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Structure Optimization on Combine Rubber Cylinder of Gas Injection Packer

Lianyu Zhang*, Shijie Wang*, Wei Lv*, Guangtao Yue*, Zecheng Wang**, Hao Fang*** and Xianjun Zhou***

Keywords： gas injection packer; rubber cylinder; structure optimization; response surface method.

ABSTRACT

Taking the JY445 packer combination rubber as the object, a three-dimensional model was established by using ANSYS finite element analysis software. The sealing performance of the rubber was analyzed by measuring the contact stress and the displacement of the steel cover. At the same time, the indoor test of the rubber tube was carried out, and the contact stress curve of the rubber tube was obtained and compared with the simulation results. The results verified the effectiveness of the simulation. Under the setting force of 7600Kg, five single factors were simulated and analyzed. The response surface method was used to simulate the model, and the optimal combination of the rubber cylinder was obtained. The results showed that the height of the middle rubber cylinder was 61mm, the height of the steel cover was 24mm, the angle interval of the end face of the middle rubber cylinder was 29°, the angle interval of the end face of the middle rubber cylinder was 11.01°, the secondary thickness of the middle rubber cylinder was 13mm, the contact stress of the better rubber cylinder was 9.584MPa, which increased by 36.46%, and the displacement of the steel cover was 1.224mm, which increased by 5.15%. The research shows that the single factor combined with the response surface method can significantly improve the sealing effect of the gas drive packer, improve the opening of the rubber cylinder, effectively improve the outburst prevention performance and prevent the gas explosion problem.

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* *Sinopec Shengli Oilfield Petroleum Engineering Technology Research Institute*

** *China Heavy Duty Automobile Group Co., Ltd.*

*** *China University of Petroleum (East China) Mechanical and Electrical Engineering College.*

INTRODUCTION

In the gas injection well, because of the oil case leakage, the packer failure and the cement leakage, the gas flows into the annular space surrounded by each layer of string and forms the pressure, which affects the stress of the packer, and the rubber tube produces the phenomenon of "gas explosion". The cylinder structure design and the sealing performance determine the safe and reliable sealing of the packer.

At present , more foreign enterprises have developed and improved packers , and hundreds of packers and parts are series （Doane J, 2012） (Bisset S, 2011) (Themig D, 2011) , such as Shell (Thomas. C. Frick, 1961) and Baker (Guiberson, 1979). Shell has invented an expandable elastomer for separating packers, Baker has invented hydrostatic FH and FHL-1 removable packers, and Buroak and NODECO have worked together to develop three-tube packers, RR2 permanent packers and so on (Zhang Lei, 2008) (Song Wanchao et al , 2000) . Detachable packers have been designed abroad to solve the limitations of permanent and removable packers and make packers more widely used (Zhan Jinghua, 2005). Taylor D. studied new material for new packer with 400°F, 30000 psi (Kleverlaan M, 2005) . Polonsky et al. improved the combination rubber tube with different hardness, added the spring ring anti-outburst device, put forward the conical rubber tube structure, and improved the performance (Taylor D, 2012) .

By repeatedly comparing and analyzing the specific conditions of various domestic oilfields and introducing advanced technology and forming structure, with the continuous efforts of many experts and scholars, China's packer research has made remarkable progress and achieved more results(Zou Dapeng, 2014) . Zhang Ruixia et al, designed a new double acting CO_2 gas displacement sealing packer, which improves the setting effect of the packer through the dual action of hydraulic and mechanical setting (Zhang Ruixia, 2015) ; Tian Qizhong designed a new type of gas injection packer, which can be released and adopts double acting setting rubber cylinder to ensure the sealing performance of the packer (Tian Qizhong, 2015) . Wang Shijie designed a new type of gas injection packer, which can realize two-way three force loading and realize no casing pressure production of high-pressure gas injection wells on site (Wang Shijie, 2016) Liu Jianxin and others designed a new bidirectional compression Y341-115 packer. The packer is equipped with setting mechanism and locking mechanism at the upper and lower ends of the rubber cylinder, which can withstand 35MPa bidirectional alternating gas sealing pressure (Liu Jianxin et al., 2017) .

The existing studies mostly focus on the single factor analysis of the rubber cylinder structure of the hydraulic packer, and there are relatively few studies on the multi factor interaction of the rubber cylinder structural parameters of the gas drive packer. Therefore, according to the working conditions and performance requirements of the rubber cylinder of the packer, it is of great significance to find the optimal combination of the rubber cylinder structural parameters for improving the sealing effect and outburst prevention performance of the gas drive packer.

Numerical simulation and experimental verification

Rubber cylinder sealing structure

The sealing structure of the packer is mainly composed of middle rubber cylinder, end rubber cylinder, spacer ring, end ring, etc. The end of the end rubber cylinder is provided with a slotted double-layer steel cover, which is staggered and vulcanized with the end rubber cylinder, which solves the problem of gas explosion of the combined rubber cylinder under high pressure difference, as shown in Figure 1.

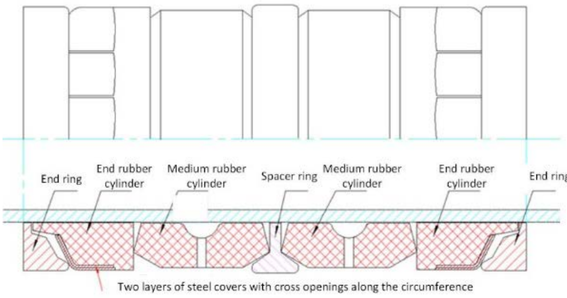


Fig. 1. JY445 packer structure.

Establishment of finite element model of rubber cylinder

The rubber material is hydrogenated nitrile rubber. Mooney Rivlin constitutive model is selected. “The method for determining the parameters of hydrogenated nitrile rubber constitutive model” (Zhao Xiaolong et al., 2019) is followed. The calculation results show that the model parameters C10 of the end rubber cylinder are 1.875MPa and C01 are 0.621MPa, and the parameters C10 of the middle rubber cylinder are 1.41MPa and C01 are 0.465MPa. Poisson's ratio is 0.5. The end ring, spacer ring, casing, center pipe and other materials are 35CrMo. The elastic modulus is 2.06GPa, and the Poisson's ratio is 0.3.

