Design and Simulation Study on Continuous Circulation Valve Drilling System

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Abstract: Continuous circulation valve (CCV) drilling is an important form of continuous circulation drilling (CCD), whose key technology lies in the design of CCV. In this paper, a T-type integrated triple valves is designed and developed, which integrates the by-pass pressure relief valve and the main channel three-way ball valve in the same principal axis section. The CCV can be switched up and down and bypass through manual adjustment mechanism, which achieves the switch between normal circulation drilling and bypass circulation drilling. In order to verify the rationality of the design, ABAQUS software is used to analysis the situation with different tension, pressure, bending, twist, internal pressure and external pressure. The result confirmed that the overall strength met the requirements. So as to analyze the feasibility of manually rotating hexagon wrench to adjust and switch the three-way valve, the maximum torque of T-type three-way valve is discussed by combining simulation analysis and numerical calculation, and the Switch t-type three-way valve can be realized manually. Further simulation verifies that the overall sealing is good of the three-way valve body when the three-way valve is opened and closed. The change of the diameter of T-type three-way valve causes the acceleration of liquid flow rate and the increase of mud internal pressure, which has certain impact on the three-way body. Generally, the three-way body has no influence on the flow flux of mud in the whole drill pipe. Finally, it is verified through field application that the T-type integrated three-way valve design is reasonable, and the simulation and calculation analysis reach the expected goal.

1. Introduction
Continuous circulation drilling (CCD) is a new drilling technology that ensures continuous injection of drilling circulation medium, maintains constant drilling cycle displacement and equivalent cycle density, and avoids complex accidents caused by downhole pressure fluctuations during single or vertical column and tripping process. According to the equipment used to achieve continuous circulation drilling, it is divided into continuous circulation drilling system and continuous circulation valve (CCV) drilling system. Among them, the continuous circulation valve drilling system is the most easily realized continuous circulation drilling method, in which the core device is a continuous circulation valve.

2. Research on design and manufacture of integrated three-way valve
2.1 Researches in domestic and foreign
Based on the researches of continuous circulation valve drilling systems [1-6], there are many different
types of continuous circulation valves, such as the first separation of ball valve type three-way valves used by NOV, and the E-CD system improved by the Italian ENI Group (ENI), the Continuous Flow System, etc., which are all applied. However, there are problems such as inconvenient operation and easy failure; China National Offshore Oil Corporation separation ball valve improvements were carried out in the HZ25-4-6 large displacement wells of Huizhou 25-4 oilfield, but the central valve plate was damaged by erosion. PetroChina Bohai Drilling Technical Service Company proposed that the central valve should be a ball valve, and the bypass valve was a continuous circulation valve with a plate valve structure, which was also applied\(^4\)–\(^7\).

2.2 Structural design
This study designed an integrated T-type circulation valve (see in Figure 1, assembly diagram of integrated T-type three-way valve), including three-way valve main body, three-way ball valve body, bypass valve, etc., the bypass valve is placed in the same position of the main shaft section of the three-way ball valve, the bypass pressure relief valve is integrated with the main passage ball valve, and the bypass pressure relief valve is integrated with the main passage ball valve, which becomes an integrated T-type ball valve, and its valve core becomes a three-way valve core 4 (see in Figure 1, an integrated T-ball valve). The three-way ball valve body is composed by a three-way ball valve 6 and an upper ball seat 5, a lower ball seat 10, a knob 7, a fastening bolt 2, an adjusting bolt 3, a fixed knob 9 and an auxiliary wave spring washer 4, a wave spring washer 11, and a hexagon socket adjusted screw 8 and so on. It can be used to adjust the pre-tightening force of the three-way ball valve. The three-way ball valve body connection knob has an adjusting mechanism, and the integrated three-way valve can be switched up and down and bypassed by this adjusting mechanism to realize the upper and lower opening and the bypass closing, and the upper and lower closing and the bypass opening, thereby performing the upper and lower and bypass switching to change between normal circulation drilling and bypass circulation drilling.

