

Study on Sealing Performance of Packers for Supercritical CO₂ Flooding

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Abstract

During the process of supercritical CO₂ injection, the corrosion of rubber materials frequently leads to the sealing failure of packer elements. To address this issue, this study employs Hydrogenated Nitrile Butadiene Rubber (HNBR) sealing elements and conducts finite element simulations based on the Yeoh hyperelastic constitutive model. The impact on sealing performance is analyzed from four dimensions: the phase state of the corrosive medium, temperature, acid gas composition, and corrosion duration. The simulation results indicate that: Phase state and temperature primarily compromise structural integrity: Under conditions involving formation water or high temperatures (160°C), physical swelling and constrained thermal expansion induce severe stress concentrations at the element's shoulder (with increases of 80.47% and 165.81%, respectively). This phenomenon significantly increases susceptibility to bulk rupture or extrusion failure. H₂S content and service duration primarily govern the decay of contact pressure: Chemical attack by H₂S and prolonged service (8 days) lead to modulus degradation and stress relaxation. These factors result in a substantial decline in contact sealing stress (reductions of 28.26% and 62.92%, respectively), thereby significantly elevating the risk of interfacial leakage. Based on finite element analysis, this study elucidates the impact of various corrosion factors on sealing performance, providing a theoretical basis for the long-term safety evaluation of packers in supercritical CO₂ injection applications.

Keywords

Packer Element; Supercritical CO₂; Sealing Performance; Corrosion; Finite Element Analysis.

1. Introduction

Carbon Capture, Utilization, and Storage coupled with Enhanced Oil Recovery (CCUS-EOR) technology offers the dual benefits of carbon emission reduction and enhanced oil recovery^[1-5]. During the injection process, as formation temperature and pressure rise, CO₂ transitions into a supercritical state ($T > 31.1^{\circ}\text{C}$, $P > 7.38\text{ MPa}$)^[6]. As a critical downhole tool for the precise injection of CO₂ into target reservoirs, the packer relies on the sealing performance of its element, which directly dictates the integrity and safety of the entire injection system. However, supercritical CO₂ exhibits strong solvency and corrosivity toward rubber materials, frequently leading to sealing failure of the packer element^[7-8].

Hydrogenated Nitrile Butadiene Rubber (HNBR) is regarded as the preferred material for CCUS-EOR packer elements due to its exceptional performance in high-temperature, high-pressure, and corrosive environments. Experimental studies demonstrate that HNBR exhibits excellent corrosion resistance and mechanical property retention, sustaining temperatures up to 120°C and pressures of

35MPa, with favorable performance in field applications [9-14]. Regarding simulation studies, researchers have investigated the sealing behavior of packer elements by establishing finite element models. Wang et al. [15] analyzed the sealing process of HNBR elements through combined experiments and simulations, utilizing compression distance to evaluate sealing performance. Zhu et al. [16] indicated that supercritical CO₂ environments increase the shear stress within the element, while the setting distance and working differential pressure significantly influence the sealing contact stress. Zou [17] found that corrosion induced by supercritical CO₂ exacerbates stress concentration at the element's shoulder, thereby compromising the sealing reliability of the packer. Furthermore, Zhang et al. [18] emphasized that contact stress is a critical indicator for evaluating sealing performance, noting that a reduction in maximum contact stress directly leads to a decline in sealing capability.

These studies have laid a foundation for the optimization and selection of rubber cartridge materials and the evaluation of their sealing performance. However, most existing research has focused on the variation laws of mechanical properties of rubber materials under single environmental factors or constant working conditions, lacking systematic comparative analysis on the sealing performance of rubber cartridges after corrosion. In addition, conventional finite element analysis mostly conducts predictions based on the initial performance parameters of rubber, often ignoring the nonlinear effects of material mechanical property deterioration caused by corrosion damage (such as changes in stress-strain relationships, hardening or softening) on sealing behavior. Therefore, it is difficult to truly reflect the sealing reliability of rubber cartridges after long-term downhole service.

To address the above problems, this paper focuses on the complex working conditions of CCUS-EOR. The stress-strain test data of HNBR under typical corrosive working conditions were selected for parameter fitting of the Yeoh model, and then a packer sealing finite element model capable of characterizing the nonlinear time-varying damage characteristics of materials was established. The effects of different corrosion factors on sealing performance were analyzed, aiming to provide theoretical basis and data support for the optimal design and safety evaluation of CCUS-EOR packers.

2. Finite Element Analysis of Packer Sealing Performance

2.1 Finite Element Model

Given that the packer system (comprising the central pipe, rubber element, and casing) exhibits axisymmetric characteristics in terms of both structure and loading, a two-dimensional (2D) axisymmetric geometric model was established to enhance computational efficiency while ensuring accuracy. The rubber element is defined as a nonlinear visco-hyperelastic body, and its geometric model is illustrated in Figure 1(a). The element measures 70 mm in length and 21.5 mm in width, with an initial assembly gap of 2 mm between the element and the casing.

The central pipe and the outer casing are simplified as rigid bodies. Spacer rings are positioned at both ends of the element to transmit the axial setting force and constrain the element's axial displacement. The model specifically defines two contact pairs: 'element inner surface–central pipe outer wall' and 'element outer surface–casing inner wall.' A small-sliding contact algorithm is employed, with the friction coefficient set to 0.2, and the normal behavior is governed by the 'hard contact' criterion.

