Drilling Hydraulic Parameters Design Method under the Limited Circulating System Bearing Capacity Condition

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Abstract

Hydraulics design is important for achieving the maximum bit hydraulic horsepower or jet impact force and improving the bottom hole cleaning. The existing hydraulic parameters design method is suitable for the low pump capacity. As the large-power-and-high-pressure pump is widely used on the drilling site, the existing hydraulic parameters design method is not sufficient to make the drill bit obtain the maximum hydraulic energy. In this paper, a new hydraulics design method is presented, and a larger bit hydraulic horsepower can be achieved compared to the existing design method. A contrastive analysis under different modes of pump pressures is conducted using the new design method, which shows that the improvement of the limited pump pressure can significantly increase the bit hydraulic horsepower. The circulating system pressure bearing capacity should be improved as much as possible.

Key Words: Ground Pump, Circulating System, Bit Hydraulic Horsepower, Hydraulic Parameter, Design Method

1. Introduction

As the world energy consumption increases, considerable effort has been expended on how to explore and utilize energy resources [1–8]. Drilling is widely used to explore the onshore and offshore oil and gas across the world. Hydraulic parameters design is an important part of the drilling design, which aims to achieve the maximum bit hydraulic horsepower, clean the rock fragments near the bit, carry the drill cuttings to the surface, and improve the rate of penetration (ROP) under given ground pump conditions. Many studies [9–19] have been conducted on the hydraulic parameters design, but most of which focus on the bit and circulating system, not on the ground pump. As the development of the oil and gas exploration, drilling pumps with large power and displacement and high pressure are manufactured to meet the on-site needs [20–22]. The existing hydraulic parameters design method was designed based on the low pump capacity (i.e. low power and displacement, low rated pressure). Therefore, the existing hydraulic parameters design method needs further discussion. Furthermore, when the pump pressure increases, the pressure bearing capacity of the circulating system has limited the use of the pump pressure. It is necessary to investigate how to make full use of the capacity of the ground pump to maximize the drill bit hydraulic power.

2. The Existing Hydraulic Parameter Design Method and the New Method

The general steps of the existing hydraulic parameter design method are as follows [23]: (1) Determine the minimum displacement that ensures the drill cuttings to be carried to the surface; (2) Divide the entire wellbore into several well sections and calculate the circulating system pressure loss coefficient for each section; (3) Determine the pump cylinder diameter. Select the smallest
cylinder size whose rated displacement is bigger than the minimum cuttings-carrying displacement; (4) Determine the hydraulic parameter optimization criterion, accordingly calculate the first and the second critical depth, and then calculate the optimum displacement and determine the bit nozzle size and other jet parameters. In this study, the maximum bit horsepower is selected as the hydraulic parameters design criterion. The hydraulic design method for selecting other criterion such as the maximum bit jet force is similar.

In the step 3, the purpose of selecting small-diameter cylinder is to obtain a larger rated pump pressure to overcome the pressure loss of the drilling fluid in the circulating system. As the improvement of the pump capacity, the rated pressures of different-size cylinders are sufficient to meet the drilling requirements in most cases. The performance parameters of the 3NB1600 pump are shown in Table 1. When the circulating system pressure bearing capacity is smaller than the rated pressure of the pump cylinder, the maximum allowable operating pressure of the ground pump is actually the circulating system pressure bearing capacity. In this case, the pump displacement becomes the primary consideration instead of the cylinder size.

The bit hydraulic horsepower is a function of the pump displacement, and the optimum pump displacement can be found corresponding to the maximum bit hydraulic horsepower on the bit hydraulic horsepower—displacement curve, as shown in the example.

Based on the analysis above, the general steps of hydraulic parameters design under the limited circulating system pressure bearing capacity can be expressed as follows:

Step 1 and step 2 are similar with the existing design method.
Step 3: determine the optimum pump displacement corresponding to the maximum bit hydraulic horsepower through formulas or by drawing curves.
Step 4: choose the cylinder whose rated displacement is closer and larger than the optimum displacement with the rated pump pressure larger than the circulating system pressure bearing capacity.
Step 5: calculate other bit hydraulic parameters.