ANSYS software was used to establish a parametric three-dimensional model of the sealing structure of the YJ445 packer combination rubber. Based on the three-dimensional model, three-dimensional solid element is selected to simulate the sealing performance of combined rubber tube. The middle rubber cylinder and the end rubber cylinder adopt 8-node solid185 element, which has good simulation performance for large deformation of elastic-plastic materials. The anti-outburst steel cover uses 20-node solid186 element to improve the calculation accuracy, and solid45 element is selected for central tube, spacer ring, end ring and casing. According to the experience of rubber cylinder simulation analysis, the vent hole on the middle rubber cylinder has little effect on the overall contact stress and will increase the calculation amount, so the influence of vent hole is not considered in the finite element analysis.

Because the casing is connected to the surface by cement in the actual working condition of the casing, it is in a fixed state, so the full constraint degree of freedom is set on the outer side of the casing. Similarly, the inner side of the central tube is set with full constraint. In order to ensure the uniform force of the rubber, the radial degree of freedom is limited on the inner end of the end ring. Because the combined rubber tube structure and the spacer ring are symmetrical structures, and the setting method is double-ended setting, 1/2 modeling is adopted in the axial direction, and the symmetrical surface of the spacer ring is set as the symmetrical constraint boundary condition. Because the rubber cylinder anti-burst steel cover has a 30° staggered distribution of slits, a 1/12 modeling method is adopted in the circumferential direction and a circumferential cyclic symmetrical boundary condition is set on both sides of the symmetrical surface to reduce the amount of calculation.

In the meshing, because there is no large deformation between the central pipe and the casing, the main research goal is the sealing performance of the internal rubber cylinder. Therefore, in the meshing, the mesh accuracy is determined according to the target size and importance. Although the higher the mesh accuracy, there will be more nodes for calculation, and the results will be more accurate. However, in the actual analysis, the mesh accuracy will also have a limit, and the higher the mesh accuracy will not affect the results. Therefore, after the initial mesh size is determined, the mesh accuracy is continuously improved until the analysis results have no significant change, that is, the mesh convergence is considered. Finally, the hexahedral mesh is used to determine the mesh size of each part. The central tube and casing are 0.003 m, the end ring and spacer ring are 0.002 m, the middle rubber tube and the end rubber tube are 0.001 m, and the contact part refinement grid is 0.0005 m, and the steel cover grid size is 0.0005 m.

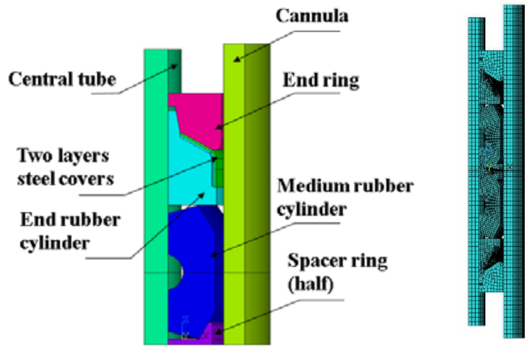
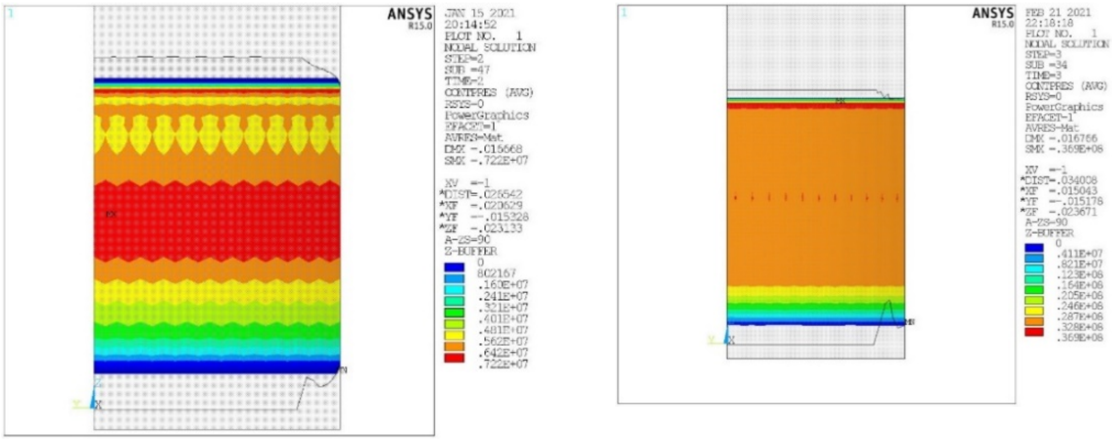


Fig. 2. Finite element model of rubber cylinder seal structure.

Analysis of rubber cylinder simulation results

The cloud diagram of the contact stress of the rubber cylinder is shown in Figure 3. The maximum contact stress is evenly distributed in the belt area in the middle of the middle rubber cylinder. Being set, the middle rubber cylinder has been in full contact with the casing, and the peak value of the contact stress reaches 7.22MPa. During the sealing inspection, the maximum contact stress between the packer rubber cylinder and the casing is 36.9MPa, which appears in the strip area at the upper part of the middle rubber cylinder. As shown in Figure 4, the center line path of the middle rubber tube is selected, that is, the inner side line of the frame in the figure, and the contact stress curve on the path is shown in Figure 5.



（a） Setting seal （b） Seal inspection

Fig.3 Cloud diagram of contact stress of rubber cylinder.

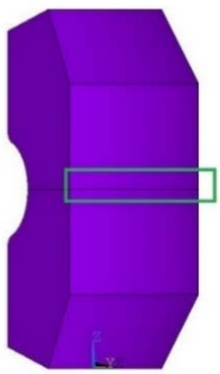


Fig4 Path of middle plastic cylinder.

