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Simulation Study on Static Sealing Performance of Packer Rubber Cylinder in SC-CO_2 Environment

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ABSTRACT

Aiming at the problems of sealing and tearing failure of packer rubber cylinder during CO_2 downhole injection.Using Comsol multi-physical field simulation software, the packer rubber cylinder model in SC-CO_2 environment is established. Based on the thermal analogy method to simulate the gas invasion swelling process, analyze the deformation and stress of the rubber cylinder caused by temperature, pressure and CO_2 gas invasion swelling.The results show that under the SC-CO_2 environment, with the influence of gas invasion and swelling, the packer rubber cylinder body is prone to large deformation, and the maximum shear stress is significantly increased, leading to shear failure of the rubber cylinder.Reducing the initial setting pressure can alleviate the impact of deformation, but the reduction of the maximum contact pressure can easily cause the rubber cylinder to lose its seal.Analyze the change rule between various factors and the maximum contact pressure of the rubber cylinder, which provides a certain theoretical basis and technical support for improving the sealing performance of the packer rubber cylinder in the SC-CO_2 environment.

Keywords: SC-CO_2, Packer Rubber Cylinder, Sealing Performance, Swelling

1. INTRODUCTION

CCUS is the main technology to realize large-scale carbon emission reduction in China at present. In the field of oil development, CO_2 flooding technology, as an effective means to improve oil recovery, not only conforms to the concept of effective carbon capture, utilization and storage in the CCUS concept, but also gives full play to the unique advantages of CO_2 as a carbon carrier in the field of enhanced oil recovery in tertiary oil recovery.Supercritical CO_2 (SC-CO_2) can effectively reduce the residual oil saturation of the reservoir by reducing the interfacial tension between oil and water and the extraction effect, and maximize the carbon storage while improving the oil displacement efficiency[1-3].

The downhole environment in which CO_2 enters the well is different from the conventional injection environment such as water drive. When the temperature exceeds 31.26℃ and the critical pressure exceeds 7.2MPa, CO_2 will be converted into a liquid with approximate density and viscosity close to the supercritical state of gas, and the diffusion ability will be further enhanced.Packer is one of the core tools to realize CO_2 layered injection. However, with the increase of injection time and temperature, SC-CO_2 molecules are more likely to diffuse into the rubber matrix, causing the overall swelling of the rubber cylinder, further expanding the deformation of the rubber cylinder, which may cause the rubber cylinder to tear and fail in extreme cases[4-6].At present, there are few studies on the influence of CO_2 swelling effect on the sealing performance of packer rubber cylinder, and there is also a lack of appropriate numerical simulation means for the swelling effect.In this study, Comsol multi-physical field simulation software was used to establish the packer rubber cylinder model in SC-CO_2 environment. Based on the thermal analogy method, the gas invasion swelling process was simulated to analyze the influence of the rubber cylinder deformation and stress caused by temperature, pressure and CO_2 gas invasion swelling, and the change rule between various factors and the maximum contact pressure of the rubber cylinder. It provides a theoretical

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basis and technical support for improving the sealing performance of packer rubber casing in SC-CO_2 environment.

2. THEORETICAL CALCULATION OF MECHANICAL PROPERTIES OF RUBBER CYLINDER

At present, fluororubber, nitrile rubber and hydrogenated nitrile rubber are mainly used to manufacture packer rubber. According to the large deformation of rubber and the elastic mechanics theory, the stress of the rubber cylinder is studied. In order to ensure the convergence of calculation, the absolute volume of the rubber cylinder is regarded as incompressible without exceeding its elastic limit, and the radial and circumferential deformation caused by the contact between the rubber cylinder and the casing is ignored. Poisson's ratio is set as 0.5 according to the incompressibility of rubber. The Monney-Rivilin two-parameter model was selected as the constitutive model of the rubber cylinder, and the contact pressure between the rubber cylinder and the casing after setting was calculated through the constitutive model[7].

Monney-Rivilin two-parameter model

$$W_{siso} = C_{10}(\overline{I}_1 - 3) + C_{01}(\overline{I}_2 - 3) \quad (1)$$

W_{siso} —Strain energy density，J； C_{10}， C_{01} —Material constant； $\overline{I}_1$ —First-order strain invariant； $\overline{I}_2$ —Second order strain invariant.

