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Research article

Design of continuous circulation sub for gas drilling and the mechanical analysis on the sub body

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Abstract

Gas drilling, as an important part of underbalanced drilling, can increase drilling speed. But in the process of conventional gas drilling, it tends to cause cutting settlement, borehole collapse, sticking and other safety hazards because gas circulation has to be interrupted. Therefore, this paper presents a continuous circulation sub which can be installed and removed easily. With this sub, gas circulation will not be interrupted when drilling tools are connected and removed. This sub is composed of body, main valve, bypass valve and side entry sub. The structure design of its key components (i.e. main and bypass valves) were fulfilled. Based on statics analysis on the sub body, its force situations under extension, torsion and internal pressure were simulated by using the ANSYS finite element analysis software. It is shown that its stress distribution trend is consistent with its elastic–plastic mechanics analysis results. Stress concentrates around the two round holes of the sub body, and the maximum deformation amount is still at the stage of elastic deformation. The analysis results are in line with the elastic–plastic mechanics analysis results, and the requirement of body strength is satisfied. This paper provides a new program to guarantee the drilling safety of extended-reach wells, underbalanced wells and narrow-density window wells.

Keywords: Gas drilling; Continuous circulation sub; Main valve; Bypass valve; Sub body; Structural design; Strength check; Finite element analysis

During conventional gas drilling operations, interruption of gas circulation due to the makeup or breakout of the drill pipe may easily lead to cutting settlement, water production, borehole instability, kicks or other safety hazards [1]. The continuous circulation techniques may be deployed to maintain continuous gas circulation during the makeup of joints. In this way, stable gas circulation and continuous discharging of cuttings can be maintained to ensure uninterrupted drilling operations [2]. With the advancement of continuous circulation techniques and improvement of auxiliary facilities and techniques, continuous circulation techniques for gas drilling have attracted more attentions at home and abroad. These techniques play an increasingly important role in the exploration and development of oil/gas fields [3]. Since there are few researches on their application in gas drilling and there are limitations in their applications, this paper presents a continuous circulation sub for gas drilling through studies. The continuous circulation sub is characterized by simple structure and easy application. It may maintain continuous circulation of gas during drilling. In addition to enhancing drilling efficiency, the newly developed sub can effectively minimize drilling cost and eliminate relevant safety hazards. Accordingly, it lays a reliable foundation for the application of the continuous circulation techniques in gas drilling.

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1. Introduction of continuous circulation technologies

1.1. Continuous circulation technologies abroad

Continuous circulation techniques were proposed for the first time in 1995 by Maris International Corporation of the United States. The company initialized the plan for fabrication of the prototype and implementation of relevant tests in 2000. The plan gained firm supports from major international oil companies, such as BP, Shell and Total, etc. [4]. In subsequent efforts, BP tested the prototype of the continuous circulation system in 2003 [5], and ENI put these techniques into commercial application in the Agri Oilfield of Italy and the Port Fouad Oilfield of Egypt [6]. Currently, there are two types of continuous circulation technologies, i.e. continuous circulation system (CCS) and continuous circulation valve (CCV) [7]. Generally, continuous circulation systems are highly adaptable to common rigs. These systems are difficult to operate due to their complicated structures. In contrast, continuous circulation valves have advantages of simple structure and easy application. Since conventional makeup and breakout techniques can be deployed, continuous circulation valves have better applicability. However, since these valves will be deployed in the borehole together with drill pipes, severe operational environments may present high requirements for safety and reliability of such valves. Without protection of sealing chambers, these valves are also susceptible to safety accidents under high pressures.

1.2. Continuous circulation technologies in China

Though both technologies involve certain problems, continuous circulation techniques have advantages in maintaining open flow of drilling fluids and stabilizing borehole pressures without suspension of pumping operations. Consequently, continuous circulation techniques can effectively reduce the time required for drilling, minimize drilling costs and eliminate safety incidents induced by circulation interruption due to the makeup and breakout of the drill pipe [8]. For these reasons, continuous circulation techniques have attracted attentions of researchers in multiple companies and research institutes in China. Researches have been conducted on the above-mentioned two continuous circulation technologies by CNPC Drilling Research Institute, CNPC Chuanqing Drilling Engineering Company Limited, China University of Petroleum (Beijing), Yangtze University and other organizations/institutes. There are few researches with regard to continuous circulation techniques for gas drilling. Under such circumstances, the authors made in-depth researches on the continuous circulation sub.