2.3 Three-way valve working process
Working process: First, the three-way valve is linked with the upper and lower drill pipe, the system enters the normal circulation drilling condition; Second, the three-way valve core is in the open position, the main channel is in the open state, the drilling fluid is in normal circulation; Third, the bypass circulation drilling condition is installed. Bypass continuous circulation joint, turn pressure relief plug 7, pressure relief by pressure relief plug and pressure relief mechanism, remove the pressure relief plug, link bypass circulation joint; turn the hexagonal adjustment screw 6 connected knob 5 to drive the three-way ball valve 4 to rotate 90°, the main channel three-way valve 4 is closed, and the third channel of the three-way valve is opened to the pressure relief valve position (see in Figure 2, the integrated T-type ball valve core), so the bypass line is opened and the drilling fluid is established through the bypass. The channel is kept in continuous circulation; after the standing root is completed, the knob 5 connected by the hexagonal adjustment screw 6 is rotated to drive the three-way ball valve 4 to rotate by 90°, and the main passage pipe is opened to enter the normal circulation drilling condition. The design advantage is that the hex socket adjusting screw can complete all the work, no need to install the opening bypass, the switching is convenient, and the structure is simplified.
2.4 Three-way valve design requirements
The new structure brings many new problems and puts forward higher requirements for the three-way valve. The system is designed as follows: 1. On the same section, open 4 holes, the tension, compression, bending and torsion strength of the three-way valve body need to meet the strength requirements, and at the same time The overall diameter does not exceed the maximum diameter of the column, ensuring that it is sent to the well; 2. The seal must be reliable, and the contact surface is not required to be too large. The maximum sealing pressure and the maximum rotating torque need to be considered. It can be applied to the ordinary hex wrench to easily rotate the adjusting screw, and avoid the use of the afterburner affects the working efficiency; 3. The influence of the circulating mud fluid flow, especially the fluid flow during the valve opening and closing process; 4. The overall development is convenient and reliable, and the cost is low.

3. T-type three-way valve modeling and structural strength analysis

3.1 Three-way valve modeling
The material used was 40CrMnMo, the modulus of elasticity was 205GPa, the shear modulus was 80 GPa, the Poisson's ratio was 0.254, and the yield strength was 750MPa. The ABAQUS software is selected and modeled strictly according to the three-way valve body structure diagram. The three-way valve body with corresponding thread is called model 1, the three-way valve body with circumferential space is called model 2, and the unit type with finite element analysis is 10 nodes for C3D10H. Tetrahedral second-order unit. Meshing: Using the free meshing method, the model meshing is shown in Figure 3. The total number of meshes is 112,287.

Considering the safety strength requirements of the three-way valve body, the simulation calculations of tension, compression, bending, torsion, internal pressure and external pressure are carried out respectively. Only the ultimate bearing capacity of the three-way valve body is considered for each working condition based on the fourth strength theory. Under different load conditions, the
structure does not yield and is the maximum load under such conditions.

Figure 3. Through the ontology grid division diagram

Figure 4. Schematic diagram of three-way body tensile constraint and load loading

3.2 Tensile capacity analysis
The three-way valve is subjected to the weight of the lower drill assembly and its maximum load is equal to the maximum hook load. This study used a 50-type drilling rig with a maximum hook load of 3150kN. Constraint: The degree of freedom in the Y and Z directions on the right end of the constrained structure, only the degree of freedom in the direction of the pulling force is released. The left end face is fully constrained. Loading conditions is: Using the static solver, the Laplacian iterative solution algorithm is used to calculate the overall strength of the three-way valve body. The tensile load is applied on the right end face, and the tensile load increment is 1kN. When the maximum Mises stress in the stress concentration part of the three-way valve body model reaches the yield limit, this calculation ends. The ultimate tensile load is 1632.2 kN.

3.3 Analysis of bending resistance
The three-way valve is subjected to the bending stress of the lower drill assembly, especially under conditions such as horizontal wells. Loading conditions is: Using the static solver, the Laplacian iterative solution algorithm is used to calculate the overall strength of the three-way valve body. The bending moment load is applied to the right end face, and the bending moment load increment is 1kN.m. When the maximum misses stress in the stress concentration part of the three-way valve body model reaches the yield limit, the calculation ends. The bending moment is the maximum bending moment load of the structure.

Analysis of the results: The mises stress distribution of the three-way valve main body is shown in Figure 5. According to the fourth strength theory, the equivalent stress misses stress reaches the yield limit. For safety considerations, the load at the stress concentration position of the entire three-way valve body model is the maximum tensile load, and the corresponding ultimate compressive load is 56.5 kN.m.

