Structure Design and Sealing Performance of Downhole Emergency Packer

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Abstract. In the drilling process of offshore exploration wells and high-risk wells, the possibility of high-pressure overflow and kick increases greatly when encountering unknown or inaccurate formation conditions. If it is not handled properly, it may cause catastrophic accidents. Overflow and kick are the early warnings of blowout accidents, and the wellhead blowout preventer can be shut off first to cope with such emergency conditions. However, once the bottom hole high pressure spreads to the wellhead, it may bring safety risks to the wellhead emergency disposal. In this work, a new type of downhole packer while drilling was designed to quickly seal the annulus when high-pressure fluid appears underground. ABAOUS software is also used to simulate the sealing performance of the rubber cylinder, and analyze the stress changes of the rubber cylinder during the setting process. When the working stress is 10MPa, the maximum Mises stress of the rubber cylinder is 14.3MPa, and the contact stress of the rubber cylinder presents a "shoulder protrusion" distribution. By comparing the stress changes in the rubber cylinder with or without a metal skeleton, it was found that the overall contact stress with a metal skeleton will increase, which has a good impact on the sealing of the rubber cylinder.

Keywords: Downhole emergency packer; structure; setting effect; metal skeleton.

1. Introduction

In the drilling process of offshore exploratory wells and high-risk wells, the formation condition is generally unknown or the prediction is inaccurate, and the possibility of high-pressure overflow and well kick is greatly increased. Overflow and kick are early warnings of blowout accidents, it will have serious consequences once the overflow or kick evolves into a blowout accident [1]. To reduce the occurrence of blowout accidents, the packer can be installed on the drill pipe when running down the well. In case of downhole overflow, the emergency packer can effectively prevent the high-pressure liquid in the lower annulus from flowing to the wellhead, and prevent the annulus from the packer to the wellhead from high pressure, thus reducing the probability of blowout and wellhead operational risk [2].

Downhole packers mainly include compression and expansion packers. The setting of compression packers is achieved by compressing the rubber cylinder from the gravity

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or hydraulic load of the string. The sealing performance depends on the contact stress generated by the rubber cylinder compressing the wellbore, and is suitable for small gap annular sealing. The sealing of expansion packers relies on pressing outward the rubber cylinder to well fit the casing pipe by the liquid insider. The sealing performance depends on the stress generated by the compression of the rubber cylinder and the casing pipe, and is suitable for sealing annular spaces with large gaps [3, 4]. The earliest invention of downhole packers can be traced back to 1980 [5, 6]. Rune designed an expansion packer and used it in the field of Glen Oilfield [7]. Alyami et al. used water swelling elastomers WSR to study the sealing effect of the water expansion packer, and proposed an LRFDbased external pressure vessel design method [8, 9]. As the main sealing element of the annular packer, the sealing performance of the rubber cylinder directly determines the setting effect of the downhole packer, especially in high-temperature and high-pressure environments [10]. Zhang et al used a genetic algorithm to determine the optimal structural parameters of nylon cord rubber according to the field operation, which improved the sealing performance of the rubber cylinder [11]. Hu optimized the structural parameters of the rubber cylinder of the compression packer by analyzing the failure mechanism and provided a better selection of rubber materials [12, 13]. Zhang et al. established the model of steel-strip PEMFCs and analyzed the stress-strain distribution of sealing systems in single-cell and multi-cells structures under three different working temperatures [14].

When a well kick and high-pressure overflow occurs during drilling, the ram blowout preventer can be started to forcibly pull out the downhole emergency blowout preventer after shutting in the well. The ram blowout preventer can be used to forcibly trip in achieving emergency plugging of the outer annulus of the drill pipe. The emergency annulus plugging can effectively prevent high-pressure fluid from spreading to the wellhead, and win valuable time for platform emergency disposal. Therefore, a downhole emergency blowout preventer is designed based on the above principles in this work, and the setting effect of the blowout preventer is simulated using the finite element method to obtain the contact stress and Mises stress changes with or without a metal skeleton rubber cylinder. According to the comparison of simulation results of the rubber cylinder setting process and the sealing inspection process, it is found that the metal skeleton can significantly improve the setting effect. At the same time, the structure of the metal skeleton has been optimized to make the metal skeleton in the elastic stage before and after the setting, achieving the purpose of reuse.