2. Structural design of a continuous circulation sub for gas drilling

2.1. Main features

1) Help guarantee continuous circulation during drilling, eliminate pressure surge induced by the interruption of circulation and maintain stable bottom-hole pressure.
2) Help reduce the time required for removing cuttings in bottom hole assembly, and consequently, can enhance gas drilling efficiency.
3) Effectively reduce the time required for pressure build-up and releasing during the makeup or breakout of the drill pipe.
4) Expand the application scope of the gas drilling techniques in water-producing formations.
5) Promote the efficiencies of gas drilling in deep and super-deep wells and complex formations and reduce the possibility of safety accidents during drilling.
6) Being widely applied to under-balanced wells, narrow-density window wells and pressure-sensitive wells.

Generally, the continuous circulation sub may provide an effective way to drill wells in a safe and efficient manner.

2.2. Components

Major components of the circulation sub for gas drilling include sub body, main valve, bypass valve and side entry sub. During gas drilling, continuous circulation sub can be installed between two joints or between two stand pipes. As an integral part of the drill pipe, the sub may be lowered into the well. Specific number of circulation subs can be determined in accordance with the demands of the circulation system. See Fig. 1 for the structure of the sub.

2.3. Working principles

During normal drilling operations, drilling fluid flows into the lower parts of the drill pipe through the upper parts of the drill pipe and the continuous circulation sub. The continuous circulation sub has identical working conditions and functions with the drill pipe (Fig. 1). During the makeup and breakout of

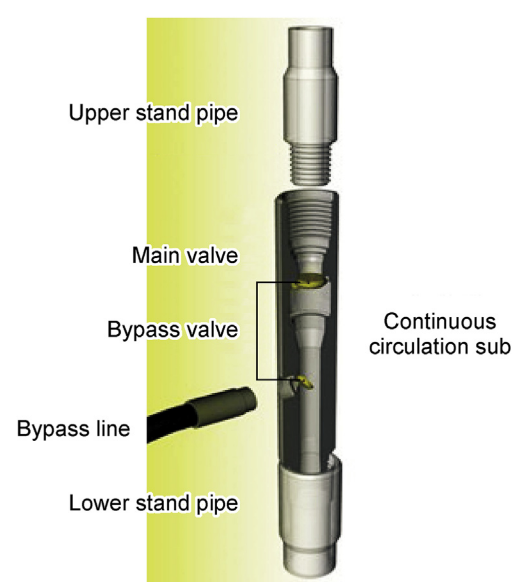

Fig. 1. Structure of the continuous circulation sub.

the drilling tools, the fitting of bypass line is connected with the bypass valve of the continuous circulation sub. By manipulating internal mechanism of the sub, the main valve in the sub can be closed to divert the drilling fluid into the bypass valve. In this way, continuous circulation of the drilling fluid at the bottom hole can be maintained during the replacement of the drilling tools. Upon completion of the makeup of the drill pipe, the main valve in the sub can be re-opened by using the internal mechanism to divert the drilling fluid through the main valve of the sub body. At the same time, volume of drilling fluid flowing through the bypass line can be reduced. The bypass valve may be closed automatically due to the differences between internal and external pressures. With the fitting of bypass line removed, normal circulation of the drilling fluids may be restored. Through the alternating utilization of the two flowing channels, continuous circulation of the drilling fluids can be maintained.

2.3.1. Structure and working principles of the main valve

Installed on the round holes of the sub body [9], the main valve is the core component in the direct flowing channel established by the continuous circulation sub. See Fig. 2 for the overall structure of the main valve. When the main value is put in the open position, orifice in the valve ball lines up with the main flowing channel to ensure an open channel. When the orifice of the valve ball rotates to the direction vertical to the flowing channel in the sub, the main valve is closed to stop the fluid circulation through the main channel of the sub. The valve ball and the knob in the main valve are connected with each other through grooves. Moreover, the upper and lower valve seats of the main valve can provide supports for the valve ball. According to the design, springs are deployed between the lower valve seat and the main valve body. Tiny up-and-down movements of the valve ball under differential pressures between the upper and lower ends may make the valve ball in floating conditions. In this way, the problems related to the incapability of manual valve operations under significant differential pressures between the upper and lower ends of the ball valve can be effectively solved.