3.4 Torsion resistance analysis
The three-way valve is subjected to a maximum torque equal to the maximum torque of the rig, and is selected to be 8033N.m according to the Type 50 rig. Constraint: The degree of freedom in the Y and Z directions on the right end of the constrained structure, only the degree of freedom in the direction of the pulling force is released. The left end face is fully constrained. A distributed coupling constraint is applied to the right end face to the reference point ref1 to load the bending moment.
Figure 5. Mises stress distribution cloud diagram (stretching) at yielding

Loading conditions: Using the static solver, the Laplacian iterative solution algorithm is used to calculate the overall strength of the three-way valve body. The torque is applied to the right end face, and the torque load increment is 1 kN.m. When the maximum misses stress in the stress concentration part of the three-way valve body model reaches the yield limit, the calculation ends. At this time, the bending moment value is the maximum torque load of the structure, and the corresponding ultimate compressive load is 58.2 kN.m.

Table 1. CoMParison of the ultimate strength of the three-way valve body and the drill pipe

| Object      | Stretch /kN | Compressive /kN | Bending moment /kN.m | Torque /kN.m | Internal pressure /MPa | External pressure /MPa |
|-------------|-------------|-----------------|----------------------|--------------|------------------------|------------------------|
| Drill pipe  | 5862        | 5862            | 135                  | 158          | 316                    | 297                    |
| model 1     | 1632.2      | 1635.4          | 56.5                 | 58.2         | 115.7                  | 78.9                   |
| model 2     | 1588.3      | 1589.6          | 57.8                 | 58.8         | 110.5                  | 89.6                   |

It can be seen from Table 1 that the ultimate strength of the three-way valve main body is reduced to a certain extent compared with the drill pipe, and the bending moment and torque reduction are most obvious. When the working internal pressure is 35 MPa, the strength of the material reaches 248 MPa, which is much lower than the yield strength of the material of 785 MPa, which meets the safety requirements.

4. T-type three-way valve rotation torque analysis

Due to the large number of T-type integrated three-way valves, each drill pipe needs to be equipped with a three-way valve. According to the design requirements, it is necessary to achieve manpower under normal conditions. That is, the manpower relies on a hex wrench to rotate the hexagonal adjustment screw. Instead of relying on tools and equipment such as the force bar, so as not to reduce the efficiency, this requires the T-type three-way valve rotational torque analysis. The factors affecting the rotational torque include: the friction coefficient of the contact surface of the spherical surface, the pressure between the friction pair affected by the fastening bolt, the adjusting bolt and the corrugated spring, and can be adjusted.

4.1 Stress analysis

The bonnet and valve body need to be tightened when equipped. When the three-way valve is opened, the friction torque T1 of the thread pair and the friction torque T2 of the bonnet support surface are overcome. To get the maximum torque when the three-way ball valve is open, you need to calculate T1 and T2 separately as follows:

When the three-way ball valve is unscrewed, the torque is:

\[ T = T_1 + T_2 \]  
\[ T_i = F \alpha \frac{d}{2} \tan(\psi + \rho) \]

In the formula:
\[ \psi = \arctan \frac{P}{\pi d_2} \]  
--- Thread angle

\[ d_2 \] -- Thread diameter, unit: mm

\[ \rho' = \arctan f_i = \arctan \frac{f}{\cos \beta} \]  
--- Equivalent friction angle

\[ f \] -- Friction coefficient

\[ \beta \] -- Lateral angle

\[ T_2 = fF_ar_f \]  
--- (3)

\[ r_f = \frac{1}{3} \frac{D_1^3 - D_0^3}{D_1^3 - D_0^3} \]  
--- Equivalent friction radius

\[ D_1, D_0 \] -- Support surface (friction surface) outer diameter and inner diameter, unit: mm

Bring the above parameters into Equation 1, the torque is:

\[ T = F_a \frac{d_2}{2} \tan(\psi + \rho') + fF_a r_f = F_a \frac{d_2}{2} \tan(\psi + \rho') + \frac{1}{3} fF_a \frac{D_1^3 - D_0^3}{D_1^3 - D_0^3} \]  
--- (4)

When the working load pressure is 35MPa, the three-way valve body acts as an axial pre-tightening force on the twisting valve. When the valve is opened, it needs to overcome T1 and T2. T2 can be calculated through the structural drawing of the valve, and T1 needs to calculate the valve direction. Axial section force.

The three-way valve body is subjected to 35MPa internal pressure, and the three-way ball is in contact with each sealing structure. Therefore, the finite element simulation is used to calculate the overall structure, and an internal pressure of 35MPa is applied to establish a contact relationship between the contact surfaces. Through the finite element calculation, the section force of the valve is extracted and brought into the above formula to obtain the maximum torque.

