Systematic Study on Hydraulic Cylinder of Farmland DTH Drilling Machine

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Abstract. Connecting and unloading rod is one of the important processes in the drilling process of DTH drilling rig. The unloading device not only affects the operator's labor intensity and safety, but also affects the efficiency of drilling rig and the service life of drilling rod. Therefore, the research and design of unloading rod structure is of great significance to improve the efficiency of DTH drilling rig. Firstly, the selection of unloading rod hydraulic cylinder is analyzed, including the calculation of main parameters, cylinder design, piston design and calculation, cushioning and exhaust device. Secondly, the clamp rod hydraulic cylinder is designed and calculated, including the structure of the clamp rod cylinder, the clamp force calculation of the clamp rod cylinder and the wall thickness calculation of the clamp rod cylinder. Finally, we set the structure and parameters correctly to increase the efficiency of the hydraulic cylinder of the down-the-hole drill in the field operation.

Key words: Unloading rod hydraulic cylinder; clamping rod hydraulic cylinder; design and calculation; down-the-hole drill.

1. Introduction
Connecting and unloading rod is one of the important processes in the drilling process of DTH drilling rig. The unloading device not only affects the operator's labor intensity and safety, but also affects the efficiency of drilling rig and the service life of drilling rod. Therefore, the research and design of unloading rod structure is of great significance to improve the efficiency of DTH drilling rig.

2. Selection of hydraulic cylinder for unloading rod
The function of hydraulic cylinder in the hydraulic system is to convert hydraulic energy into mechanical energy, so that the machine can realize linear motion or less than 360 degrees of reciprocating swing motion. The unloading rod device consists of a unloading rod cylinder and four clamping rod cylinders. When the unloading rod cylinder works, it pushes the upper clamp rod cylinder, and the clamp rod cylinder clamps the drill rod, forming a "hydraulic wrench" on the drill rod, which makes the drill rod rotate about 15 degrees, thus loosening the connecting threads between the drill rods, and smoothly
unloading the drill rod with developed rotation and reversal. According to the working condition of the unloading rod cylinder, the double-acting piston hydraulic cylinder is selected. The cylinder sketch is shown in Figure 1:

![Figure 1. Cylinder sketch](image)

The bottom of the unloading rod cylinder is connected with the hinged support fixed on the boom, and the other end is hinged with the upper clamp rod cylinder. The installation of the fixed unloading rod cylinder is hinged at both ends. According to the technical parameters of SWDB120 DTH drilling rig, the cylinder inlet pressure \( P \) is 21 MPa, the return pressure \( P \) is 1 MPa, and the pressure loss is neglected.

### 2.1. Calculation of main parameters of unloading rod cylinder

#### 2.1.1. Speed ratio calculation. Speed Ratio of Reciprocating Motion of Hydraulic Cylinder Piston:

\[
\phi = \frac{V_2}{V_1} = \frac{A_1}{A_2} = \frac{\pi D^2}{4} \left( \frac{\pi}{4} (D^2 - d^2) \right) = \frac{D^2}{D^2 - d^2}
\]

\( V_2 \) — Retraction speed of piston rod, m/s
\( D \) — Piston Diameter of Hydraulic Cylinder, i.e. Internal Diameter of Cylinder Barrel of Hydraulic Cylinder, m/s
\( d \) — Piston rod diameter, m

As the intake pressure of the hydraulic cylinder is 21 MPa, greater than 20 MPa, it can be seen from Table 1, we know that \( \phi = 2 \)

#### Table 1. Hydraulic Cylinder Oil Intake Pressure Gauge

| Nominal pressure, MPa | \( \leq 10 \) | \( 12.5 \sim 20 \) | \( \geq 20 \) |
|-----------------------|-------------|----------------|-------------|
| \( \phi \)             | 1.33        | 1.46           | 2           |

As the intake pressure of the hydraulic cylinder is 21 MPa, greater than 20 MPa, it can be seen from Table 1, we know that \( \phi = 2 \)

#### 2.1.2. Calculation of Piston Thrust: Piston thrust:

\[
F = P_1A_1 - P_2A_2 = \frac{\pi}{4} D^2 P_1 - \frac{\pi}{4} (D^2 - d^2) P_2
\]