The elastic modulus and shear modulus of rubber are shown in Formula 2 and 3:

$$E = 6(C_{10} + C_{01}) \quad (2)$$

$$G = 2(C_{10} + C_{01}) \quad (3)$$

E—Elastic modulus， MPa； G—Shear modulus， MPa.

Regardless of the friction between the rubber cylinder and the casing and the central pipe, the additional contact pressure generated on the inner wall of the casing under the action of the differential pressure between the upper and lower pressure during the working process of the rubber cylinder can be calculated by Formula (4):

$$2\pi H_1 R_t \tau_{rz} = \Delta P \pi R_t^2 - \Delta P \pi R_m^2 \quad (4)$$

H_1 —The axial length of the rubber cylinder under working condition，m； R_t —Casing inner wall radius，m； R_m —Metal ring radius，m； τ_{rz} —Shear stress on the contact surface between rubber cylinder and casing wall，MPa； ΔP —Working pressure difference，MPa.

For incompressible materials, there is the following relationship between the micro-element shear stress and the axial stress：

$$\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\partial \tau_{z\theta}}{\partial_\theta} = 0 \quad (5)$$

The strain of rubber cylinder has the following relationship：

$$\begin{cases} \varepsilon_r = \varepsilon_\theta = 0 \\ \tau_{z\theta} = \tau_{r\theta} = 0 \end{cases} \quad (6)$$

It can be obtained from simultaneous equations (4), (5) and (6):

$$\sigma_z = \frac{\Delta P}{2}\left(\frac{R_t^2 + R_m^2}{R_t^2}\right) \quad (7)$$

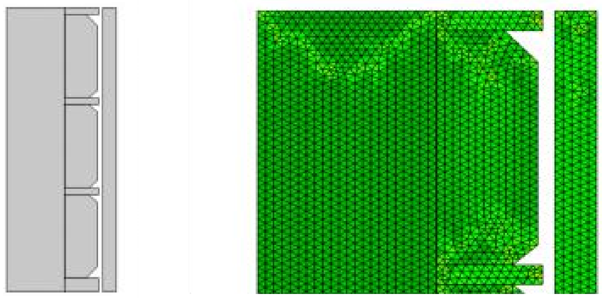
$$\sigma_r = \frac{\mu}{1-\mu}\sigma_z \quad (8)$$

σ —The axial length of the rubber cylinder under working condition，m； R_t —Casing inner wall radius，m； R_m —Metal ring radius，m； τ_{rz} —Shear stress on the contact surface between rubber cylinder and casing wall，MPa； ΔP —Working pressure difference，MPa.

3. ESTABLISHMENT OF FINITE ELEMENT MODEL OF PACKER RUBBER CYLINDER

3.1 Geometric model establishment and mesh generation

Refer to Y341-114 packer supporting conventional rubber cylinder for overall dimensions of packer rubber cylinder, with inner diameter of 73mm and outer diameter of 114mm. Add 40° chamfer outside the upper and lower rubber cylinders. The inner diameter of the metal spacer ring of the packer is 73mm and the outer diameter is 116mm. The outer diameter of the central pipe is 73mm, and the inner diameter of the sleeve is 121.4mm.Considering the structural characteristics of the assembly model and reducing the computational intensity, select two-dimensional axisymmetric in the dimension of the simulation space, and establish the section geometric model as shown in Figure 1. In the selection of solving physical field, first select the "solid mechanics" solution module. In order to solve the stress relationship of each part in the setting process, each imported part is formed into an assembly. Select "free triangular mesh" as the mesh cell, the maximum cell size is 2mm, the minimum cell size is 0.004mm, the maximum cell growth rate is 1.2, the curvature factor is 0.2, and the narrow area resolution is 1. The number of mesh elements is 8150, and the average element quality is 0.935. The finite element model and mesh division are shown in Figure 1.



a)Finite element model b) Mesh division

Fig. 1. Finite element model and mesh division of rubber cylinder

3.2 Setting of material properties

Hydrogenated nitrile rubber is selected as the rubber cylinder material. Compared with fluororubber, it has better performance of heat resistance, oxygen aging resistance and chemical resistance. It is a common material for packer rubber cylinder. The rubber cylinder material model is set as hyperelastic material. C_{10} and C_{01} in the Money-Rivilin model are closely related to the ambient temperature, so different C_{10} and C_{01} values are set for the simulation model at different temperatures. The rubber density is set as 1300kg/m^3, the material model of the central pipe and metal spacer ring is set as linear elastic material, the material type is set as 3Cr13, and the sleeve material is set as 42MnMo7.

