Design and performance experiment of staged fracturing degradable bridge plug for horizontal well

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Abstract. With the gradual transformation of oil and gas exploration and development objects to low-permeability and low-grade resources, horizontal well staged fracturing technology has become an important means for reservoir reconstruction and effective improvement of single well production. As an important downhole layered plugging tool for staged fracturing of horizontal wells, bridge plugs are increasingly widely used. In this paper, firstly, the structure of the degradable bridge plug is designed according to the design principles and working conditions, and the technical parameters of the main body of the bridge plug are determined. Secondly, the performance of the sealing and anchoring structure is analysed, as well as the hydrodynamic performance analysis of the influence of the water flow on the bridge plug. Thirdly, a test prototype of the degradable bridge plug is manufactured according to the engineering drawings and material selection requirements. Finally, the pressure-bearing performance of the designed degradable bridge plug is tested by the prototype test, which provides a theoretical basis for future field applications.

1. Introduction
Reservoir segmentation isolation technology is a very important downhole operation technology. In view of the advantages of bridge plug sealing layer technology with fewer construction procedures, short operation cycle and accurate setting position, it has been widely used in oil and gas well sealing layer and is constantly being developed and improved [1-3]. According to different uses and unsealing methods, bridge plug sealing technology can be divided into drillable bridge plug sealing technology, recyclable bridge plug sealing technology and multifunctional bridge plug sealing technology [4-5]. Soluble composite materials are widely used in the petroleum field due to its good mechanical properties and solubility [6]. The downhole tool of soluble composite material represents the most advanced downhole technology, including partial parts soluble and overall soluble. The soluble bridge plug is automatically dissolved after the operation, which greatly reduces the operation procedure, saves the operation cycle, and improves the operation efficiency. Therefore, the research and analysis of degradable composite materials and downhole tools, and the development of downhole tools for soluble composite materials suitable for oil and gas fields can reduce costs. In this paper, a degradable bridge plug is designed, and its sealing performance, anchoring performance and fluid erosion characteristics are analysed by numerical simulation methods.
2. Scheme design of degradable bridge plug

2.1. Design requirements
Fracturing bridge plug is one of the core tools of the horizontal well pumping bridge plug staged fracturing technology. The structure is designed according to the application conditions of the degradable bridge plug, the setting type and the unsealing method, etc. The basic principles of the design are as follows:
- In the case of meeting the requirements of use, reduce the maximum outer diameter of the bridge plug as much as possible.
- In the case of meeting the strength requirements, increase the fluid flow space as much as possible.
- Shorten large diameter parts as much as possible.
- Each part of the design must be safe, accurate and reliable, but also simple and compact.
- The designed components should be easy to process and assemble.

2.2. Technical parameter
The main technical parameters of the degradable bridge plug are summarized from the operating conditions and design parameters of the bridge plug structure, as shown in Table 1.

| Diameter /mm | Length /mm | Temperature /℃ | Pressure /MPa | Applicable casing /mm | Degradation time /day |
|--------------|------------|----------------|--------------|-----------------------|-----------------------|
| 112          | 780        | 150            | 50           | 118-124               | 5-10                  |

2.3. Overall program
According to the horizontal well pumped bridge plug staged fracturing process principle and bridge plug structure design technical requirements, the design structure of the degradable bridge plug is shown in Figure 1. The working principle is: the bridge plug and the tool string of the setting tool are lowered to a predetermined position by the cable. Then, the fracturing pump truck on the ground injects fluid into the tubing to drive the tool string to a predetermined location in the horizontal section. The control signal is transmitted through the cable to ignite the gunpowder in the burning chamber of the setting tool. After the explosion, high-pressure gas is generated to drive the outer cylinder downward as the setting force of the bridge plug. Driven by the setting force, the safety shear nails are cut first, and then the outer cylinder pushes the slip seat, upper and lower slips, cone and shoulder guard to squeeze the sealing unit. When the setting force reaches the opening pressure of the slips, the lower slips begin to break and set. Subsequently, the upper and lower shoulder guards and the upper slips are opened in sequence, and the slips are inserted into the casing to fix the setting position. After that, the setting force continued to increase, the weak point at the upper end of the centre tubing is broken, the bridge plug is separated from the tubing, and the tubing is lifted to the wellhead to complete the operation.

3. Structure analysis of degradable bridge plug

3.1. Seal structure analysis
In the case of large deformation of rubber materials, it involves the nonlinearity and geometric
nonlinearity of the combined material. Under the action of axial load, the frictional contact between the rubber cylinder and other parts of the sealing unit is nonlinear in state. The nonlinear analysis is more complicated and requires higher-level finite element software. ABAQUS is adopted in this paper due to its advantages in non-linear analysis. The established finite element model of the rubber structure with shoulder protectors is shown in Figure 2.

The finite element analysis model is composed of tubing, casing, shoulder protectors, combined rubber cylinders, and upper and lower cones. The middle rubber cylinder is made of softer rubber material with a hardness of 80HA, the two ends of the rubber cylinders are made of harder material with a hardness of 90HA. The casing is made of steel, and the remaining parts are made of aluminum-magnesium alloy composite materials. Since each part is a rotating body, for the convenience of analysis, an axisymmetric model is adopted to establish the finite element model. The function of the shoulder protectors is to protect the rubber cylinder from deforming and causing a shoulder protrusion.

The analysis results show that the maximum compression distance of the rubber cylinder is 42.16mm under the setting pressure of 26MPa. According to theoretical calculations, the maximum compression distance is 46.8mm, and the setting pressure is 25.21MPa. The theoretical and simulation analysis results are basically the same, indicating that the pressure of the compressed rubber cylinder acting on the pressure ring is 26MPa, which can be regarded as the setting pressure. The displacement cloud diagram of the rubber cylinder in the x and y directions is shown in Figure 3.
rubber cylinder plays the main sealing role, and the upper and lower rubber cylinders mainly play a protective role.