\( A_1 \) — Piston rod less \( \frac{D^2}{D^2 - d^2} \) Side effective area, m²
\( A_2 \) — Effective area of piston rod side, m²
According to the technical parameters of SWDB120 drilling rig, the rotary torque is 2500, and the unloading moment $M$ is only three times of the rotary torque, then $M$ is more than 7500. \( N \cdot m \)

\[ M = F \cdot s \]  

Note: $s$——Unloading lever arm  
$s = 0.5m$  
$F \geq 15000N$

2.2. Design of cylinder barrel for rod unloading cylinder

There are eight commonly used cylinder structures, flange connection, external thread connection, internal thread connection, external half ring connection, internal half ring connection, tie rod connection, welding and steel wire connection. Flange connection is simple in structure, easy to process and assemble, but heavy in weight. Thread connections are lighter in weight and smaller in outer diameter, but the end structure is complex and special tools are needed for loading and unloading. The semi-ring connection has compact structure and light weight. When installed, the end enters the cylinder body deeply, and the sealing ring may be scratched by the edge of the oil inlet hole. The tie rod connecting cylinder block is the easiest to be machined, and its structure is universal, but its weight and size are large. The welding structure is simple and the size is small, but the cylinder block may be deformed.

2.2.1. Calculations of Cylinder Inner Diameter.

\[ F = \frac{\pi}{4} D^2 P_1 - \frac{\pi}{8} D^2 P_2 \geq 15000N \quad \Rightarrow \quad D \geq 30.5mm \]

Check mechanical design manual, take $D = 50mm$

According to cylinder bore $D=50mm$, piston rod diameter $d=36mm$

2.2.2. Calculation of Cylinder Wall Thickness.

Cylinder wall thickness is:

\[ \delta = \delta_0 + c_1 + c_2 \]  

$\delta_0$——Minimum strength requirement for cylinder material, m  
$c_1$——Tolerance margin of cylinder outer diameter, m  
$c_2$——Corrosion allowance, m

when $\delta/D \leq 0.08$ , A Practical Formula for Calculating Thin-walled Cylinders:

\[ \delta_0 \geq \frac{P_{max} \cdot D}{2 \sigma_p} \]  

$P_{max}$ —— Maximum working pressure in cylinder: 25MPa  
$\sigma_p$——Stress Required for Cylinder Materials, MPa  
$\sigma_b$——Tensile Strength of Cylinder Materials, MPa  
$n$——safety factor, under normal conditions $n=5$  
$\delta_0 \geq \frac{25 \times 50}{2 \times 120} = 5.21mm$

$\delta/D \leq 0.08 \quad \sigma \leq 4mm \quad \sigma \geq \delta_0 \quad \Rightarrow \quad \delta/D \leq 0.08 \quad \text{Not satisfying the conditions}$
\[ \delta / D = 0.08 \sim 0.3 \implies \delta_0 \geq \frac{P_{\text{max}} \cdot D}{2.3 \sigma_p - 3P_{\text{max}}} \quad (7) \]

Substitute data to draw conclusions
\[ \delta_0 \geq \frac{25 \times 50}{2.3 \times 120 - 3 \times 25} = 6.22 \text{ mm} \]

According to conditions \( \delta / D = 0.08 \sim 0.3 \), \( \implies \sigma = 4 \sim 15 \text{ mm} \),
Therefore, \( \delta / D = 0.08 \sim 0.3 \) Meeting the conditions
If \( \delta / D \geq 0.3 \), We can use formulas

\[ \delta_0 \geq \frac{D}{2} \left( \sqrt{\frac{\sigma_p + 0.4P_{\text{max}}}{\sigma_p - 1.3P_{\text{max}}}} - 1 \right) \quad (8) \]

or
\[ \delta_0 \geq \frac{D}{2} \left( \sqrt{\frac{\sigma_p}{\sigma_p - 3P_{\text{max}}}} - 1 \right) \quad (9) \]

According to model (8): \( \delta_0 \geq 12.14 \text{ mm} \)
According to model (9): \( \delta_0 \geq 14.08 \text{ mm} \)

According to conditions \( \delta / D \geq 0.3 \rightarrow \sigma \geq 15 \text{ mm} \), So \( \delta / D \geq 0.3 \) meeting conditions. Cylinder bore diameter: \( D_1 = D + 2\delta \).