3.3 Boundary condition settings

During setting, the rubber cylinder contacts with the central pipe, metal spacer ring and the inner wall of the casing respectively, so 12 contact pairs are set, namely, the rubber cylinder and the central pipe, the rubber cylinder and the upper metal spacer ring, the rubber cylinder and the lower metal spacer ring, the rubber cylinder and the inner wall of the casing. All contact pairs are set with Coulomb friction model, and the friction coefficient is set to 0.3. The contact method is set as a penalty function, and the penalty factor is controlled by the comsol built-in program. Considering that the central pipe and the metal spacer ring at the lowest layer do not move during the whole setting process, it is set as a fixed constraint. Point constraints are set at the upper and lower boundaries of the casing, and the contact surfaces of the remaining metal spacer rings and the rubber cylinder are supported by virtual springs to ensure the convergence of the calculation process. Set the specified displacement on the uppermost metal spacer ring, and the displacement parameter is set through the function to gradually add the displacement.

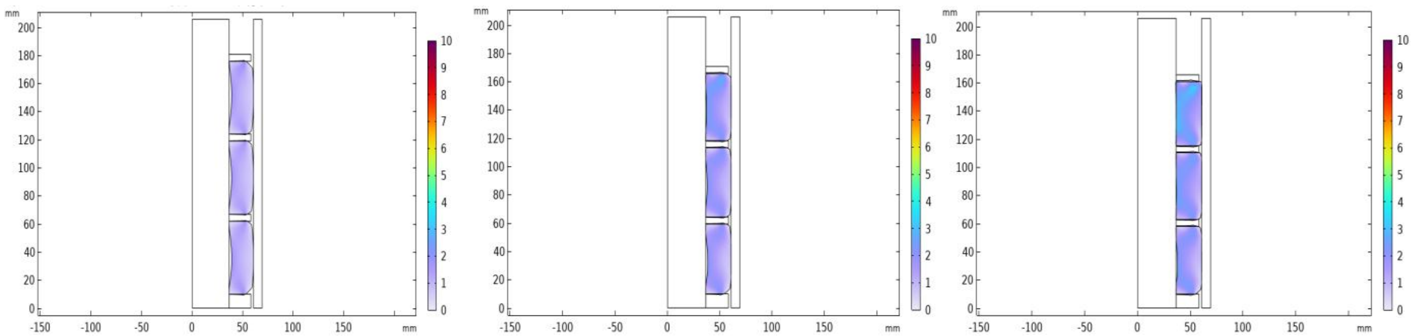
3.4 CO_2 swelling finite element model setup

At present, there is no relevant calculation model for gas invasion and swelling effect of CO_2 and rubber structure. Referring to the finite element calculation method of hydrogen absorption expansion of rubber materials, ignoring the CO_2 diffusion caused by stress or other factors, only considering the effect of concentration gradient on the diffusion of CO_2 in rubber, comparing this diffusion process with the heat transfer process of zero heat transfer, using the temperature field to replace the CO_2 concentration field in rubber, comparing the thermal expansion of the object caused by the heat transfer process with the phenomenon of rubber absorbing CO_2 gas swelling, and establishing a finite element model of heat conduction, And calculate the stress and strain of packer rubber cylinder caused by CO_2 swelling benefit through thermal-mechanical coupling.