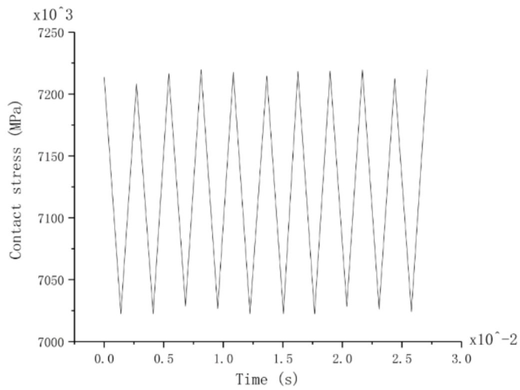
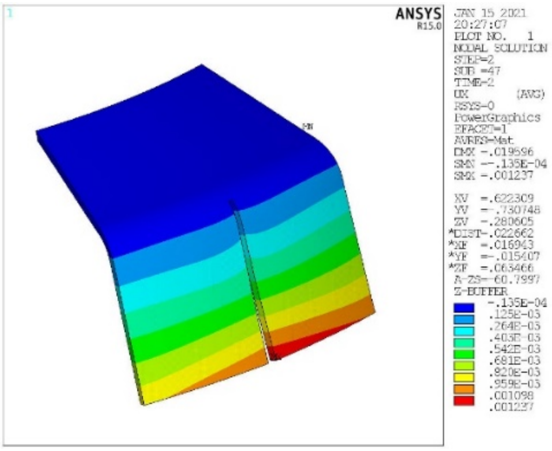
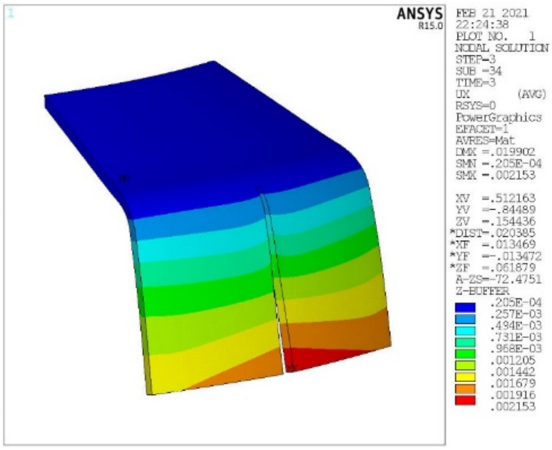


Fig.5 Dynamic behavior of contact stress of plastic cylinder.

The axial displacement cloud picture of the end rubber cylinder steel cover is shown in Figure 6. The maximum radial displacement of the rubber cylinder steel cover at the rear end of the setting seal is 1.237mm, and the maximum displacement occurs in the right area of the slit at the lowest end of the outer steel cover. During the sealing inspection, the peak value of the radial displacement of the steel cover reaches 2.153mm, and the maximum axial displacement of the outer edge is 2.139mm. After analysis, the x-axis radial displacement of the outer steel cover is selected, as shown in Figure 7, select the edge line in the box, that is, the path to the lower right end of the outer steel cover slit, the maximum radial displacement on the same path is used to compare the anti-outburst performance of the rubber tube, that is, the larger the radial displacement of the steel cover of the optimized rear rubber tube, the better the sealing performance of the rubber tube. The x-axis radial displacement distribution curve 8 of the outer steel cover is shown, and the maximum axial displacement of the outer edge is 1.164mm



（a）Setting seal



（b）Seal inspection

Fig.6 Cloud diagram of displacement of steel cage

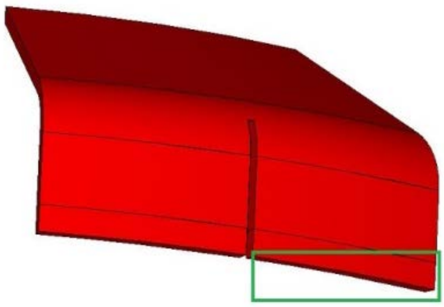


Fig.7 Path of end plastic cylinder.

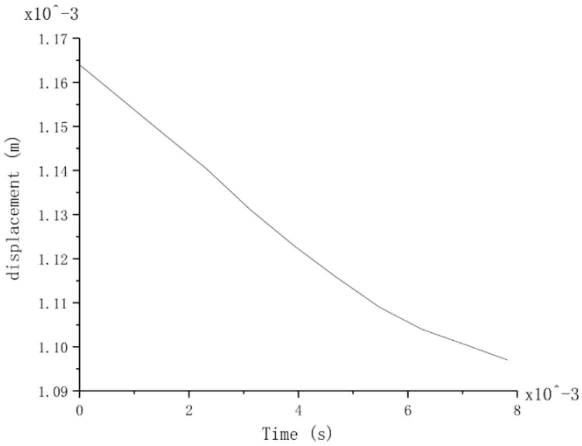
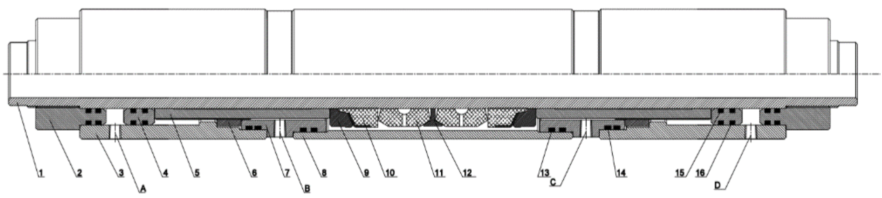


Fig.8 Distribution curve of displacement of steel cage

Laboratory test verification of rubber cylinder

DH5983 dynamic signal tester is used for indoor test, as shown in Figure 9. The special test tooling for testing is designed and processed by pressing at both ends (Fig. 10). Through the test, the strain data of the rubber cylinder under setting and pressure conditions is obtained, and the contact stress distribution of the rubber cylinder is calculated.



1-central pipe; 2-sealing ring; 3-piston sleeve; 4-piston; 5-locking sleeve; 6-lock ring; 7-lock ring sleeve; 8-casing; 9-end ring; 10-end rubber cylinder; 11-medium rubber cylinder; 12-spacer ring; 13、14、15 and 16-sealing rings; A. B, C, D-pressure opening

Fig.9 Physical drawing of tool

Fig.10 Diagram of test fixture and setup of plastic cylinder

In the setting test stage, pressurize 0 ~ 14.5MPa from the tooling inlet, and record the strain curve with the strain gauge (Fig. 11). The contact stress distribution curve is calculated according to the average strain (Fig. 12).

In the sealing inspection test stage, the pressure sealing inspection shall be carried out according to four steps of 20MPa, 25MPa, 30MPa and 35MPa respectively, the strain curve of the strain gauge shall be recorded (Fig. 13), and the contact stress distribution curve shall be calculated (Fig. 14). After seal inspection, being set, the rubber cylinder is in full contact with the casing, the steel cover is fully opened, and the anti-outburst steel cover is deformed, as shown in Figure 15.