2. Structure Design of Emergency Packer Setting Effect Evaluation

2.1. Overall Structure of Packer

To realize the plugging of high-pressure overflow in the downhole, the emergency packer was designed with the overall structure shown in Figure 1. The emergency packer for includes the center pipe, one-way valve, inner and outer rubber cylinders, metal skeleton, and pressure-released hole. The central pipe is a hollow tubular structure with an internal flow path, with threaded joints at both ends for connecting other downhole tools. A setting fluid passes through a liquid inlet located on the side wall near the upper end of the central pipe, and the one-way valve to the gap between the central tube and the rubber cylinder. The rubber cylinder is pressured open to achieve the setting. A pressure-released hole is located at the side wall near the lower end. When the drill pipe is lifted,

the pressure-released hole communicates with the gap between the central tube and the rubber cylinder. The high pressure inside the rubber cylinder is released, and the packer is unsealed. Support rings and shoulder protectors are provided at both ends of the packer rubber cylinder, and the extension portions at both ends of the inner rubber cylinder form a compression fit through the upper sleeve. The metal skeleton is integrated with the inner and outer rubber cylinders through vulcanization to increase the stiffness of the packer.



Figure 1. Structure of the packer (1- center pipe, 2- liquid inlet, 3- one-way valve, 4- outer rubber cylinder, 5- metal skeleton, 6- inner rubber cylinder, 7- pressure-released hole).

2.2. Working Principle

After the emergency packer is lowered to a distance below the wellhead, a soluble ball is thrown into the drill pipe and pressurized on the ground. When the wellbore is pressurized to a predetermined value, the fluid inlet mechanism is opened, and the fluid in the center pipe enters the gap between the packer rubber cylinder and the center pipe passing through the fluid inlet and one-way valve. The pressure squeezes the rubber cylinder outwards to seal the outer annulus of the drill pipe, achieving the sealing purpose, as shown in Figure 2. The rubber sleeve shoulder of the packer is made of a metal plastic material with good ductility and is designed in serrated shape. The serrated structure can increase the friction between the packer and the shoulder during the setting process, and prevent the rubber sleeve from being damaged and extruded due to the high pressure in the lower annulus. When the packer needs to be unsealed, the central pipe can be lifted and the pressure-released hole at the central pipe connects with the gap between the packer rubber cylinder and the central pipe, and the pressure inside of the emergency packer can be released. The unsealing is completed from the deformation recovery of the rubber cylinder.



Figure 2. The setting process (a. initial stage; b. start sealing; c. complete sealing).

3. Setting Effect Evaluation

3.1. Material and Methods

In this work, ABAQUS software was used to simulate the sealing process of the rubber cylinder. Due to the symmetry of the model, the downhole packer is simplified to an axisymmetric two-dimensional planar model, as shown in Figure 3. Q235 steel is used for casing and metal seat. The materials of inner and outer rubber cylinders are NBR, and the tensile strength is 28MPa. Moony-Rivlin constitutive model is used to express its deformation with specific parameters listed in Table 1. In the process of establishing finite element models, the finite element type is CAX4H, a four-node bilinear axisymmetric quadrilateral element.

The main technical parameters of the emergency packer are: the plugging pressure is 10MPa, and the sealed annular space is between the casing pipe 9 ⁵/₈ "(outer diameter 244.48 mm, inner diameter 216.5mm) and the 5" drill pipe (outer diameter 127mm). Due to the annulus limitation between the drill pipe and casing pipe, the inner and outer diameters of the packer rubber cylinder are 148 mm and 198 mm, respectively, and the thickness of the rubber cylinder is 25 mm. The finite element models of packer models with and without metal frameworks were established respectively, to evaluate the impact of metal frameworks on the sealing effect.

Structure name	Inner diameter/mm	Outer diameter/mm	Material constant
Central tube	118.00	148.00	
Casing pipe	238.00	298.00	
Rubber cylinder seat	148.00	198.00	
Rubber cartridge	148.00	198.00	C_{10} =1.87, C_{01} =0.95

Table 1. Relevant parameters of calculation mode.



Figure 3. Finite element mode.