3.2. Anchor structure analysis

Slips are an important element to ensure the reliability of the bridge plug. In the case of the same setting force, the bite force distribution between the slip and casing affects the damage degree of the casing and the implementation of oil recovery and water injection process. The elastic-plastic contact finite element method is adopted to analyse the strength of bridge plug slips anchored to the casing. The study of the bite force distribution between slips and casing has important guiding significance for the optimal design of bridge plug slips. When the setting force of the bridge plug slip reaches the opening pressure, the slip breaks along the stress groove, and then is embedded and anchored on the casing. The slips in this process are mainly affected by the setting force. Considering the axial symmetry of the components, a 1/12 finite element analysis model of the slip anchor system is established. The model is mainly composed of slip body, slip carburized layer, casing and cone, as shown in Figure 4.

Figure 4. Finite element model of slip structure.

The analysis result is shown in Figure 5, which shows that the contact area and contact stress of the slip and the casing are distributed relatively uniformly along the axial direction, and the stress on both sides of the slip from the symmetrical surface shows a decreasing trend along the circumferential direction. The maximum contact stress between the slip and the casing is concentrated between 916.89MPa ~ 1178.9 MPa, which is significantly greater than the yield strength of the casing at 850 MPa. This means that the slips have been well embedded in the casing and have good anchoring performance. Since the outer diameter of the main body of the slip is smaller than the inner diameter of the casing, it is impossible for the slip to completely fit on the inner wall surface of the casing. Therefore, the occlusal area between the slip and casing is mainly concentrated near the symmetry plane of the slip.

Figure 5. Slip equivalent stress cloud diagram.
3.3. Fluid erosion analysis
The fluid mechanics method is used to analyse the effect of the water flow on the bridge plug during the
downhole process, and to study the key factors affecting the lowering speed of the bridge plug and the
driving force of the bridge plug, which is conducive to the optimization of the structure of the degradable
bridge plug. In order to facilitate the finite element analysis, simplify the contour structure of the outer
wall of the bridge plug, as shown in Figure 6. The maximum and minimum outer diameters are 112mm
and 96mm, respectively, and the minimum annulus gap is 4.5mm.

Figure 6. Finite element model of bridge plug flow field.

The analysis result is shown in Figure 7, which shows that the fluid in the left area is in a uniform
and slow flow state, and after entering the annular flow field, the flow velocity becomes significantly
larger, and the maximum flow velocity is 16.8m/s. When the fluid passes through the variable cross-
section, due to the existence of the groove, part of the fluid impacts the wall changes the direction of
flow velocity, thereby returning along the wall surface to form a vortex. When the fluid flows out of the
annulus field, the flow velocity is large, which drives the surrounding fluid to move forward. Due to the
low speed of the bridge plug, a negative pressure area is formed near the right end surface of the bridge
plug, which causes the fluid with higher pressure in the right area of the basin to flow back to the negative
pressure area, thereby forming a backflow.

Figure 7. The velocity field of fluid.

4. Degradable bridge plug processing and experiment

4.1. Degradable bridge plug processing
Since the degradable bridge plug plays an important role in the field application of oil and gas fields, its
performance reliability has a significant impact on the entire horizontal well fracturing operation.
Therefore, a detailed design of the degradable bridge plug part drawing is based on the overall structure
of the degradable bridge plug. Subsequently, the degradable bridge plug is manufactured according to
the parts drawing. In accordance with the requirements of the working environment on site, performance
tests are carried out on the degradable bridge plug to check whether it meets the strength conditions and
the functional requirements of the construction. The prototype of the degradable bridge plug is shown
in Figure 8.

Figure 8. Degradable bridge plug prototype.

4.2. Degradable bridge plug test
The indoor pressure-bearing performance test of the bridge plug prototype is carried out to check
whether the bridge plug meets the design requirements. The test bridge plug is subjected to a pressure-
bearing performance test in a high-temperature environment, and the test data is recorded. The schematic
diagram of the connection of the test device is shown in Figure 9.
The setting process uses a power pump to pressurize the setting pipeline. When the pressure increases to 5MPa, the shear nails are cut and the degradable bridge plug starts to be set. Continue to pressurize to 50MPa, stabilize the pressure for 10 minutes. During the period, the pressure is stable and the pressure leakage is small. Close the one-way valve between the power pump and the setting pipeline. After the setting pressure is removed, the pressure gauge reading quickly drops to 0. This shows that the performance of the bridge plug is stable and has reached the expected design goal.

5. Conclusion
According to the structural composition and working principle of the fracturing bridge plug currently used in oil and gas fields, determine the structure of the hydraulic pumping bridge plug. The bridge plug adopts the integral slip anchor structure and the sealing unit of the combination of three rubber cylinders, and the gunpowder type setting tool controlled by the cable.

The degradable sealing structure, anchoring structure, and midway anti-setting structure are designed. The strength of key components is checked and calculated, and ANSYS is used to perform finite element analysis and simulation on the threaded locking structure, and finally the degradable bridge is determined.

The hydrodynamic analysis of the influence of the water flow in the process of the bridge plug descending into the well is carried out. It is found that the injection speed and the annulus clearance are the main factors affecting the driving force of the bridge plug, while the influence of the bridge plug lowering speed and the bridge plug eccentricity can be ignored.

The bridge plug prototype is manufactured according to the designed engineering drawings, and the indoor test is carried out under the set conditions. The test results show that the performance of the designed bridge plug has reached the expected design index.

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