### 3. Comparison of the Two Design Methods

The analysis above shows that the existing hydraulic parameter design method should be improved when ground pump performance parameters change. The comparison of the new method with the existing method is shown in the example below.

The drilling parameters are as follows: two 3NB1600 drilling pumps, a 241.3 mm drill bit, 140 m drill collars with an outer diameter of 241.3 mm and inner diameter of 71.4 mm, internal flush drill pipes with an outer diameter of 139.7 mm and inner diameter of 118.6 mm. The circulating system pressure bearing capacity is 18 MPa based on common experiences; the circulating pressure loss coefficient of ground pipelines \( K_g \) is \( 1.07 \times 10^{-3} \) MPa.s.L\(^{-1}\); the fluid density is 1.60 g/cm\(^3\) at the depth of 3000 m; the plastic viscosity is 0.045 Pa.s; the minimum annular velocity is no less than 0.6 m/s.

The first two steps of the two design methods are similar:

(1) Determine the minimum cuttings-carrying displacement \( Q_a \).
The minimum annular velocity:

\[
V_a = \frac{18.24}{\rho d_h} = 0.472 \text{ m/s}
\] (1)

Because the minimum annular velocity is no less than 0.6 m/s, \( V_a \) takes the value of 0.6 m/s. Therefore, the minimum cuttings-carrying displacement:

\[
Q_a = \frac{\pi}{40} (d_h^2 - d_p^2)V_a = 18.24 \text{ L/s}
\] (2)

where \( \rho \) is the fluid density, g/cm\(^3\); \( d_h \) is the wellbore diameter, cm; \( d_p \) is the drill pipe outer diameter, cm.

(2) Calculate the circulating pressure loss coefficient at this depth.

<table>
<thead>
<tr>
<th>Cylinder size (mm)</th>
<th>Pump stroke rate (times/min)</th>
<th>Rated displacement (L/s)</th>
<th>Rated pump pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>120</td>
<td>51.9</td>
<td>20.7</td>
</tr>
<tr>
<td>180</td>
<td>120</td>
<td>46.6</td>
<td>23.1</td>
</tr>
<tr>
<td>170</td>
<td>120</td>
<td>41.5</td>
<td>25.9</td>
</tr>
<tr>
<td>160</td>
<td>120</td>
<td>36.8</td>
<td>29.2</td>
</tr>
<tr>
<td>150</td>
<td>120</td>
<td>32.3</td>
<td>33.2</td>
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<tr>
<td>140</td>
<td>120</td>
<td>28.2</td>
<td>38.1</td>
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<tr>
<td>130</td>
<td>120</td>
<td>24.3</td>
<td>44.2</td>
</tr>
<tr>
<td>120</td>
<td>120</td>
<td>20.7</td>
<td>51.9</td>
</tr>
</tbody>
</table>
The circulating pressure loss coefficient of the whole system at the depth of 3000 m:

\[
K_L = mD + a = 0.0158
\]

where \( \mu_{pl} \) is the fluid plastic viscosity, Pa.s; \( D_{pi} \) is the drill pipe inner diameter, cm; \( d_i \) is the drill collar outer diameter, cm; \( d_{ci} \) is the drill collar inner diameter, cm; \( L_c \) is the total length of the drill collar, m; \( B \) is an constant for inner flush drill pipe, which is 0.51655; \( K_c \) is the drill collar circulating pressure loss coefficient.

The next steps of the existing hydraulic parameter design method are as follows:

Choose the smallest-size cylinder while ensuring that the rated displacement is larger than the minimum cuttings-carrying displacement. In this example, select the 120 mm cylinder whose rated displacement is 20.7 L/s and rated pump pressure is 51.9 MPa, according to Table 1. Set 18 MPa as the limited pump pressure because the ground pump pressure is no more than 18 MPa.

The first critical well depth:

\[
D_{pc} = \frac{p_s}{2.8mQ^{1.8}} - \frac{a}{m} = 6404 \text{ m}
\]

Below the first critical well depth, the drilling pump works in the rated pump horsepower state, and the drill bit horsepower decreases with the increase of the pump displacement. The drill bit horsepower reaches its maximum value at the rated pump displacement, so the optimum pump displacement to achieve the maximum bit horsepower is the rated pump displacement. Because the depth of 3000 m is less than the first critical well depth \( D_{pc} \), the rated pump displacement 20.7 L/s is selected as the optimum displacement.