Based on the above calculation, a mechanical design manual is available. \( D_1 = 70 \text{ mm} \)

2.2.3. Checking calculation of cylinder wall thickness. The rated working pressure should be lower than a certain limit value in order to ensure work safety:

\[ P_n \leq 0.35 \frac{\sigma_s (D_1^2 - D^2)}{D_1^2} \quad (10) \]

or
\[ P_n \leq 0.5 \frac{\sigma_s (D_1^2 - D^2)}{\sqrt{3D_1^4 + D^4}} \quad (11) \]

\( \sigma_s \) ——Yield Strength of Cylinder Materials, \( \sigma_s = 355 \text{ MPa} \)

According to model 10, \( P_n \leq 0.35 \frac{355 (70^2 - 50^2)}{70^2} = 60.8 \text{ MPa} \)

According to model 11, \( P_n \leq 0.5 \frac{355 (70^2 - 50^2)}{\sqrt{3 \times 70^4 + 50^4}} = 48.1 \text{ MPa} \)

The rated pressure is 21 MPa, which meets the above requirements. At the same time, the rated working pressure should be proportional to the full plastic deformation pressure in order to avoid the occurrence of plastic deformation:
\[ P_n \leq (0.35 \sim 0.42) P_{\text{Lr}} \]
Lr ——Pressure of Cylinder Cylinder with Complete Plastic Deformation, MPa

\[ P_{Lr} \leq 2.3 \sigma_1 \log \frac{D_1}{D} \]  

So \[ P_{Lr} \leq 2.3 \times 355 \log \frac{70}{50} = 119.3 \text{MPa} \]

So \[ P_n \leq 41.7 \sim 50.1 \text{MPa} \]

In summary, the wall thickness selection meets the requirements, cylinder diameter \( D_1 = 70 \text{mm} \), external diameter \( D = 50 \text{mm} \)

2.2.4. Cylinder length. Cylinder length:

\[ L = L + B + A + M + C \]  

1 - Maximum working stroke of piston rod, M  
B - Piston width, generally \((0.6-1) D, M\)  
A - Piston rod guide length, take \((0.6-1.5) D, M\)  
M-Piston Rod Seal Length  
C - Other Length  

Cylinder Cylinder Manufacturing and Processing Requirements:

(1) The cylinder inner diameter \( D \) is matched by H7 or H8, and the surface roughness is generally 0.16-0.32 um, which requires grinding.

(2) Heat treatment: tempering, hardness HB (> 241-285).

(3) The roundness, taper and cylindricity of cylinder inner diameter \( D \) are not greater than half of the tolerance of inner diameter.

(4) The tolerance of cylinder linearity is not greater than 0.03 mm in length of 500 mm.

(5) The perpendicularity of cylinder section \( T \) to inner diameter is not greater than 0.04 mm in diameter of 100 mm.

2.3. Piston design  
(1) Piston structure

The size of hydraulic pressure is related to the effective area of the piston. The diameter of the piston should be the same as that of the cylinder. So when designing piston, the main task is to determine the structure of piston.

The piston structure is selected according to the type of sealing device. Usually it can be divided into two categories: integral piston and hindrance piston. The integral piston can adopt piston rings, O-rings, lip rings, labyrinth seals, etc. The combined piston can adopt the combined seal rings, but its structure is complex and the processing workload is large. Piston seal type figure 2:
(2) Piston Size and Processing Requirements:
The piston width is usually 0.6-1 times of the piston outer diameter, but the type, number of seals and the size of guide rings should also be considered. Sometimes, the piston width can be determined according to the arrangement of the diaphragm ring. The outer diameter of piston is usually matched by f9. The coaxiality tolerance of outer diameter to inner hole is not more than 0.02 mm. The perpendicularity tolerance of end face and axis is less than 0.04 mm per 100 mm. The roundness and cylindricity of outer surface are generally less than half of the tolerance of outer diameter. The piston rod body adopts a solid rod and the outer end of the rod is round earrings.