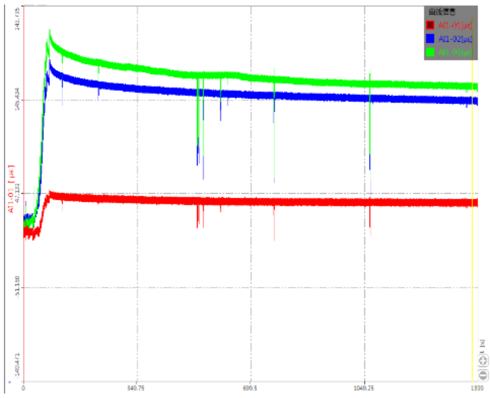


Fig.11 Strain curve of setting seal of equipment channel

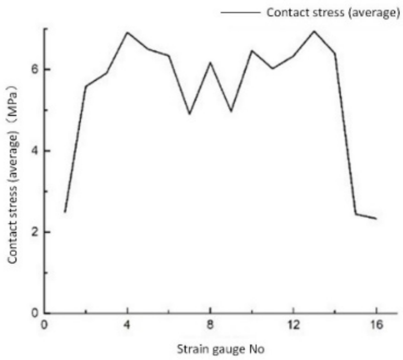
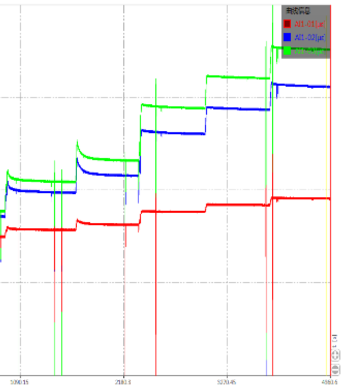


Fig.12 Setting seal of foil gage-contact stress curve



Examining seal of strain curve
ent channel

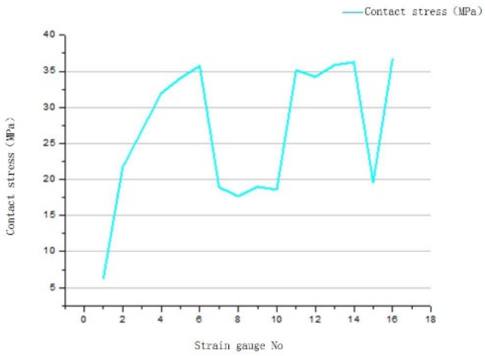


Fig.14 Examining seal of foil gage-contact stress curve

Fig.15 Steel cage mation

Through the sealing performance test and finite element simulation of the packer rubber cylinder, the contact stress between the rubber cylinder and the casing during the setting and sealing inspection of the rubber cylinder is obtained, as shown in Table 1. The difference of setting contact stress is 0.077MPa, and the difference of inspection contact stress is 0.231MPa. The error is within the allowable range, which proves that the simulation is consistent with the test, and the finite element numerical simulation is effective.

Table.1 Contact stress data comparison

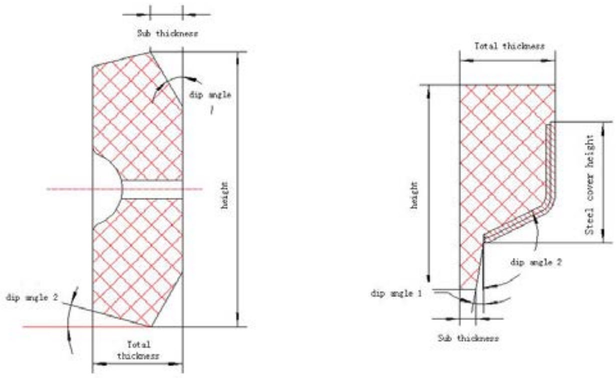
Contact stress/MPa	Test	Simulation	Difference
Setting seal	6.946	7.023	0.077
Seal inspection	36.669	36.9	0.231

Optimization of structural parameters of rubber cylinder

Based on the above simulation analysis, firstly, the rubber cylinder structure is analyzed by single factor.

Single factor analysis of rubber cylinder structure

Five single factors of rubber cylinder structure (Fig. 16) including the height of the middle rubber cylinder, the thickness of the middle rubber cylinder, the height of the steel cover, the inclination 1 and inclination 2 of the end of the middle rubber cylinder are selected to study their effects on the sealing effect and outburst prevention performance of the rubber cylinder through finite element model analysis.

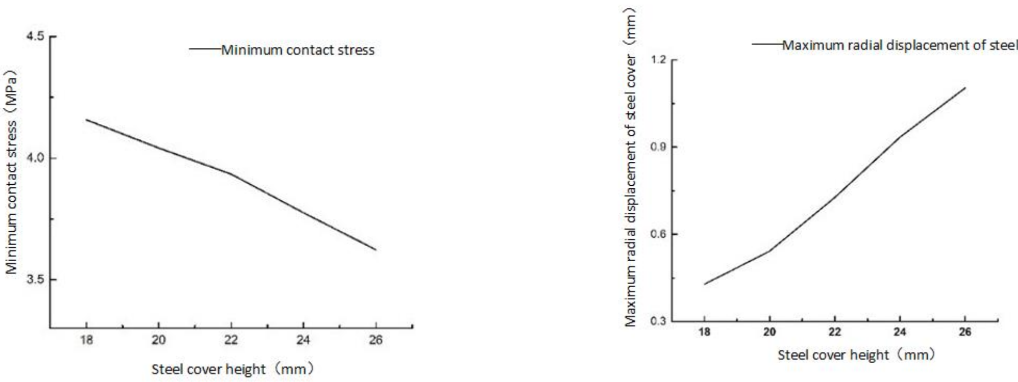


（a）Medium rubber cylinder （b）End rubber cylinder

Fig. 16 Rubber barrel structure parameters of packer.

（1）Height of middle rubber cylinder

The height of the original middle rubber cylinder is 60mm and the variation range is 54-70mm. The relationship curve between the height of the middle rubber cylinder and the contact stress and the displacement of the steel cover, as shown in Figure 17.