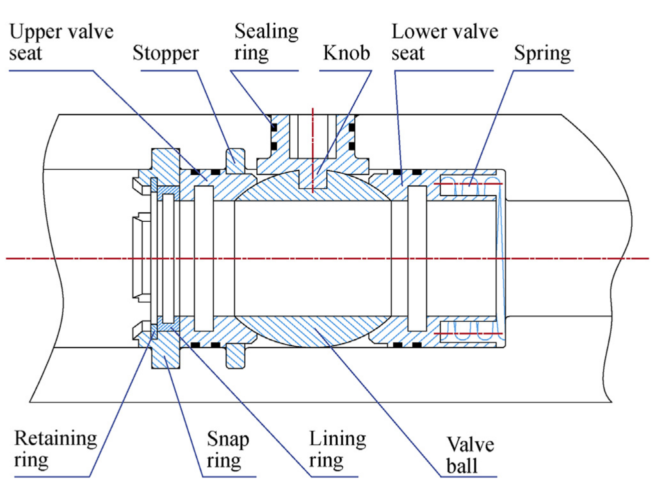

Fig. 2. Structure of the main valve.

2.3.2. Structure and working principles of the bypass valve

Installed on the lower round hole of the sub body, the bypass valve is a core component in the bypass flowing channel of the continuous circulation sub for gas drilling. Major components of the bypass valve include valve core, spring, valve plate, hexagon nut, washer and sealing ring, as shown in Fig. 3.

The bypass valve can be used to establish the connection with the bypass line and to divert the circulating gas in the bypass line into the internal channel of the sub body. When it is necessary to use the bypass line, the protective plug of the bypass valve can be removed and the fitting of the bypass line can be inserted into the seats of the bypass valve. With the side entry sub and sealing surface in the seats of the bypass valve closely attached to each other, proper seating between the side entry sub and the bypass valve can be established. High-pressure circulation gas imported to the controlling system of the bypass line can drive to open the bypass valve, and eventually to open the bypass valve.

3. Mechanical analysis of the sub body

During gas drilling, the continuous circulation sub is run into the hole together with the drill pipe. Downhole working conditions are extremely severe with great uncertainties in forces on the sub. High-strength tensional and torsional loads may lead to regional yield and highly-concentrated stresses regionally on high-risk sections around the round hole of the sub body. Accordingly, it is necessary to perform mechanical analysis on the continuous circulation sub body. In this study, some factors with minor impacts on the analysis of the sub body have been ignored to simplify the process.

3.1. Analysis on the tension, torsion and internal pressure of the sub body

3.1.1. Tensile strength

The tensile strength of the sub body can be determined as follows:

$$F = \sigma_s A \tag{1}$$

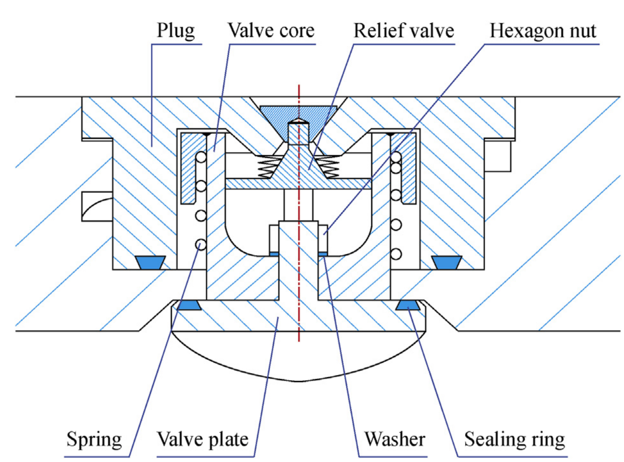

Fig. 3. Structure of the bypass valve.

in which, F is the minimum tensile strength, N; σ_s is the yield strength, MPa; A is the area of cross section, mm^2.

3.1.2. Torsion mechanical analysis

According to theories of material mechanics, the sub body can be seen as an empty spindle with the maximum shearing stress:

$$\tau_{max} = \frac{TR}{I_p} \tag{2}$$

in which, R is the maximum radius of the circular shaft, m; I_p is the sectional polar moment of inertia, cm^4.

According to the theory of energy strength, when$\tau_{max} = \tau_s = \frac{\sigma_s}{\sqrt{3}}$, the torque ($T$) is the minimum yield torque:

$$T = \frac{2I_p\sigma_s}{1000\sqrt{3}D}$$

in which, D is the outer diameter of the sub, mm.

3.1.3. Mechanical analysis of the internal pressures in the sub body

Whenever the sub body is subject to internal pressures, the stress on the internal walls of the sub body induced by such internal pressures should be lower than the yield strength of the materials to ensure its deformation still within the extent of elasticity. Generally, the sub body under internal pressures may be subject to primary stresses, i.e. circumferential stress σ_c, radial stress σ_r and axial stress σ_a.