Add a "thermal expansion" physical reaction interface under the hyperelastic material node, the volume reference temperature is defined as 293.15K, and the thermal expansion coefficient is set as tangent form. During the heat transfer calculation, the boundary concentration of the rubber cylinder in contact with SC-CO_2 is saturated, and the boundary temperature is 393.15K according to the temperature gradient of 100K. The boundary concentration of the rubber cylinder in contact with the central tube is 0, and the initial boundary temperature is set as the volume reference temperature. The thermal expansion generated on the rubber cylinder after the steady-state temperature field is obtained through the simulation and calculation of heat transfer process can obtain various mechanical parameters generated after CO_2 gas enters the rubber cylinder[8-9]. Reference [10] obtained the CO_2 swelling law of hydrogenated nitrile rubber under high temperature and high pressure through indoor test, and set the tangent thermal expansion coefficient of rubber material to 0.002/K.

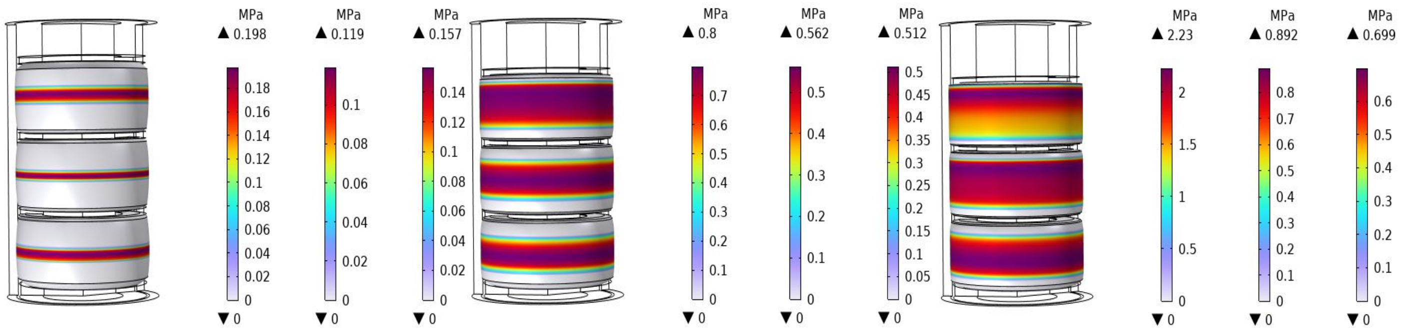
4. ANALYSIS OF SIMULATION RESULTS

Before the packer is put into the well, a reasonable setting distance shall be set for the rubber cylinder to ensure the effective sealing of the rubber cylinder to the oil jacket annulus. Too low setting distance will easily lead to incomplete setting of the rubber cylinder, resulting in the reduction of the contact area and



a)Compress distance 25mm b)Compress distance 30mm c)Compress distance 40mm

Fig. 2 Von mises stress nephogram of rubber cylinder



a)Compress distance 25mm b)Compress distance 30mm c)Compress distance 40mm

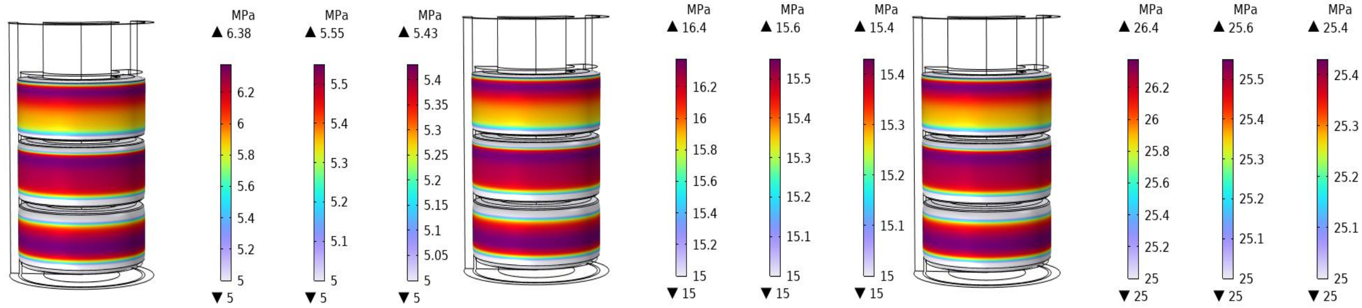
Fig. 3 Contact pressure nephogram between rubber cylinder and inner wall of casing

contact pressure between the rubber cylinder and the inner wall of the casing. Too high setting distance will easily destroy the rubber cylinder and also reduce the sealing reliability. For the above simulation model, the setting distance is set as 25mm, 30mm and 40mm respectively. Figure 2 shows the Von mises stress nephogram of the rubber cylinder corresponding to three setting distances at normal temperature without considering the influence of SC-CO_2 gas invasion swelling and working pressure difference.