（a）Influence of steel cover height on contact stress

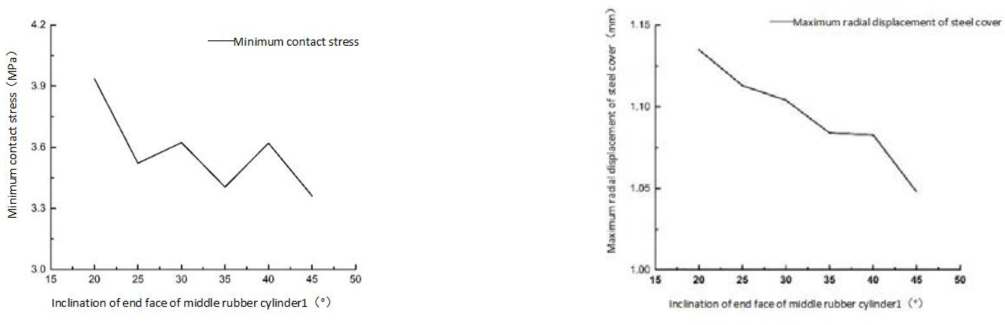
（b）Influence of steel cover height on steel cover displacement

Fig.18 Height optimization of steel cage.

It can be seen from Figure 18 that with the increase of the height of the steel cover, the contact stress of the rubber cylinder decreases and the radial displacement of the steel cover increases. The middle interval of steel hood height of 20-24mm is selected as the optimization interval.

（3）Inclination of end face of middle rubber cylinder 1

The inclination of the original middle rubber cylinder 1 is 30°, and the variation range is 20°-45°. The relation curves between the inclination of the middle rubber cylinder 1 and the contact stress and steel cover displacement are shown in Figure 19.



（a）Influence of dip angle 1 of middle rubber cylinder on contact stress

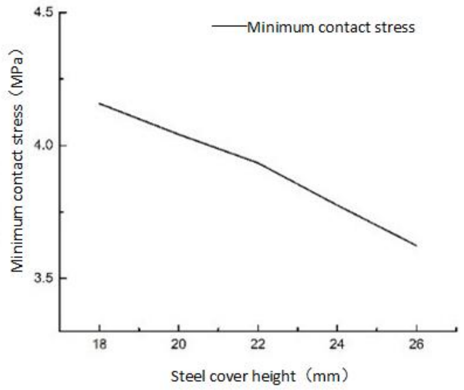
（b）Influence of dip angle 1 of middle rubber cylinder on displacement of steel cover

Fig. 17 Height optimization of rubber cylinder

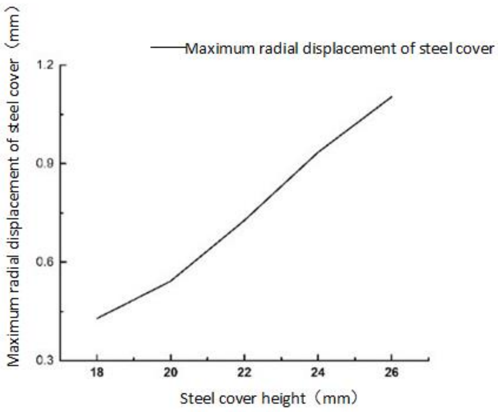
As can be seen from Figure 10, when other parameters remain unchanged, the height of the middle rubber cylinder increases. The contact stress of the rubber cylinder first increases and then decreases The radial displacement of the steel cover first increases, then decreases and then sharply increases. Through comprehensive consideration, the optimization interval of medium rubber cylinder height is 56-60mm.

（2）Steel cover height

The height of the original rubber cylinder is 44.5mm, and the steel cover height is 26mm. The change range is 18-26mm. The relation curve between the height of the steel cover and the contact stress and the displacement of the steel cover are shown in Figure 18.



（a）Influence of steel cover height on contact stress



（b）Influence of steel cover height on steel cover displacement

Fig.18 Height optimization of steel cage.

It can be seen from Figure 18 that with the increase of the height of the steel cover, the contact stress of the rubber cylinder decreases and the radial displacement of the steel cover increases. The middle interval of steel hood height of 20-24mm is selected as the optimization interval.

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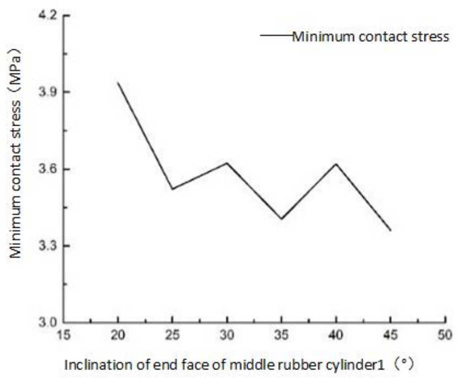
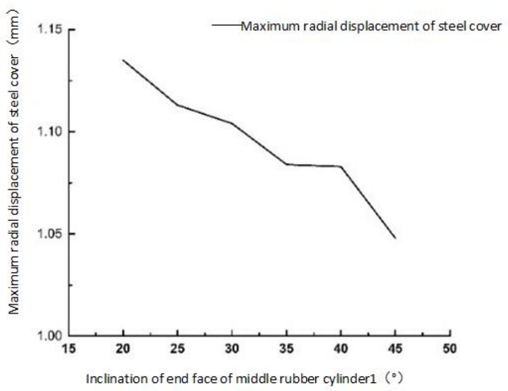


（a）Influence of dip angle 1 of middle rubber cylinder on contact stress



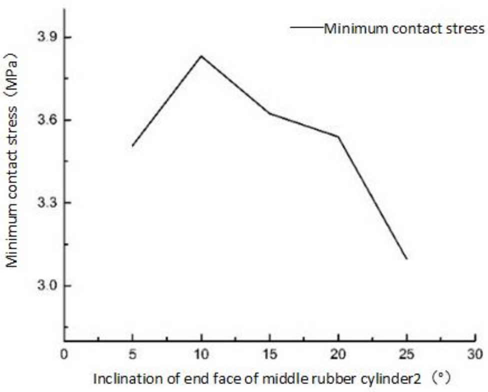
（b）Influence of dip angle 1 of middle rubber cylinder on displacement of steel cover

Fig.19 Optimization of end face inclination 1 of rubber cylinder.

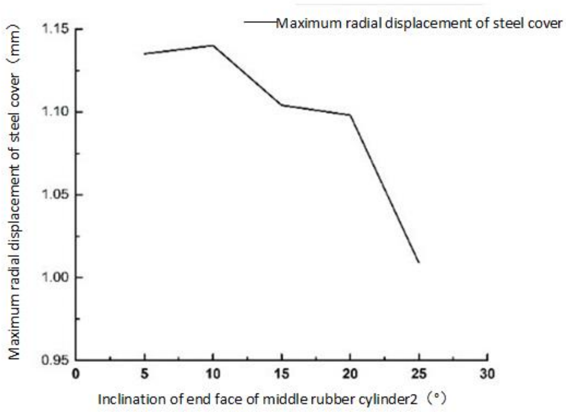
As Figure 19 displays, with the increase of the inclination 1 of the end face of the middle rubber cylinder, the contact stress of the rubber cylinder fluctuates as a whole, and the displacement of the steel cover decreases with the increase of the inclination. The inclination angle of 30°-40° is selected as the optimization interval of the end face inclination angle 1 of the middle rubber cylinder.