Mathematic formulas for the 3 primary stresses on the sub body can be expressed by the Lame Formula:

$$\begin{cases} \sigma_c = \dfrac{p_i - p_o k^2}{k^2 - 1} + \dfrac{(p_i - p_o)k^2}{k^2 - 1}\left(\dfrac{r_i}{r_o}\right)^2 \\ \sigma_r = \dfrac{p_i - p_o k^2}{k^2 - 1} - \dfrac{(p_i - p_o)k^2}{k^2 - 1}\left(\dfrac{r_i}{r_o}\right)^2 \\ \sigma_a = \dfrac{\mathrm{p_i} - p_o k^2}{k^2 - 1} \end{cases} \tag{3}$$

With external pressure on the sub body close to zero, and with the sub body as an open cylinder:

$$\begin{cases} \sigma_c = \dfrac{p_i}{k^2 - 1}\left[1 + \left(\dfrac{r_i}{r_o}\right)^2\right] \\ \sigma_r = \dfrac{p_i}{k^2 - 1}\left[1 - \left(\dfrac{r_i}{r_o}\right)^2\right] \\ \sigma_a = \dfrac{p_i}{k^2 - 1} \end{cases} \tag{4}$$

in which, r_i is the inner radius of the sub body, mm; r_o is the outer radius, mm; p_i is the internal pressure, MPa; p_o is the external pressure (outside), MPa; k is the aspect ratio of the thick-wall cylinder, which can be determined in accordance with the inner and outer radius of the sub,$k = \frac{r_i}{r_o}$.

Circumferential stresses on the internal and external surfaces of the sub body can be expressed as follows:

$$\begin{cases} \sigma_{ci} = p_i \dfrac{k^2 + 1}{k^2 - 1} \\ \sigma_{co} = p_i \dfrac{2}{k^2 - 1} \\ \dfrac{\sigma_{co}}{\sigma_{ci}} = \dfrac{2}{k^2 + 1} \end{cases} \tag{5}$$

Clearly, when the sub is run into the hole together with the drill pipe during gas drilling, under pressures induced by internal gases, stresses in the thick walls distributed unevenly due to geometric structures of the sub. The maximum stress is expected to be presented on the inner wall. The higher aspect ratios of the thick-wall cylinder of the sub body, the more uneven distributions of stresses will be. On the other hand, values of aspect ratios of the thick-wall cylinder in the sub body may determine scales of stresses.

3.2. Stress concentration of the sub body

In structural design calculations of the sub, its maximum allowable load under normal working conditions should be taken as the calculation load, whereas strengths of other components can be calculated in accordance with the allowable stresses of corresponding materials. Generally, stress on the cross section with highest risk of these components shouldn't be higher than the allowable stress of the material.

$$\begin{aligned} &\sigma = [\sigma] \\ &[\sigma] < \frac{\sigma_s}{S} \end{aligned} \tag{6}$$

in which, σ is the computational stress, $[\sigma]$ is the allowable stress, σ_s is the yield stress, S is the material safety factor.

3.3. Finite element analysis of the sub body

When the main valve and bypass valve are installed, holes should be provided on the continuous circulation sub body. In this way, the sub strength is reduced and relatively high regional peak stresses are produced. Under such circumstances, positions with such openings on the continuous circulation sub body may have the lowest strength. During the course of downhole operations, the sub body may be subject to tensions, pressures, torsions and other loads. Regional yields produced around the opening of the sub body may significantly affect the fatigue strength and eventually lead to brittle rupturing or fracturing of the sub body.

3.3.1. Model construction

With the outer diameter of 178 mm, the newly designed continuous circulation sub is deployed together with the **Ø**139.7 mm drill pipe. The internal channel within the sub body serves as the access for gas circulation and for the deployment of tools during downhole operations. According to SY/T 5525-2009 "The upper and lower kelly cock of the rotary equipment on drilling industry", subs with the inner diameter of 71.4 mm and screw configuration of NC50 can be used. The internal structures of the sub body are required to conform to the installation size of the main valve, and the size of the side opening should be identical to the size of the bypass valve to be installed. The maximum diameter of the side opening is 52 mm. By using SolidWorks, models for the sub body can be constructed and simplified before the introduction of the model in ANSYS to generate the finite-element model (Fig. 4).

