} d_{ho}^2 \tau + 0.9974 \times \frac{\Delta p_{fh}}{L_{fh}}}$$

(23)

2.5 Restrictive conditions of the horizontal extension ability

According to the working principle of RJD system, jet bit connected to flexible hose keeps moving forward under the backward jet self-propelled effect and the rock-breaking effect of forward jet. In order to maintain the RJD operation, the flow rate and circulating pressure loss should be lower than the rated capacity and pressure of drilling pump. Then, the working pressure of each RJD tools must be less than its yield pressure. That is, the flow rate and pressure loss should satisfy the following restrictive conditions simultaneously:

$$\begin{cases} 
\Delta p_f \leq p_r, \\
Q \leq Q_r, \\
p_{ci} \leq p_{cy}, p_{bi} \leq p_{bfi}
\end{cases}$$

(24)

Where, $p_r$ and $Q_r$ are the rated capacity and pressure of drilling pump, respectively; $p_{ci}$ and $p_{cy}$ are the drilling fluid pressure in the coiled tubing and flexible hose, respectively; $p_{cy}$ and $p_{bfi}$ are the yield pressure of coiled tubing and flexible hose, respectively; $\Delta p_f$ is the circulating pressure loss of RJD and can be calculated as follows:

$$\Delta p_f = \Delta p_{cs} + \Delta p_{cv} + \Delta p_{fh} + \Delta p_{b} + \Delta p_{ca}$$

(25)
Where, $\Delta p_{cs}$ and $\Delta p_{cv}$ are the pressure loss in spiral and vertical section of coiled tubing respectively, $\Delta p_{ca}$ is the pressure loss in annulus.

### 2.5.1 Pressure loss in coiled tubing

According to the research of Ma, the pressure loss of drilling fluid in spiral and vertical section of coiled tubing can be written as:

$$\Delta p_{cs} = 0.2596 \frac{\mu_f^{0.2} \rho_f^{0.8} Q^{1.8} L_{cs}}{d_{cti}^{4.7} D^{0.1}}$$

$$\Delta p_{cv} = 0.2399 \mu_f^{0.25} \rho_f^{0.75} Q^{1.75} \frac{L_{cv}}{d_{cti}^{4.7}}$$

Where, $\mu$ is the viscosity of drilling fluid, $L_{cs}$ and $L_{cv}$ are the length of spiral and vertical section of coiled tubing, respectively; $d_{cti}$ is the ID of coiled tubing.

### 2.5.2 Pressure loss in flexible hose

Wang proposed a calculation model for the pressure loss in flexible hose by considering its materials and specifications:

$$\Delta p_{fh} = \alpha \mu_f^{0.25} \rho_f^{0.75} \frac{L_{fh}}{d_{fwh}} Q^{1.75}$$

Where, $\alpha$ is the fictional-related coefficient, which is related to the materials and specifications of flexible hose. The flexible hose shown in table 3 is employed to modify the calculation model of pressure loss in flexible hose and its test length is 15m. The test results are shown in figure 8. The arithmetic average value of experimental data 0.4558 can be employed to the value of $\alpha$.

| Type         | No. | OD (m) | ID (m) | Total Length(m) | Yield Pressure(MPa) | Linear Density(kg·m⁻¹) | Reel Diameter(m) |
|--------------|-----|--------|--------|-----------------|---------------------|------------------------|------------------|
| Coiled Tubing| 1   | 0.038  | 0.032  | 2000           | 83                  | 2.733                  | 1.828            |
| Flexible Hose| 1   | 0.017  | 0.010  | 50             | 40                  | 0.521                  | /                |
|              | 2   | 0.014  | 0.009  | 50             | 40                  | 0.417                  | /                |

Table 3 Specifications of coiled tubing and flexible hose

![Figure 8. Test results of pressure loss in flexible hose.](image-url)
2.5.3 Pressure loss of jet bit
The pressure loss of jet bit is written as:

\[ \Delta p_b = \frac{0.5136 \rho_f Q^2}{C^2 (md_f^2 + nd_b^2)^2} \]  

(29)

2.5.4 Pressure loss in annulus
Pressure loss in annulus is the sum of the pressure loss in horizontal and vertical section, which is equal to the value of \( p_{out} \) on the basis of drilling hydraulics. Ma proposed a calculation model for pressure loss in annular space [9]. The research indicates that the pressure loss in annulus can be neglected because it only accounts for 0.37% of the total pressure loss.