It can be seen from the figure that with the increase of the setting distance, the shape of the rubber cylinder begins to produce large deformation, and the increase of deformation and stress decreases from top to bottom. When the setting distance is 25mm, the rubber cylinder has not been fully compressed; When the setting distance is 30mm, the Von mises stress in the rubber cylinder begins to produce stress concentration, and the deformation is further intensified; When the setting distance is 40mm, the Von mises stress concentration is further increased, and the rubber cylinder shape has completely filled the enclosed space.

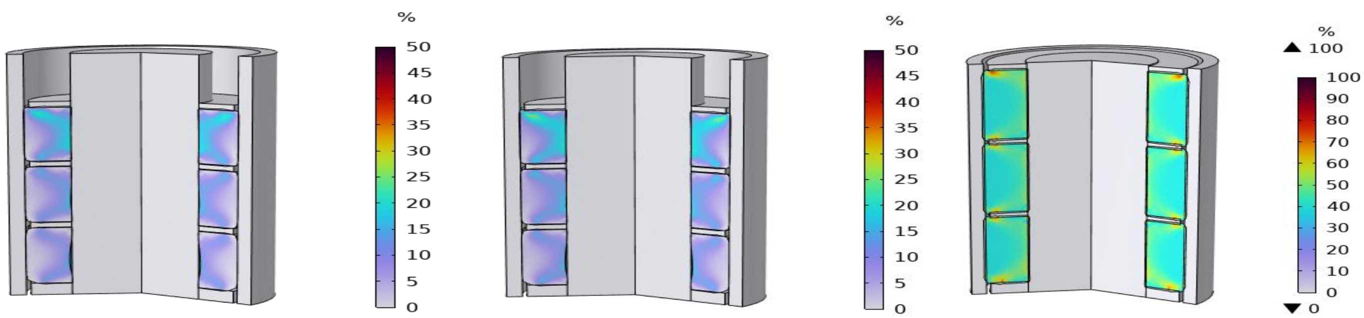
Figure 3 shows the contact pressure between the rubber cylinder and the inner wall of the casing under three setting distances. It can be seen from the figure that when the setting distance is 25mm, the upper and lower rubber cylinders first contact with the inner wall of the casing and produce extrusion. With the increase of the setting distance, the contact pressure of the middle rubber cylinder increases faster than the lower rubber cylinder. The setting mode of the conventional packer is one-way compression of the upper spacer ring. There is uneven deformation of the three rubber cylinders and uneven stress distribution on the contact surface of the upper rubber cylinder. The simulation results are consistent with the actual situation. When the setting distance reaches 40mm, the upper rubber cylinder has been fully compressed, and the maximum contact pressure is 2.23MPa. Continued compression will lead to damage and tear of the upper rubber cylinder. Therefore, the setting distance of 40mm is set as the setting distance of the simulation rubber model.

The downhole working temperature of CO2 injection wells is generally high, and the maximum temperature is generally close to 120℃. Under high temperature, the aging rate of rubber material will further increase, and the stress situation will change.The contact pressure of the rubber cylinder will decrease with the aging of the rubber as the downhole temperature increases. Under the steady state condition of 120 ℃, the contact pressure of the rubber



a)Contact Stress after compression(Working Pressure Difference 5MPa); b)Contact Stress after compression(Working Pressure Difference 15MPa); c)Contact Stress after compression(Working Pressure Difference 25MPa)

Fig. 4 Contact pressure nephogram of rubber cylinder under different working pressure difference conditions



Volume Strain after compression (Gas invasion wasn`t considered)

Volume Strain after compression (Gas invasion was considered)

Volume Strain after unsealing (Gas invasion was considered)

Fig. 5 Comparison of volumetric strain of rubber cylinder before and after SC-CO_2 gas invasion and swelling and nephogram of volumetric strain after unsealing

cylinder decreases by about 40% compared with that when it is just set.