3.3.2. Material attributes and loads

A sub body can be made of 40CrMo with maximum strength of 1080 MPa, yield strength of 930 MPa, elastic modulus of 2.06×10^5 MPa, Poisson ratio of 0.3 and total strain of 15%. With consideration to gas drilling data in Dagang Oilfield, at the well depth of 3000 m, the newly designed continuous circulation sub is subject to maximum tension of 2720 kN, maximum working torque of 96 kN m and maximum internal circulation pressure of 35 MPa. During the loading of the finite-element model for the sub, overall loads composed by tensions, torsions and internal pressures should be used. For restricting the freedom degrees in 6 directions on the top end of the sub body, tensional loads should be deployed on the bottom end of the sub, torsional loads should be deployed on the internal surface of the bottom end of the sub and the internal pressures should be deployed on the internal surfaces of the sub.

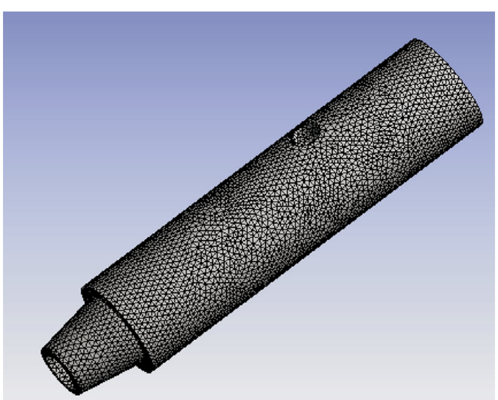

Fig. 4. Finite element model of the sub body.

3.3.3. Finite-element analysis results

See Fig. 5a for the Von Mises stress distribution on the sub body. The maximum stress on the sub body is 817.75 MPa, which is lower than the stress beyond the yield strength of the 40CrMo material. In addition, peak stresses are concentrated in small areas around the openings on the sub body. With the distribution trend of stresses coincided well with the elastic–plastic mechanics analysis results, it can be seen that areas around the openings on the structural components are susceptible to stress concentrates.

See Fig. 5b for the distributions of strains on the sub body under combined loads. It can be seen that the maximum strain is observed around the opening of the main valve on the sub body. With the maximum deformation amount still in elastic deformation stage of the material and with the minor deformation around these two holes, requirements for the design of the sub can be properly satisfied.

4. Conclusions

1) Basic structures and working principles of a newly designed continuous circulation sub were reviewed to highlight the structural designs for the main valve, bypass valve and other core components.
2) Finite element analysis was made on the sub body by using ANSYS. It can be seen that stress distribution trends coincided well the with elastic–plastic mechanics analysis results and areas around openings on the structural components are susceptible to stress concentrates. In addition, stresses in areas further away from the opening areas are lower. With the maximum deformation amount of the sub body still in elastic deformation phase of the materials and with the minor deformation around the two openings, the newly designed sub body has sufficient strength and rigidity. With design requirements properly satisfied, the sub can be used safely with high reliability.

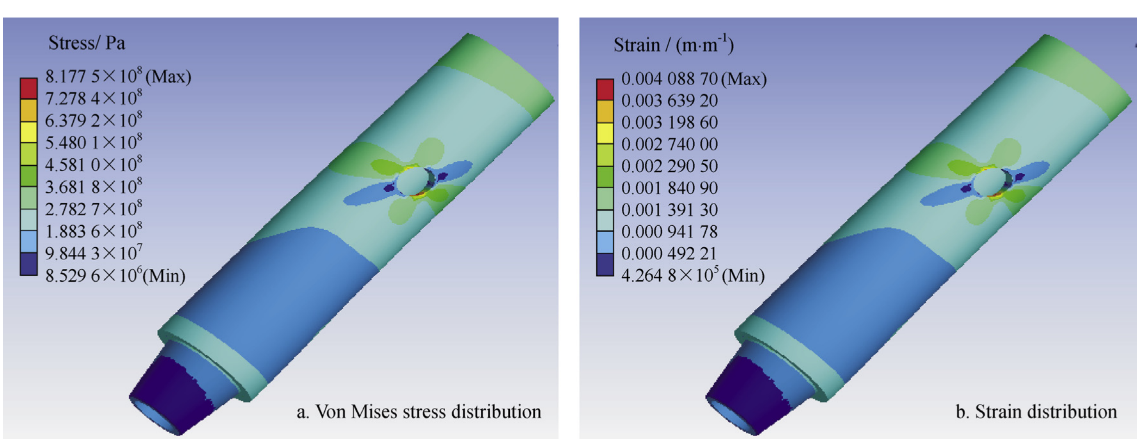

Fig. 5. Von Mises stress & strain distribution on the sub body.

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