3.2. Finite Element Analysis Results

Figure 4 shows the change curve of the Mises stress and contact stress at the middle section of the rubber during the setting process. As the rubber cylinder expands towards the inner wall of the casing pipe due to the setting pressure, the curve can be divided into three stages, namely, the OA stage (pre-contact extrusion), AB stage (just contact), and

BC stage (complete setting). During the extrusion stage before contact, it is evident that the Mises stress gradually increases, reaching the maximum of 3.74 MPa after contact with the casing pipe. Since the rubber cylinder does not contact the casing pipe, the contact stress is 0 in the OA stage. When in contact with the casing pipe, the Mises stress of the rubber cylinder stabilizes at 3.74 MPa. After that the contact stress rapidly increased, indicating the close contact between the rubber cylinder and casing pipe. At BC section, the Mises stress at the middle part of the rubber here remains unchanged, but the contact stress continues to increase due to the presence of the setting pressure. At this stage, the contact stress and the stress inside the casing pipe gradually increase, indicating the eventually complete setting is achieved. Figure 5 depicts the contact stress between the rubber and casing pipe, the contact stress gradually increases and reaches its maximum 10.3MPa at complete sealing.



Figure 4. Stress variation during setting.

Figure 5. Contact variation change during setting.

Figures 6-7 show the Mises stress changes and contact stress changes at different stages. At the beginning of the setting, the Mises stress in the middle of the rubber cylinder is the largest. Due to the setting pressure on the rubber cylinder, contact stress is generated at the contact area between the rubber cylinder and the upper and lower rubber cylinder seats. At the initial contact stage, with the increase of the contact area between the rubber cylinder stress gradually increases, and the contact stress begins to appear at the contact area.

During the complete setting stage, the contact area between the rubber cylinder and the casing pipe slowly increases, and the Mises stress does not increase after the middle part of the rubber cylinder contacts the casing pipe. Due to the tension at both ends of the rubber cylinder, the maximum Mises stress occurs at the contact part between the two ends of the rubber cylinder and the upper and lower rubber cylinder seats. But the maximum contact stress is mainly distributed at the contact part between the rubber cylinder and the sleeve. Due to the application of setting pressure, the rubber cylinder expands and deforms, reducing the thickness of the rubber cylinder in contact with the sleeve. Due to the contact stress between the two continue to increase. After setting, the maximum Mises stress occurs on the casing, reaching 37.0MPa, and the maximum contact stress reaches 12.1MPa, which occurs at the contact area between the rubber cylinder and the casing pipe.



A. extrusion stage B. start the contact phase C. complete setting stage D. complete sealing Figure 6. Mises stress at different stages



Figure 7. Contact stress at different stages.

3.3. Evaluation of the Setting Effect

After the packer is set, the outer wall of the rubber cylinder completely adheres to the inner wall of the casing. However, whether the expansion of the rubber cylinder can effectively prevent the upward flow of high-pressure fluid at the bottom and achieve the true sealing effect, it is necessary to test the setting effect of the emergency packer. In this paper, the following methods are used to check the sealing of the packer after setting. According to the actual stress situation of the packer, in the model after setting, the setting pressure of 10 MPa on the inner side of the rubber cylinder remains unchanged, and a high-pressure fluid pressure of 10 MPa is applied to the bottom of the rubber cylinder that seals the annulus, as shown in Figure 8.



Figure 8. Finite element model of sealing test.

Figure 9 depicts the stress distribution of the rubber cylinder in the sealing test. Due to the pressure difference between the high-pressure fluid at the bottom and the setting pressure, the two ends of the rubber cylinder in contact with the casing after setting have undergone significant deformation. Select the outermost side of the rubber cylinder as the path to quantitatively analyze the impact of high-pressure fluid at the bottom on the stress and deformation of the rubber cylinder, as shown in Figure 10. It can be seen that the Mises stress on the rubber cylinder has two peaks, corresponding to a maximum of 7.1 MPa at 50 mm-110 mm and a maximum of 17.1 MPa at 650 mm-700 mm section, respectively, while the maximum displacement occurs at 50 mm-150 mm section and a maximum of 9.3 mm and 15.3 mm at 600 mm-700 mm section. Large deformation occurs at both ends of the rubber cylinder where not in contact with the casing, while the deformation and stress of the rubber cylinder in the middle sealing area are equal to zero, as shown in Figure 10. The pressure difference had no impact on the sealing performance of the rubber cylinder in the middle. However, in practical situations, due to long-term use, the rubber damage at both ends of the rubber cylinder after setting is significant, and increasing the stiffness of the rubber cylinder can effectively resist relatively large deformation. In subsequent research, it is considered to add a metal skeleton to the setting rubber cylinder to reduce the deformation of the rubber cylinder and improve the setting strength.