The circulating pressure loss at this displacement:

\[
\Delta P_L = K_L \cdot Q^{1.8} = 3.69 \text{ MPa}
\]

The bit hydraulic horsepower:

\[
P_b = \Delta P_b \cdot Q = (p_r - \Delta P_L) \cdot Q = 296.15 \text{ kW}
\]

The pressure drop at the drill bit:

\[
\Delta P_b = P_b/Q = 14.31 \text{ MPa}
\]

The drill bit nozzle flow area:

\[
A_0 = \left[\sqrt{(0.05Q^2)}/(C^2\Delta P_b)\right] = 1.61 \text{ cm}^2
\]

The jet velocity:

\[
V_j = 10Q/A_0 = 128.41 \text{ m/s}
\]

The jet impact force:

\[
F_j = \rho Q^2/(100A_0) = 4.25 \text{ kN}
\]

The next steps of the new hydraulic parameters design method are as follows:

When the drilling pump pressure is limited, the output pump pressure \( p_s \) is a constant of 18 MPa, so the bit hydraulic horsepower:

\[
P_b = p_r - P_L = p_s - K_LQ^{1.8}
\]

Let \( \frac{dP_b}{dQ} = 0 \), so \( \frac{dP_b}{dQ} = p_s - 2.8K_LQ^{1.8} = 0 \).

Therefore, the optimum displacement:

\[
Q_{opt} = \left(\frac{p_s}{2.8K_L}\right)^{1/8} = 28.16 \text{ L/s}
\]

Because \( \frac{d^2P_b}{dQ^2} = -5.04K_L\left(\frac{p_s}{28K_L}\right)^{0.8} < 0 \), the bit hydraulic horsepower corresponding to the optimum displacement is the maximum bit hydraulic horsepower. Therefore, the 140 mm cylinder is selected whose rated displacement is 28.2 L/s, according to Table 1.

The circulating pressure loss:

\[
\Delta P_L = (mD + a)Q^{1.8} = 6.43 \text{ MPa}
\]

The maximum bit hydraulic horsepower:

\[
P_b = \Delta P_b \cdot Q = (p_r - \Delta P_L) \cdot Q = 325.81 \text{ kW}
\]

Comparing the two methods, the bit hydraulic horsepower of the new method is 10.02% larger than the existing method, so the new design method will achieve a better bottom hole cleaning effect and larger ROP.

The curve of the relationship between the bit hydraulic horsepower and different displacements can be
drawn from Eq. (13), as shown in Figure 1. The dash lines indicate the values of the bit hydraulic horsepower corresponding to the rated displacements when selecting the two different sized cylinders. It can be seen from Figure 1 that selecting the 140 mm cylinder in the new design method can make the bit hydraulic horsepower achieve the maximum value under limited pump pressure while selecting the 120 mm cylinder cannot achieve it.

The comparison of the hydraulic design parameters when choosing different cylinders is presented in Table 2. It can be seen from Table 2 that when choosing the 140 mm cylinder rather than the 120 mm cylinder, the drill bit horsepower and jet impact force increase, which indicates better bottom hole cleaning when using the new design method. The drill bit pressure drop and the jet velocity decrease because the parasitic pressure loss in the circulating system increases as the displacement increases.

4. New Method Analysis

4.1 Comparison of the Bit Hydraulic Horsepower under Different Limited Pump Pressures Using the Same Drilling Pump

In the example, increasing the circulating system pressure bearing capacity from 18 MPa to 20 MPa with other parameters unchanged, calculate the maximum bit hydraulic horsepower under these two different limited pump pressures using the new design method, and the result is shown in Table 3, where $P_1$ is the bit horsepower corresponding to 18 MPa and $P_2$ is the bit horsepower corresponding to 20 MPa.

It can be seen from Table 3 that increasing the limited pump pressure can greatly increase the bit hydraulic horsepower because the increase of the pump power supply will directly provide more energy for the drill bit. Therefore, increasing the limited pump pressure is favorable for increasing the ROP.