（4）Inclination of end face of middle rubber cylinder 2

The inclination 1 of the original middle rubber cylinder is 15°, and the variation range is 5°-25°. The relationship curve between the inclination 2 of the middle rubber cylinder and the contact stress and steel cover displacement are shown in Fig 20.



（a）Influence of dip angle 2 of middle rubber cylinder on contact stress



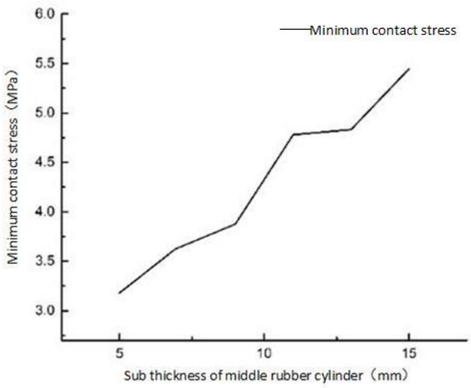
（b）Influence of dip angle 2 of middle rubber cylinder on displacement of steel cover

Fig.20 Optimization of end face inclination 2 of rubber cylinder.

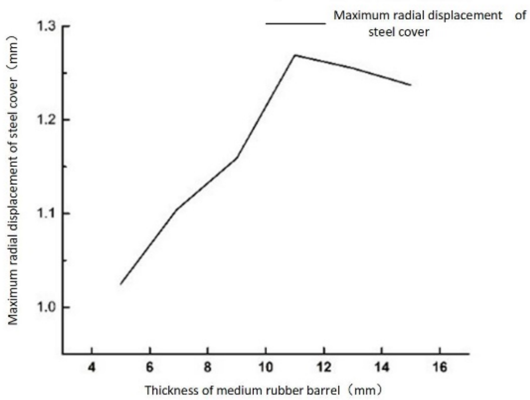
It can be seen from Figure 20 that with the increase of inclination 2, the contact stress and steel cover displacement of the rubber cylinder first increase and then decrease. 10°-20° is selected as the optimization interval of end face inclination 2 of the middle rubber cylinder.

（5）Medium rubber bobbin thickness

The thickness of the original medium rubber bobbin is 6.9mm and the variation range is 5-15mm. The relationship curve between the thickness of the medium rubber bobbin and the contact stress and the displacement of the steel cover are shown in Figure 21.



(a) Effect of the thickness of the medium rubber bobbin on the contact stress



(b) Influence of the thickness of the medium rubber bobbin on the displacement of the steel cover

Fig.21 Optimization of bobbin thickness.

It can be seen from figure 21 that the contact stress increases with the increase of the thickness of the medium rubber barrel, and the displacement of the steel cover first increases rapidly and then decreases. 9mm-13mm is selected as the optimization interval of the thickness of the medium rubber barrel.

Experimental design of rubber cylinder response surface

The height of the middle rubber cylinder, the height of the steel cover, the thickness of the middle rubber cylinder, the inclination of the end face of the middle rubber cylinder 1 and the inclination of the end face of the middle rubber cylinder 2 are selected as five independent variable test factors, and the minimum contact stress of the rubber cylinder and the maximum displacement of the steel cover are taken as two response output variables to complete the rubber cylinder response surface test design.

Minitab software is used to establish 2v5-1 partial analysis factor design of rubber cylinder structural parameters, and carry out the first-order design. The results show that the bending test curvature exists and is significant, so the second-order design continues. Select the central composite sequential design to complete the second-order design, and the test data is shown in Table 2. The model is simplified according to the ranking principle. The simplified ANOVA analysis table is shown in Table 3 and table 4. After observing the simplified model, the p value = 0 in the mismatch column is less than 0.05, indicating that the model is effective.

Table 2 The CCC table

Running sequence	Center point	District group	Height of middle rubber cylinder /mm	Steel cover height /mm	Inclination of middle rubber cylinder 1/°	Inclination of middle rubber cylinder 2/°	Medium rubber bobbin thickness /mm	Contact stress /MPa	Displacement of steel cover /mm
22	1	1	56	20	30	10	13	8.473	0.723
15	1	1	60	20	30	10	9	6.766	0.710
17	1	1	56	24	30	10	9	8.143	1.013
19	1	1	60	24	30	10	13	9.345	1.104
28	1	1	56	20	40	10	9	7.744	0.731
32	1	1	60	20	40	10	13	7.702	0.753
29	1	1	56	24	40	10	13	8.32	1.091
14	1	1	60	24	40	10	9	7.044	1.011
16	1	1	56	20	30	20	9	8.102	0.765
23	1	1	60	20	30	20	13	9.227	0.780
18	1	1	56	24	30	20	13	9.472	1.005
25	1	1	60	24	30	20	9	7.775	1.016
30	1	1	56	20	40	20	13	8.441	0.739
21	1	1	60	20	40	20	9	7.356	0.734
26	1	1	56	24	40	20	9	7.557	1.076
31	1	1	60	24	40	20	13	8.029	1.036
20	0	1	58	22	35	15	11	8.164	0.939
24	0	1	58	22	35	15	11	8.188	0.942
27	0	1	58	22	35	15	11	8.176	0.940
5	-1	2	54	22	35	15	11	8.336	0.919
7	-1	2	62	22	35	15	11	7.407	0.915
3	-1	2	58	18	35	15	11	8.305	0.557
10	-1	2	58	26	35	15	11	8.08	1.117
1	-1	2	58	22	25	15	11	9.552	0.970
12	-1	2	58	22	45	15	11	7.699	0.897
13	-1	2	58	22	35	5	11	7.803	0.946
2	-1	2	58	22	35	25	11	7.572	0.938
9	-1	2	58	22	35	15	7	6.933	0.896
11	-1	2	58	22	35	15	15	9.541	0.942
8	0	2	58	22	35	15	11	8.186	0.941
4	0	2	58	22	35	15	11	8.165	0.940
6	0	2	58	22	35	15	11	8.254	0.941