3. Influential factors of the horizontal extension ability

3.1 Calculation parameters
Assuming that the depth of operating well is 1500m, the rated pressure of drilling pump is 70MPa. Fresh water is employed as drilling fluid, its density and dynamic viscosity are 1000kg/m\(^3\) and 1.005mPa·s. The specifications of coiled tubing and flexible hose are listed in table 3. The structure parameters of jet bit are specified in table 4.

| OD (m) | ID (m) | \( m \) | \( \beta \) (°) | \( d_f \) (m) | \( n \) | \( \theta \) (°) | \( d_b \) (m) | \( C \) |
|--------|--------|--------|----------------|-------------|-------|----------------|-------------|-------|
| 0.018  | 0.010  | 6      | 15             | 0.0007      | 8     | 30             | 0.001       | 0.8   |

3.2 Influence factors

3.2.1 Flow rate of drilling fluid
Relations between extreme extension ability of RJD and flow rate are shown in figure 9. The extension ability of RJD increases in an approximate linear with the flow rate of drilling fluid because the growth-rate of driving force of jet bit is greater than that of the resistance of RJD system with the increasing of flow rate. Thus, a larger flow rate of drilling fluid is favorable to obtain greater extension ability under the restrictive conditions. When the fluid pressure in flexible hose reaches its yield pressure 40MPa, the flow rate and extreme extension ability are 79.2L/min and 39.67m, respectively.
3.2.2 Specifications of flexible hose

Figure 10 shows the relation between the specifications of flexible hose and extreme extension ability. The extension ability of No.1 flexible hose is obviously greater than that of No.2 flexible hose at the same flow rate. The trend occurs because the pressure loss in No.2 flexible hose, which is positively correlated to the resistance due to deflector, is greater than that in No.1 flexible hose. When fluid pressure in flexible hose reaches its yield pressure, the extreme extension length of RJD with No.1 and No.2 flexible hose are 42.4m and 29.1m, respectively. Thus the No.1 or lager inner diameter flexible hose is suggested to be employed in field application.

3.2.3 Structure parameters of jet bit

(1) Number and angle of forward nozzles

The effect of the number and angle of forward nozzles are shown in figure 11. The extreme extension ability of RJD decreases sharply with the number of forward nozzles because the recoil force of water jet will be reduced with the increasing of the number of forward nozzles when the number of backward nozzles maintains constant. The result indicates that the forward nozzles generate an obvious negative effect on the extension ability. Therefore, the number of forward nozzles should be minimized under the premise of rock breaking capacity of jet bit. Meanwhile, the extreme extension ability is shown to marginally increase with the angle between the axis of forward nozzle and jet bit.

(2) Number and angle of backward nozzles

As shown in figure 12, the extreme extension ability of RJD increases with the number of backward nozzles, however its growth rate decreases. The improvement of the recoil force generated by backward jet induces this behavior. With more number of backward nozzles, the components of momentum in the horizontal direction, which are positively correlated to driving force, increase, while the flow rate of forward nozzles decreases relatively with the same flow rate of drilling fluid. Since the flow rate of forward nozzles affects the rock breaking efficiency of jet bit, thus the optimal number of backward nozzles is approximately 7-8.
Figure 10. Relationship between specifications of flexible hose and extension ability (No.1 jet bit)

Figure 11. Effect of the number and angle of forward nozzles on extension ability (Q=70L/min)

As shown, the extension ability decreases quickly with the angle of backward nozzles because the angle of backward nozzles has a significant influence on recoil force in the horizontal direction. Therefore, the angle of backward nozzles should be minimized without sacrificing the expanding ability of jet bit.