Figure 9. Simulation results of the sealing test.



Figure 10. Variation curve of stress and displacement along the inside of the packing element.

4. Effect of a Metal Skeleton on Setting Effect

4.1. Setting Process of the Packer with a Metal Skeleton

To improve the setting strength of packer rubber and prevent the high-pressure fluid generated in the annulus from moving up to the wellhead, thereby increasing the risk of emergency response, implanting a metal skeleton between the inner and outer rubber cylinders is an ideal choice. However, the structural design of the metal skeleton is a key point. If poor designed, the metal skeleton cannot be set without deformation during the setting process. Conversely, plastic deformation of the metal skeleton affects the subsequent unsealing, or even failure in unsealing. At present, the relatively common metal skeletons include linear slits, spiral slits, laminated steel strips, and woven steel strips. The linear slotted metal skeleton with thickness 3mm was attempted to quantitatively evaluate the improvement effect of the metal skeleton on the setting strength, as shown in Figure 11. The skeleton was made in 304H stainless steel for its good ductility, with a yield strength of 665MPa and a tensile strength of 930MPa. The pressure of the high-pressure fluid is 10 MPa, and the setting pressure is still 10 MPa.



Figure 11. Slotting structure of the metal skeleton.

4.2. Effect of a Metal Skeleton on Setting Effect Conclusion

The stress and displacement after deformation of the packer rubber with/without the metal skeleton after setting are shown in Figure 12. Due to the outward expansion of the rubber under the setting pressure, it subsequently involves the outward expansion of the metal skeleton, with the most severe outward expansion and deformation occurring in the middle slit portion of the metal frame. Figure 13 shows the Mises stress variation curve of the metal skeleton at different stages along an arbitrary path in the Y direction.

It can be seen that the Mises stress in the slit portion of the metal skeleton does not reach the yield limit, indicating that no plastic deformation has occurred. The Mises stress at both ends of the skeleton at the end of the slit reaches the maximum value of 223.3 MPa. Due to excessive deformation of the two ribs, tensile deformation occurs at the end of the slit, resulting in a concentration of Mises stress.



Figure 12. Stress and displacement comparison of the rubber with/without metal skeleton (a. Mises stress; b. Displacement).



Figure 13. Mises stress curve of the metal skeleton at different stages.

Whether the packer rubber cylinder can effectively seal the fluid is mainly judged by the contact stress between the rubber cylinder and the casing. To quantitatively analyze the impact of the metal skeleton on the setting effect, Mises stress and displacement on the inner layer of the rubber cylinder with/without the metal skeleton are shown in Figure 14. The peak Mises stress of the rubber cylinder is mainly located at 50mm to 150mm and 600mm to 700mm sections in the path. However, benefiting from the reinforcement of the metal skeleton, the maximum Mises stress at these points decreases significantly by 71%. The metal skeleton also improves the contact stress and the sealing effect. Generally speaking, the metal skeleton has a significant effect on reducing the overall Mises stress of rubber, achieving a better setting effect as well as making the packer more durable.



Figure 14. Comparison of stress during the sealing with/without a skeleton (a. Mises stress; b. Contact stress).

5. Conclusion

To reduce the high-pressure overflow and kick incidence during offshore drilling of exploration wells and high-risk wells, and gain precious time for platform emergency response. In this paper, a downhole emergency plugging device is designed, and the finite element method is applied to simulate the setting effect of the packer rubber. The contact stress and Mises stress of the rubber with or without a metal skeleton are compared, to evaluate the strengthening effect of the metal skeleton on the setting. The main conclusions are obtained as follows:

(1) The externally tensioned packer structure designed in this article can achieve the function of sealing the annulus between the 9 ⁵/₈"technical casing and the 5" drill pipe, thereby preventing the kick and the high-pressure overflow moving up to the platform from downhole.

(2) When a setting pressure of 10 MPa is applied inside the packer, the maximum stress of the rubber cylinder is 3.74 MPa, and the contact stress between the rubber and casing reaches 12.1 MPa, which can effectively plug the high pressure of 10 MPa.

(3) Under the setting pressure of 10 MPa, the peak stress and deformation of the rubber significantly decreased after adding a metal skeleton, while the stress of the metal skeleton is 223 MPa, which was far less than the yield limit and did not affect the release. According to the calculation results in this article, the setting pressure can be increased to achieve the effect of setting higher down hole pressure.

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