Table 3 The ANOVA for contact stress of rubber tube（Simplified model）

source	freedom	Adj SS	Adj MS	F value	P value
Model	10	14.42	1.442	21.59	0
linear	5	12.3334	2.46668	36.94	0
Middle rubber cylinder height /mm	1	0.9866	0.98658	14.77	0.001
Steel cover height /mm	1	0.0845	0.08449	1.27	0.273
Inclination of middle rubber cylinder 1 /°	1	3.2384	3.23841	48.49	0
Dip angle of middle rubber cylinder 2 /°	1	0.1601	0.16007	2.4	0.137
Medium rubber bobbin thickness /mm	1	7.8639	7.86386	117.76	0
square	1	0.4869	0.48686	7.29	0.013
Dip angle of middle rubber cylinder 2 /°· dip angle of middle rubber cylinder 2/°	1	0.4869	0.48686	7.29	0.013
Two factor interaction	4	1.5997	0.39993	5.99	0.002
Medium rubber cylinder height /mm· medium rubber cylinder thickness /mm	1	0.3031	0.30305	4.54	0.045
Height of steel cover/mm· inclination of middle rubber cylinder 1 /°	1	0.3782	0.37822	5.66	0.027
Steel cover height /mm· inclination angle of middle rubber cylinder 2 /°	1	0.3782	0.37823	5.66	0.027
Inclination of medium rubber cylinder 1 /°· thickness of medium rubber cylinder /mm	1	0.5402	0.54022	8.09	0.01
error	21	1.4024	0.06678		
Misfit	17	1.4016	0.08245	403.81	0
Pure error	4	0.0008	0.0002		
total	31	15.8224			

Select the final model and calculate the regression equation of the original data (uncoded), including the regression equation of the maximum contact pressure of the response output variable of the five single factors, consisting of the height of the rubber cylinder (A), the height of the steel cover (B), the inclination of the end of the rubber cylinder 1 (C), the inclination of the end of the rubber cylinder 2 (D), and the thickness of the rubber cylinder (E), as shown in formula (1-1):

$$\begin{aligned}&9.4-0.480A+0.798B+0.467C+0.507D-1.066E-0.00510D^2+0.0344AE\\&-0.01538BC-0.01538BD-0.01838CE\end{aligned} \tag{1-1}$$

The regression equation of the maximum displacement of the steel cover is shown in formula (1-2):

$$\begin{aligned}&-4.87+0.0059A+0.3793B+0.0746C+0.0421D-0.1800E-0.006546B^2-\\&0.001299AC+0.00358AE-0.001174BD-0.001476DE\end{aligned} \tag{1-2}$$

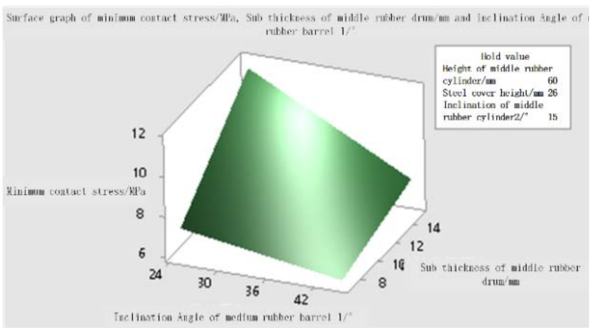
Table.4 The ANOVA for steel cage（Simplified model）

Model	freedom	Adj SS	Adj MS	F value	P value
linear	10	0.556857	0.055686	149.69	0
Middle rubber cylinder height /mm	5	0.524612	0.104922	282.04	0
Steel cover height /mm	1	0.000003	0.000003	0.01	0.932
Inclination of middle rubber cylinder 1 /°	1	0.521265	0.521265	1401.22	0
Dip angle of middle rubber cylinder 2 /°	1	0.00036	0.00036	0.97	0.336

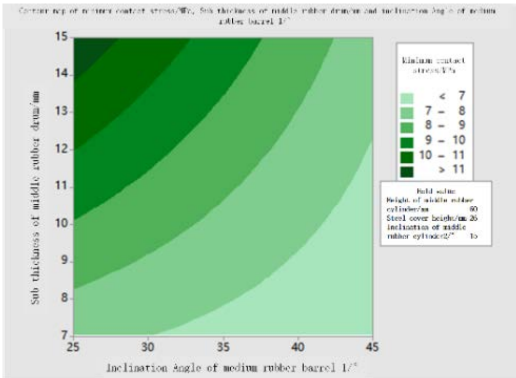
Medium rubber bobbin thickness /mm	1	0	0	0	0.99
square	1	0.002984	0.002984	8.02	0.01
Dip angle of middle rubber cylinder 2 /°· dip angle of middle rubber cylinder 2/°	1	0.020571	0.020571	55.3	0
Two factor interaction	1	0.020571	0.020571	55.3	0
Medium rubber cylinder height /mm· medium rubber cylinder thickness /mm	4	0.011673	0.002918	7.84	0
Height of steel cover/mm· inclination of middle rubber cylinder 1 /°	1	0.002699	0.002699	7.25	0.014
Steel cover height /mm· inclination angle of middle rubber cylinder 2 /°	1	0.003283	0.003283	8.83	0.007
Inclination of medium rubber cylinder 1 /°· thickness of medium rubber cylinder /mm	1	0.002204	0.002204	5.93	0.024
error	1	0.003487	0.003487	9.37	0.006
Misfit	21	0.007812	0.000372		
Pure error	17	0.007808	0.000459	436.04	0
total	4	0.000004	0.000001		
Model	31	0.564669			

Optimization analysis of rubber cylinder parameters

In the ANOVA analysis of the model, it has been confirmed that there is the largest variable with significant interaction of two factors. The response variable surface diagram and isoline diagram of output response are shown in Fig. 22 and Fig. 23 respectively. It can be seen from the figures that the end inclination 1 of the middle rubber barrel and the thickness of the middle rubber barrel have a significant impact on the contact stress, and the influence between the two factors is also significant. The inclination 2 of the end face of the middle rubber cylinder and the thickness of the middle rubber cylinder have a significant influence on the displacement of the steel cover, and the influence between the two factors is also significant.