(3) Strength calculation of piston rod
It can be seen from the foregoing that the diameter of piston rod is chosen d=36 mm. The piston rod is only subjected to axial thrust or tension under stable working conditions, so it can be calculated approximately by the simple strength formula of the straight rod under tension and compression load.

\[
\sigma = \frac{F \times 10^{-6}}{\frac{\pi}{4} d^2} \leq \sigma_p
\]  

\(\sigma_p\) ——— Allowable Stress of Materials, MPa \(\sigma_p = 100 - 110\)MPa

Substituting data into formulas 14, we can come to conclusion:

\[
\sigma = \frac{15000 \times 10^{-6}}{\frac{\pi}{4} (36 \times 10^{-3})^2} = 14.74\text{MPa} \leq 100\text{MPa}
\]

It can be seen from the above that the strength of piston rod meets the requirements.

(4) Piston rod material and technical requirements
The piston rod is quenched and tempered with 45 steel, and the quenching depth is usually 0.5-1 mm. The piston rod should slide in the guide sleeve, usually with H8/h7 or H8/f7. The tolerance of roundness and cylindricity is less than half of the diameter tolerance. The coaxiality tolerance between the Journal of the piston and the external aid is not more than 0.01mm. The tolerance of verticality between end face of shoulder and axis of piston rod installed with piston is not more than 0.04mm/100mm. Roughness of piston rod is generally 0.1-0.3 um. In order to improve wear resistance and rust resistance, chromium plating is needed on the surface of piston rod. The thickness of the plating is 0.03-0.05 mm.
2.4. **Buffer device**

The piston rod of the hydraulic cylinder has a certain mass, and it has a great momentum when it moves under the drive of hydraulic force. At the end of their stroke, when the rod head enters the end cap and bottom part of the hydraulic cylinder, it will cause mechanical collision, resulting in great impact pressure and noise. Buffer device is used to avoid this kind of mechanical collision, but the hydraulic pressure still exists, which is about twice the rated working pressure, which will inevitably seriously affect the temperature and normal operation of the hydraulic cylinder and the whole hydraulic system. Buffer device can prevent and reduce the impact of the piston and piston rod of hydraulic cylinder on the bottom of cylinder or end cap when they are in motion, and realize the decline of speed at the end of their stroke until it is zero. The working principle of the buffer device is to convert the kinetic energy into heat energy by throttling the oil in the low pressure chamber at the bottom of the cylinder, and the heat energy is brought out of the hydraulic cylinder by the circulating oil.

2.5. **Exhaust**

If the exhaust valve is not set properly or not, there will be air in the cylinder after the pressure oil enters the hydraulic cylinder. Because of the compressibility and hysteretic expansion of air, the vibration and creep of the hydraulic cylinder and the whole hydraulic system will be caused, which will affect the normal work of the hydraulic cylinder. In order to avoid this phenomenon, the exhaust valve must be installed on the hydraulic cylinder. Because the hydraulic cylinder is the last actuator of the hydraulic system, it will directly reflect the harm of residual air. The position of the exhaust valve should be reasonable, and the position of the hydraulic cylinder installed horizontally should be above the ends of the hydraulic cylinder body; the hydraulic cylinder installed vertically should be below the end cap, and should think through with the pressure chamber in order to remove the air in the hydraulic cylinder before installation and debugging.

3. **Design and calculation of clamping rod hydraulic cylinder**

3.1. **Clamp rod cylinder structure**

There are four clamping rod cylinders in the rod unloading device. The four clamping rod cylinders are identical except for one of the hinged supports connecting the end of the upper clamping rod cylinder with the piston rod of the rod unloading cylinder. The unloading cylinder is a two-stroke hydraulic cylinder, which can clamp the drill pipe for loose unloading and hold the impactor and bit at the same time. In short stroke, it plays a guiding role to the impactor when the drill hole is opened, and the guiding stroke should be appropriate and adjustable. Therefore, the clamp rod cylinder structure adopts the structure scheme as shown in Figure 3.

![Figure 3. Structural drawing of clamping rod cylinder](image-url)
He working principle of the structure is as follows:
When C cavity is filled with pressure oil and B cavity is returned to oil, the piston rod 1 of the clamp rod cylinder of this structure extends to clamp the drill rod or impactor; when B cavity is filled with pressure oil and C cavity is returned to oil, the piston rod retreats to loose clamp; when D cavity is filled with pressure oil, B cavity is returned to oil and C cavity is filled with oil, the piston rod extends to a positioned K port to make B and D cavities communicate, and the piston no longer extends (the extension position is adjusted by the adjusting rod 3), so that the drilling machine can open the hole. The piston rod retreats when oil is injected into the B chamber and returned to the C and D chambers. Therefore, the gripper with this structure can realize the functions of connecting and unloading drill pipe, drill bit and orienting control.