### 4.2 Boundary conditions

Constraint condition: Fully constrain the two end faces of the three-way valve body structure to limit the movement of the three-way valve body. Loading conditions: Using the static solver, the Laplacian iterative solution algorithm is used to calculate the overall strength of the three-way valve body. An internal pressure load of 35MPa is applied to the three-way valve body. The constraint and loading are as shown in Figure 6.

### 4.3 Result analysis and section force extraction

According to the above model, the internal pressure 35MPa static finite element solution calculation is performed, and the settlement results are shown in Figure 7 and Figure 8.
Figure 6. 35MPa pressure load loading diagram of the three-way valve body.

Figure 7. 35MPa internal pressure loading three-way body ball Mises stress distribution

As shown in Figure 9, when the working internal pressure is 35MPa, the section force is 14.28kN, and the parameter $F_a$ is taken to obtain $T_1$. At the same time, $T_2$ is obtained by the formula 2, and the formula (4) is substituted as follows:

$$T = F_a \frac{d_2}{2} \tan(\psi + \rho) + fF_a r_f = F_a \frac{d_2}{2} \tan(\psi + \rho) + \frac{1}{3} \cdot fF_a \frac{D_1^3 - D_0^3}{D_2^3 - D_0^3}$$

$$= 118.03 \text{N} \cdot \text{m}$$

The thread is designed according to M58x2, $d_2 = 55.835$. Compute $\psi = 0.65 \rho = 7.89$, The friction coefficient is 0.12 according to the lubrication between steel and steel; $D_1 = 80$, $D_0 = 55$, and the equivalent friction radius is calculated as 34.14 (refer to Figures 1 and 2).
Figure 8. 35MPa internal pressure three-way body Mises stress distribution diagram

Figure 9. Axial section force of bolts at three-way ball valve with internal pressure of 35MPa

The 27 general internal hexagonal wrench is mostly 250mm (as the effective distance is 200 mm), and the force applied to the wrench is 540N. This force can withstand the maximum endurance of the manual rotary wrench and can be manually adjusted.

5. Sealing performance analysis

5.1. Simulation modeling and analysis

Constraint condition: Fully constrain the two end faces of the three-way valve body structure to limit the movement of the three-way valve body. Loading conditions: Using the static solver, the Laplacian iterative solution algorithm is used to calculate the overall strength of the three-way valve body. An internal pressure load of 35MPa was applied to the three-way valve body.

During the use of the three-way valve body, its sealing performance directly determines the continuous safety of the entire three-way valve body, so it is necessary to analyze the tightness of the three-way ball and the entire structure. The seal of the three-way ball is mainly determined by the following two factors: the grinding luminosity of the three-way ball, the sealing pressure, and the contact pressure of the three-way ball and the sealing structure.

According to the data provided by the drilling site, the sealing pressure of the three-way ball is 100MPa. The contact pressure of the three-way structure is mainly achieved by a wave spring. In order to obtain the pressure parameters required for the wave spring, we perform simulation calculations on the tightness of the structure. The finite element calculation model and boundary conditions are as follows.

5.1. Boundary conditions

Constraint condition: Completely constrain the two end faces of the three-way valve body structure, and limit the moving loading condition of the three-way valve body. Using the static solver, the Laplacian iterative solution algorithm is used to calculate the overall strength of the three-way valve body. Using multiple analysis steps to solve the calculation, the first step is to apply an internal pressure load of 35MPa to the three-way valve body. In the second step, the pressure provided by the model spring is approximated and solved by using the load increment of 1N.

5.2. Result analysis

The internal pressure is applied to the above model 35MPa, wave loads and the spring load force, static finite element calculation, calculation results shown in Figure 10.
Figure 10. Contact force distribution cloud diagram when the three-way body valve is open

With 35MPa working internal pressure, it can be seen from the above calculation results that when the three-way valve body valve is closed, the maximum contact pressure is 113.3MPa, and when the three-way valve body valve is opened, the maximum contact pressure is 103MPa.