4.2 Comparison of the Bit Hydraulic Horsepower under Different Ground Pumps

Redesign the hydraulic parameters in the previous example using the 3NB1000 drilling pump and the 3NB1600 drilling pump under the limited or not limited pump pressure. The limited pump pressure is assumed to be 18 MPa. Select the 140 mm cylinder for the 3NB1000 pump whose rate displacement is 27.1 L/s and rated pump pressure is 24.3 MPa. Select the 160 mm cylinder for the 3NB1600 pump whose rate displacement is 37.58 L/s and rated pump pressure is 39.3 MPa. The relationship among the maximum bit hydraulic horsepower at the optimum displacement, different well depths and different limited pump pressures is shown in Figure 2.

Figure 2 indicates that: (1) for the same pump, the maximum bit hydraulic horsepower under the not limited pump pressure is much larger than that under the

![Figure 1. Relationship between the bit hydraulic horsepower and displacements.](image)

<table>
<thead>
<tr>
<th>Cylinder size (mm)</th>
<th>Optimum displacement (L/s)</th>
<th>Drill bit horsepower (kW)</th>
<th>Pressure drop at the drill bit (MPa)</th>
<th>Jet velocity (m/s)</th>
<th>Jet impact Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>20.70</td>
<td>296.15</td>
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<td>128.41</td>
<td>4.25</td>
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<td>140</td>
<td>28.16</td>
<td>325.81</td>
<td>11.57</td>
<td>115.45</td>
<td>5.20</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Well depth (m)</th>
<th>P1 (kW)</th>
<th>P2 (kW)</th>
<th>P1 (kW)</th>
<th>P2 (kW)</th>
<th>P1 (kW)</th>
<th>P2 (kW)</th>
<th>P1 (kW)</th>
<th>P2 (kW)</th>
<th>P1 (kW)</th>
<th>P2 (kW)</th>
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<td>385</td>
<td>308</td>
<td>363</td>
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<td>271</td>
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</table>
limited pressure; (2) when the pump pressure is not limited, using a pump with larger rated pressure can get a larger maximum bit hydraulic horsepower; (3) when both of the pump pressures are limited, the maximum bit hydraulic horsepower for the 3NB1600 drilling pump is a bit larger than that for the 3NB1000 drilling pump at the shallow well section, but with the increase of the well depth, the maximum bit hydraulic horsepower for both pumps becomes consistent. The reason is that the rated displacement of the 3NB1600 drilling pump cylinder is sufficient to reach the optimum displacement at the shallow well section, while the rated displacement of the 3NB1000 drilling pump cylinder cannot, and hence the bit hydraulic horsepower using the 3NB1600 drilling pump is a bit larger than that using the 3NB1000 drilling pump. However, with the increase of the well depth, the optimum displacement corresponding to the maximum bit hydraulic horsepower decreases with the change of drilling parameters, and thus the rated displacements for both pump cylinders are larger than the optimum displacement. It can be seen from Eq. (14) that the optimum displacement only changes with the limited pump pressure, so the maximum bit hydraulic horsepower using the two different drilling pumps are consistent. Although the power capacity of the 3NB1600 drilling pump is larger than that of the 3NB1000 pump, but it cannot perform its maximum capacity because of the limitation of the circulating system pressure bearing capacity, which also reflects the importance of improving the circulating system pressure bearing capacity.

Although larger bit hydraulic horsepower, better cuttings-cleaning effect and larger ROP can be achieved with the increase of the pump capacity, the pressure bearing capacity of the ground pipelines and other drill tools should also be improved. Otherwise, the incidents of frequently breaking drilling tools will offset the benefits of using high pressure and power pumps [25].

5. Conclusions

(1) The existing hydraulic parameter design method that selects the small size cylinder to obtain a larger pump pressure to overcome the pressure loss along the wellbore is suitable for the low ground pump capacity.

(2) A new hydraulic parameter design method under the limited circulating system pressure bearing capacity is presented, and a larger maximum bit hydraulic horsepower can be achieved using the new design method.

(3) The maximum bit hydraulic horsepower using different ground pumps under limited or not limited pump pressures are analyzed. The effect of using the new design method greatly depends on the limited pump pressure. The circulating system pressure bearing capacity should be improved as much as possible.

References


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