3.2. Clamping force calculation of clamping rod cylinder
The clamping force F of the clamping rod cylinder is:

$$ F = P_S A_C - P_B A_B $$  \hspace{1cm} (16)

$P_S$—System pressure regulated by pressure relief valve, MPa

$P_B$—Oil return pressure in B chamber, MPa

$A_C$—Effective Area of Oil Pressure in C Cavity, $m^2$

$A_B$—Effective Area of Oil Pressure in Cavity B, $m^2$

The force acting on the piston of the guide pin for drilling rig opening $F_1$:

$$ F_1 = P_{sl} A_D - P_B A_B - P_C A_C $$  \hspace{1cm} (17)

$P_{sl}$—System Pressure in Drilling Rig Opening, MPa

The clamping force F should satisfy the requirements that the clamping drill pipe does not slip when the rod is unloaded and that the drill tool in the drill hole does not slip when the rod is clamped:

(1) Unloading rod does not slip:

$$ F \geq \frac{M_{\text{max}}}{\phi_d \mu} $$  \hspace{1cm} (18)

$M_{\text{max}}$—The maximum torque required for threaded connection of unloading drill pipe can be approximately taken as rotary moment.

$\phi_d$—drill pipe diameter, $\phi_d = 89$mm

$\mu$—Friction coefficient between gripper and drill pipe, if $\mu = 0.2$

We put the data in the formula: $F \geq \frac{2500}{0.2 \times 0.089} = 1.4 \times 10^5 \ N$

(2) Clamp rod does not slip:

$$ F \geq \frac{W + H_{\text{max}} m_0}{\mu} g $$  \hspace{1cm} (19)

$W$—Percussion Bit Quality, mg
**H_{\text{max}}** —— Maximum depth of borehole, m  
**m_q** —— Quality of drill pipe per meter, kg/m  
Clamp rod cylinder inner diameter, outer diameter, piston rod diameter, inlet pressure, return pressure  
\[ P_1 = 1 \text{ MPa} \]  
According to the velocity ratio  
\[ D_2 = \sqrt{2} d_1 \quad (1) \]

\[
F = \frac{\pi}{4} D_2^2 P_2 - \frac{\pi}{4} d_1^2 P_3 \geq 1.4 \times 10^5 N
\]

\[ D_2 \geq 93.39 \text{ mm} \]

It is advisable to check the mechanical design manual  
\[ D_2 = 100 \text{ mm}, \quad d_1 = 70 \text{ mm} \]

### 3.3. Calculating wall thickness of clamping rod cylinder

A conclusion can be drawn by referring to the method of calculating the wall thickness of the unloading rod cylinder:  
\[ \delta / D_2 = 0.08 \sim 0.3 \text{ and } \delta / D_2 \geq 0.3 \]  
all meet the conditions,  
\[ D_3 = D_2 + 2 \delta \]  
according to  
\[ D_2 = 100 \text{ mm} \]  
Check the Mechanical Design Manual and draw conclusions:  
\[ D_3 = 121 \text{ mm} \]  
Inspection of Reference Unloading Cylinder Wall Thickness and Check of Piston Rod Strength,  
\[ D_3 = 121 \text{ mm}, \quad d_1 = 70 \text{ mm} \]  
all meet the strength requirements.

### 4. Conclusion

This paper deals with the design and calculation of unloading rod cylinder and clamping rod cylinder. Firstly, the basic parameters of the unloading rod cylinder are determined, the inner diameter of cylinder, the diameter of piston rod and the outer diameter of cylinder are calculated, and the wall thickness of cylinder and the strength of piston rod are checked. At the same time, the other parts of the cylinder, such as buffer device and exhaust device, are briefly introduced. The clamp rod cylinder is a two-stroke cylinder. According to the working principle of the clamp rod cylinder, the structure mode of the clamp rod cylinder is determined. At the same time, the parameters of the clamp rod cylinder are simplified by referring to the calculation process of the unloading rod cylinder.

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