6. Mud flow analysis

Due to the addition of a continuous cycle of 50 mm internal diameter, the diameter changes from 76 mm to 50 mm greatly, affecting the flow of the three-way valve body to the circulating mud. Mud is composed of tiny solids, liquids and various additives. It belongs to the plastic type of non-Newtonian fluid. The relationship between shear stress and shear rate is independent and irrelevant. The flow begins when the force is applied enough to break the characteristics of the network structure, which means the shear stress is proportional to the shear rate. In the tube flow, the continuity equation of the fluid and the principle of dividing the flow regime are consistent with the Newtonian fluid. The unsteady flow theory is also applicable to the study of mud flow in drilling. Therefore, the following assumptions and simplifications are made to the flow field: the mud is a one-dimensional Newtonian unsteady fluid; the mud is a uniform continuous incompressible flow; in the drill pipe, the mass points are symmetric with respect to the axis of the drill pipe.

Based on the above assumptions, we get the fluid model, setting the solver in the model to be a non-coupling implicit algorithm, the fluid to be a constant flow at this moment, and the liquid flow is a standard two-equation turbulence model, and select the energy equation. The boundary conditions set the inlet velocity is 5.31 m/s, the temperature is 313 K, and the turbulence intensity is 5%. In practical applications, different working conditions will match different drilling fluids, so the flow characteristics of the drilling fluid will also change. In this paper, the parameters of the drilling fluid are assumed by consulting the relevant literature. See in the Table 2 for the fluid performance parameters. The calculation results are shown in Figure 11-13.

| Fluid        | Density (kg/m³) | Isobaric heat ratio (J/(kg·K)) | Thermal Conductivity (W/(m·K)) | Viscosity (kg/(m·s)) | Entrance speed (m/s) |
|--------------|----------------|-------------------------------|-------------------------------|---------------------|----------------------|
| Drilling fluid | 1500           | 2800                          | 1.5                           | 0.001               | 5.31                 |
Figure 11. Vector velocity diagram of the mud in the three-way valve body

Figure 12. Pressure distribution inside the mud.

It can be seen from the above figure that when the inlet speed of the drilling fluid is 5m/s, the liquid flow rate is increased at the three-way valve body, and the maximum velocity reaches 8.22m/s, which is located inside the three-way valve body and the speed increases compared with the inlet speed by 64%, it has a certain impact on the three-way valve body. The internal pressure of the mud is shown in Figure 13. At the inlet, a certain increase of internal pressure occurs, with a maximum increase of 3.43pa. The internal pressure of the three-way has a certain pressure drop compared with the drill pipe, and the pressure drop amplitude is 2.42pa, which change is small, and the pressure change amplitude does not greatly affect the safety of the structure. After calculation, the three-way valve body has no effect on the flow of mud in the whole drill pipe. The drilling fluid flows evenly in the body of the three-way valve body, no eddy current phenomenon occurs, and the fluid is in a laminar flow state with good fluidity.
7. Field application
In this study, the T-type integrated three-way valve was applied in the complex section of the PY10-8-A1H large-displacement well in a certain block of the East of South China Oilfield in February 2016 [8,9], using 37 T-type integrated three-way valve short connecteds, all of which are hand-operated with hexagonal special wrenches. During the drilling process, the pumping pressure and displacement drilling pressure are relatively stable, and the equivalent circulating drilling fluid density (ECD) change rate during drilling is less than 3%. The whole drilling process achieved good results, and it was confirmed that the T-type integrated three-way valve was designed reasonably, and the simulation and calculation analysis reached the expected goal.

8. Conclusion
After the analysis above, the following conclusions can be drawn:
1. This paper designs a T-type integrated three-way valve, which integrates the bypass pressure relief valve with the main channel three-way ball valve body. It can be switched between up and down and bypass by manual adjustment mechanism to achieve switching between normal circulation drilling and bypass circulation drilling. The field drilling application achieved good results, which confirmed the reasonable design of the T-type integrated three-way valve, and simulation and calculation analysis achieve the expected goals.

2. Through ABAQUS modeling and simulation analysis, the tension, pressure, twist and bend of the three-way valve body are reduced to a certain extent compared with the strength of the drill pipe, but the overall strength requirement is met; when the drilling fluid passes through the three-way valve body, the speed is increased by 64%. The pressure is reduced by 2.42pa. The drilling fluid flows evenly in the body of the tee, and no eddy current phenomenon occurs. The fluid is in a laminar flow state and has good fluidity.

3. After calculation, the maximum torque provided by the bolt valve is required when the three-way valve body ball valve is opened is 118.03N•m, which can be manually operated and the overall sealing is good.

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