After the packer is set, the rubber cylinder will bear the working pressure difference superimposed by the upper and lower injection systems. Figure 4 shows the contact pressure nephogram of the rubber cylinder under the steady state condition of 120℃ without considering the influence of SC-CO_2 gas invasion and swelling, when the working pressure difference is 5MPa, 15MPa and 25MPa respectively. It can be seen from the figure that with the increase of the working pressure difference, the contact pressure of the rubber cylinder increases, and the stress distribution between the three rubber cylinders becomes more uniform. Within the limit deformation range of the rubber cylinder, the working pressure difference can increase the contact pressure between the rubber cylinder and the inner wall of the casing, and enhance the sealing effect. However, if the working pressure difference is too large, it may cause the axial shear force of the rubber cylinder to be greater than the friction force, exacerbate the uneven stress distribution on the contact surface of the rubber cylinder, and cause the rubber cylinder to slip and deform.

The influence of SC-CO_2 on the setting performance of packer rubber cylinder is calculated by the thermal analogy method. Due to the limited sealing volume of the downhole annular space, when the rubber cylinder has been completely set, the gas invasion degree of SC-CO_2 to the rubber cylinder body will be less than the results measured by the indoor sample experiment. Therefore, the parameter scanning method is adopted, and the target temperature (SC-CO_2 diffusion percentage) is taken as the variable to scan step by step until the volume of the rubber cylinder expands to the limit of the wellbore, It is considered that the swelling is complete and the final expansion coefficient is obtained. The volume strain comparison of the rubber cylinder before and after SC-CO_2 gas invasion and swelling is shown in a) and b) in Figure 5.When SC-CO_2 is not considered, the maximum volume strain in the rubber cylinder is 21.79%. When the SC-CO_2 gas invasion occurs to the rubber cylinder, the maximum volume strain value rises to 26.52%, and the swelling effect causes the rubber cylinder to further expand and fill the entire sealing space.

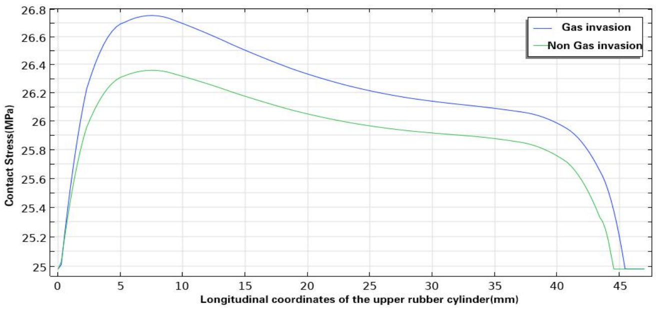


Fig.6 Comparison of the contact pressure between the upper rubber cylinder and the inner wall of the casing before and after the SC-CO2 swelling

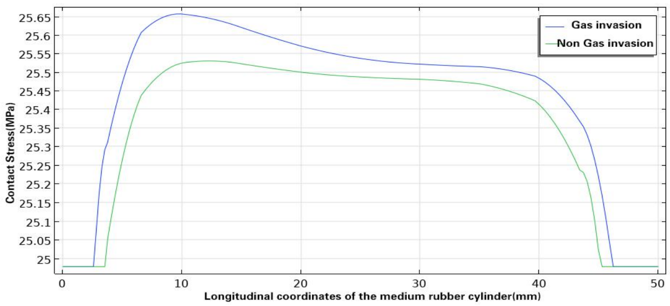


Fig.7 Comparison diagram of contact pressure between medium rubber cylinder and inner wall of casing before and after SC-CO2 swelling

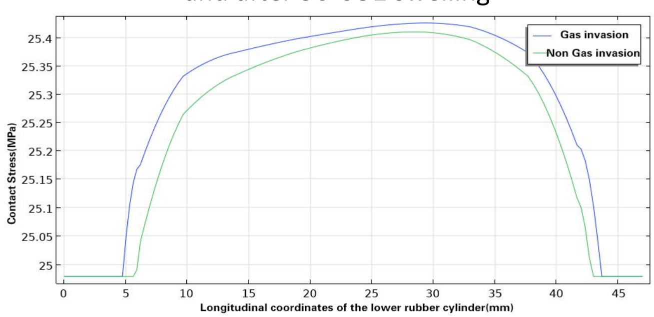


Fig.8 Comparison of the contact pressure between the lower rubber cylinder and the inner wall of the casing before and after the SC-CO_2 swelling