(3) Diameter of backward nozzles

The relationships between extension ability and the diameter of backward nozzles are shown in figure 13. When the diameter of forward nozzles is constant, the extreme extension ability increases with the diameter of backward nozzles, but its growth rate decreases. The driving force is increased with the increase of the diameter of forward nozzles, while the flow rate of forward nozzles decreases relatively when the flow rate of drilling fluid is constant. Thus, in order to obtain the maximum extension length, there is an optimal diameter of backward nozzles when a jet bit is designed.
Figure 12. Effect of the number and angle of backward nozzles on extension ability (Q=70L/min)

Figure 13. Relationship between extension ability and the diameter of backward nozzles (Q=70L/min)

4. Field application

Field test of RJD is carried out in the ZY oilfield in China. The parameters of the reservoir and Well P-23 are shown in Table 5.

| Well depth (m) | Producing zone(m) | Test zone(m) | Diameter of production casing(mm) | Thickness of production casing(mm) | Reservoir lithology (m) |
|----------------|-------------------|--------------|-----------------------------------|-----------------------------------|------------------------|
| 2452           | 2357.0-2379.7     | 2359.4-2360.2| 139.7                             | 7.72                              | Sandstone              |

The power of the high pressure pump employed in the test is 170kW, its rated pressure and the displacement are 100MPa and 80L/min, respectively. The specifications of coiled tubing are listed in Table 3 and its length is 2500m. The No.1 flexible hose listed in Table 3 is employed in the test and its length is 50m. The structure parameters of jet bit employed in test is listed in Table 6. The fresh water is adopted as drilling fluid. The depth of test lateral is 2359.4m. According to the hydraulic calculation model, the inner pressure in CT and flexible hose should always be lower than their inner yield pressure. So 70L/min is optimized the maximum flow rate. During the RJD, the pump pressure is
controlled at 43MPa. However, sharp increase of pump pressure occurs when encountering the hard rock in formation because of the heterogeneity. So the pump pressure in field test is 43-46MPa. After 164 minutes, the lateral footage is 33m. And it maintains the same length after many attempts. The extreme extension ability gained by the calculation model presented above is 35.8m. The error between calculation value and actual length is approximately 8.5%, which is acceptable in drilling engineering. However, the prediction extension length obtained by employing the calculation model proposed by Chi is 12.8m; the prediction value has a huge difference with the test result.

Table 6. Structure parameters of field test jet bit

| OD (m) | ID (m) | m  | β (°) | d_f (m) | n  | θ (°) | d_b (m) |
|-------|-------|----|-------|---------|----|-------|---------|
| 0.016 | 0.010 | 5  | 15    | 0.0008  | 8  | 25    | 0.0011  |

5. Conclusions

(1) A modified model for extreme extension ability is proposed based on the force analysis of RJD system. Resultant force $F$ is the only power to drive the high pressure flexible hose and jet bit. The RJD system advances continuously if the value of $F$ is greater than zero. The extreme extension ability of RJD is the micro-lateral length when the value of resultant force is equal to zero.

(2) A series of calculation models for frictions are established on the basis of theoretical and experimental methods. The coefficient of sliding friction between the micro-hole and flexible hose is obtained from the statistics in the experiments.

(3) The extreme extension ability increases in an approximately-linear manner with increasing drilling fluid flow, and a larger flow rate of drilling fluid is favorable to obtain greater extension ability under the yield pressure of equipment. To obtain the maximum extension length, flexible hose with larger diameter is suggested to be employed in field application.

(4) In order to achieve the maximum extension ability of RJD, the number of forward nozzles should be minimized under the premise of rock breaking capacity of jet bit. The angle of backward nozzles should be minimized without sacrificing the expanding ability of jet bit, and there is an optimal value for both the number and diameter of backward nozzles.

(5) The calculation model for extreme extension ability is proven to predict the extension length of micro-laterals and the model error is less than 8.5%.

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