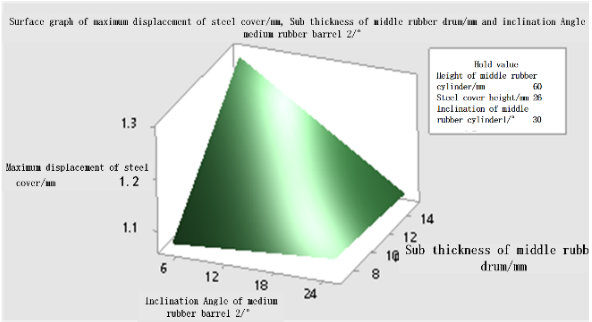


□ a□ Surface graph

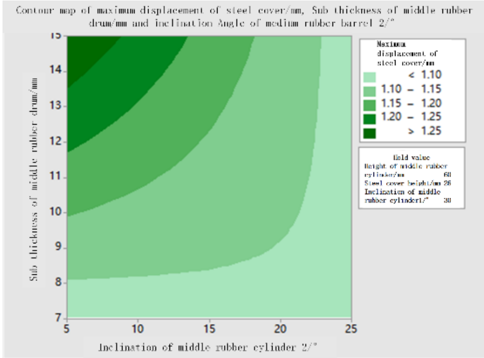


□ b□ Contour map

Fig.22 The plot of the angle 1 of the end face and the thickness of the rubber to about the response variable contact pressure.



（a）Surface graph



（b）Contour map

Fig.23 The plot of the angle 2 of the end face and the thickness of the rubber to about the response variable steel cage displacement.

It can be seen from figure 24 that when the height of the middle rubber cylinder is 61mm, the height of the steel cover is 24mm, the inclination of the end face of the middle rubber cylinder is 29°, the inclination of the end face of the middle rubber cylinder is 11.01°, and the thickness of the middle rubber cylinder is 13mm, the maximum expected contact stress is 9.569MPa and the maximum displacement of the steel cover is 1.129mm. At this time, d=1 is considered to achieve the desired goal. This combination is a better combination of the structural parameters of the packer rubber cylinder.

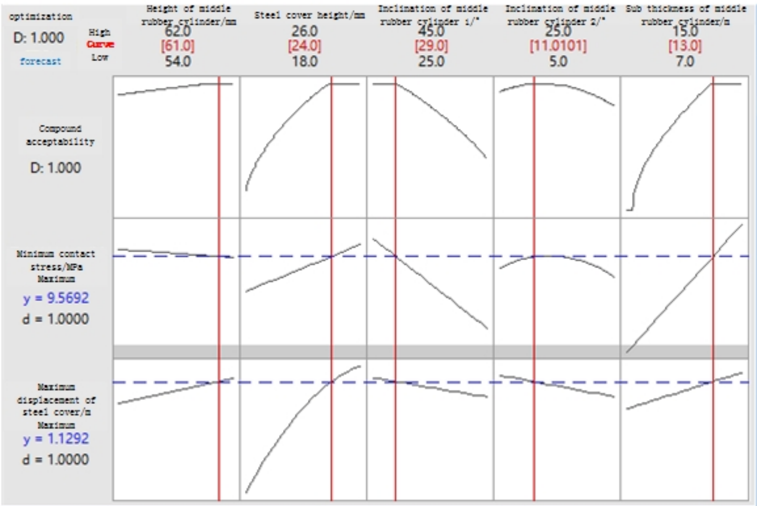


Fig.24 Optimization of the response variable.

The optimum structural parameters obtained by five factors are substituted into the finite element method, and then the contact stress value is 9.584MPa and the steel cover displacement is 1.147mm. The response prediction results of the new factor level are obtained by Minitab, as shown in Table 5. Both are within the 95% confidence interval of the average value, which proves that the response design results are effective, indicating that the surface model is correct and the prediction results are reliable.

Table 4 response prediction of new factor level

response	Fitting value	Standard error of fitting value	95% confidence interval	95% Prediction interval
Minimum contact stress /MPa	9.569	0.209	(9.134, 10.004)	(8.878, 10.261)
Maximum displacement of steel cover /mm	1.1292	0.0164	(1.0952, 1.1633)	(1.0766, 1.1818)

Conclusion

1. The contact stress distribution curve of the rubber cylinder of JY445 packer is obtained through the indoor test of the rubber cylinder. By comparing with the numerical simulation results, the

effectiveness of the numerical model simulation results is verified.

2. Through single factor simulation analysis, it is obtained that the optimization interval of middle rubber cylinder height is 56mm-60mm, the steel cover height is 20mm-24mm, the optimization interval of middle rubber cylinder end face inclination 1 is 30°-40 °, the optimization interval of middle rubber cylinder end face inclination 2 is 10°-20°, and the optimization interval of middle rubber cylinder thickness is 9mm-13mm.

3. The optimal combination of the rubber cylinder is obtained by the curved surface response method. The height of the middle rubber cylinder is 61mm, the height of the steel cover is 24mm, the inclination of the end face of the middle rubber cylinder is 1.29°, the inclination of the end face of the middle rubber cylinder is 2.11°, the thickness of the middle rubber cylinder is 13mm, the contact stress of the combined rubber cylinder is 9.584MPa, an increase of 36.46%, and the radial displacement of the steel cover is 1.224mm, an increase of 5.15%.

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注氣封隔器組合橡膠筒的結構優化

張連煜 王世傑 呂瑋 嶽廣韜
中國石化勝利油田石油工程技術研究院

王澤成 方豪
中國重型汽車集團有限公司

周先軍[3]
中國石油大學（華東）機電工程學院

摘 要

以 JY445 封隔器組合膠筒為物件，利用 ANSYS

有限元分析軟體建立三維模型,通過測量接觸應力和鋼蓋位移分析膠筒的密封性能。同時,對膠筒進行了室內試驗,得到了膠筒的接觸應力曲線,並與模擬結果進行了比較,結果驗證了模擬的有效性。在 7600Kg 的設定力下，對五個單因素進行了模擬分析，採用回應曲面法對模型進行了模擬，得到了膠筒的最佳組合，結果表明：中間膠筒高度為 61 mm，鋼蓋高度為 24 mm，中間膠筒 1 端面的角度間隔為 29°，中間膠筒 2 端面的角度間隔為 11.01°，中間膠筒的次厚度為 13mm，較好膠筒的接觸應力為 9.584 MPa,增加了 36.46%,鋼蓋的位移為 1.224 mm，增加了 5.15%。研究表明通過單因素結合回應曲面法可顯著提高氣驅封隔器密封效果,提升膠筒的張開度,有效提高防突性能並防止氣爆問題產生。