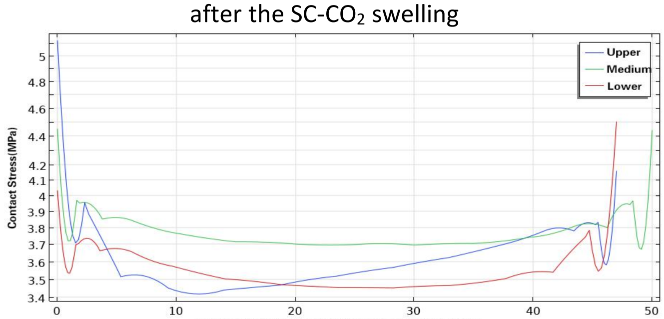


Fig.9 Considering the influence of SC-CO_2 swelling, the contact pressure curve between the rubber cylinder and the inner wall of the casing after unsealing

Figures 6 to 8 show the comparison of the contact pressure between the upper, middle and lower rubber cylinders and the inner wall of the casing before and after the SC-CO_2 swelling.Under the SC-CO_2 swelling effect, the contact pressure of the three rubber cylinders further increases, but the increase is small. The upper rubber cylinder rises from 26.38 MPa to 26.76 MPa, the middle rubber cylinder rises from 25.53 MPa to 25.66 MPa, and the lower rubber cylinder rises from 25.42 MPa to 25.45 MPa. C in Figure 5 shows the volumetric strain nephogram of the expansion of the rubber cylinder affected by SC-CO_2 swelling after the packer is unsealed. According to the swelling rule curve of SC-CO_2 under the condition of rapid decompression in hydrogenated nitrile rubber, the volumetric expansion rate of the rubber cylinder will exceed 200% of its own.Therefore, even if the packer is completely unsealed, there is still contact pressure between the rubber cylinder and the inner wall of the casing. Figure 9 shows the contact pressure curve between the three rubber cylinders and the inner wall of the casing after the rubber cylinder is unsealed. It can be seen that there is still a large contact pressure at the edge of the rubber cylinder affected by the swelling effect after unsealing. The upper rubber cylinder is more than 5MPa, the middle rubber cylinder is close to 4.5MPa, and the lower rubber cylinder isclose to 4MPa.

5. CONCLUSIONS

The setting distance is the decisive factor to determine the initial sealing effect of the packer. From the simulation results, it can be seen that the maximum contact pressure of the rubber cylinder increases significantly with the increase of the setting distance, indicating that a larger setting distance is beneficial to the initial sealing. However, too high setting distance can easily lead to structural damage of the rubber cylinder in advance, affecting the sealing effect; If the setting distance is too low, it is easy to cause insufficient deformation of the rubber cylinder and affect the sealing effect.The temperature of the working environment determines the aging rate of the packer rubber cylinder. The simulation results show that the high temperature environment reduces the contact pressure of the rubber cylinder very seriously, but compared with the impact of the working pressure difference on the contact pressure, the effect is not obvious. The working pressure difference is the main influencing factor of the contact pressure when the rubber cylinder is working. The greater the working pressure difference, the greater the contact pressure between the rubber cylinder and the outer wall of the casing, and the more sufficient the sealing. However, the swelling effect of SC-CO_2 has a positive correlation with the working pressure difference. If there is shut down or large formation pressure fluctuation during the operation of the injection well, it will greatly increase the risk of swelling and sealing loss of the rubber cylinder.

Therefore, in the design of the packer sealing system for CO_2 injection wells, the rubber material should be selected first according to the downhole working environment temperature to reduce the aging effect of high temperature on the rubber barrel. Determine the mechanical index of rubber cylinder through indoor test, design the setting distance according to the mechanical index, and increase the setting distance as much as possible without crushing the rubber cylinder. The purpose is to improve the initial sealing effect, reduce the further expansion space of the rubber cylinder affected by the SC-CO_2 swelling effect, and improve the sealing stability in the working process.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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