In terms of mesh generation (Figure 1(b)), considering the near-incompressibility of rubber materials (deformable shape with volume conservation) and their susceptibility to 'volumetric locking,' the CAX4H hybrid element was adopted for the rubber component. This element type is specifically designed for handling incompressible or nearly incompressible material problems. Furthermore, the mesh was locally refined at the 'shoulder' region—where the element contacts the casing—to accurately capture the stress concentration phenomena.

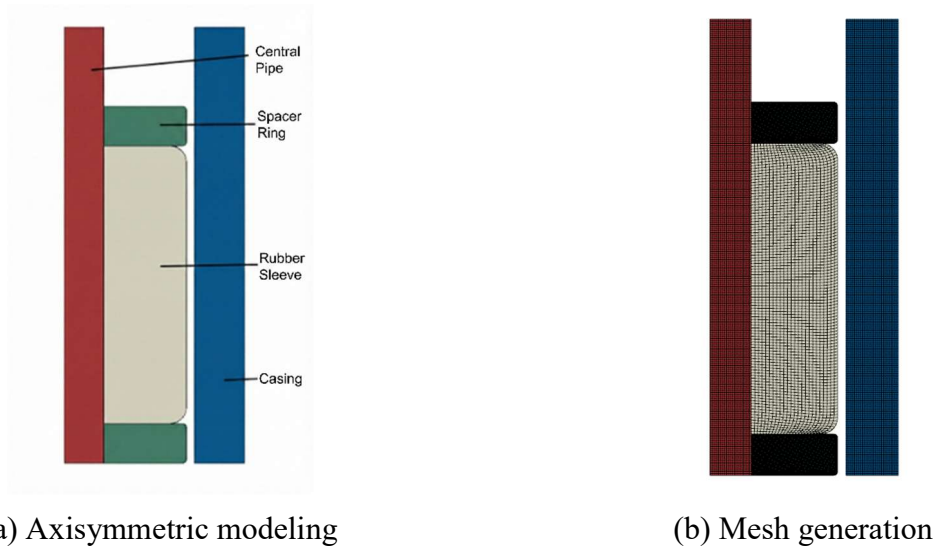


Figure 1. Finite element model.

To validate the rationality of the mesh generation, a mesh independence analysis was conducted on the rubber element, with the results presented in Figure 2. Based on the convergence behavior, the number of elements was finalized at 5,074. At this mesh density, the simulation results stabilized, thereby meeting the requirements for computational accuracy.

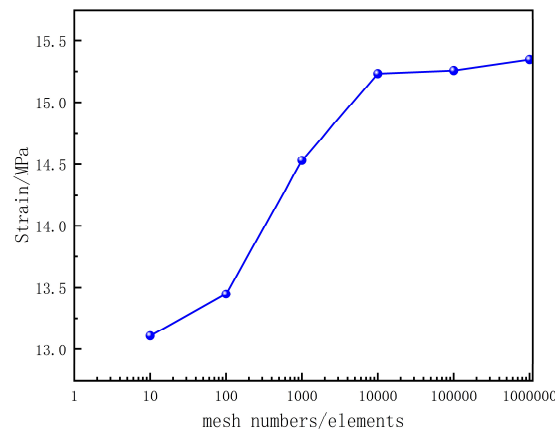
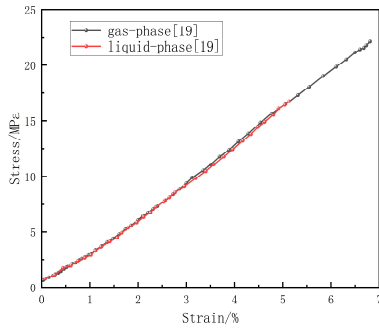


Figure 2. Simulation results with different mesh numbers.

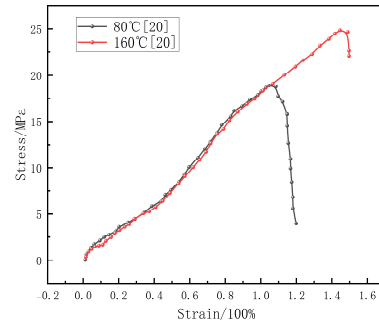
2.2 Establishment of the HNBR Hyperelastic Model

2.2.1 Mechanical Properties of HNBR After Corrosion under Different Factors

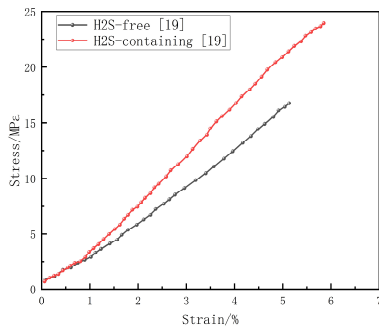
To accurately simulate the mechanical behavior of the corroded packer element, it is essential to first obtain the stress-strain data of the HNBR material under various corrosion environments. Through a literature review [19-21], mechanical property data of HNBR were collected under conditions involving gas/liquid phases, varying temperatures, H₂S-containing environments, and different corrosion durations, as illustrated in Figure 3. These data provide the foundation for establishing a hyperelastic constitutive model that accounts for corrosion damage.



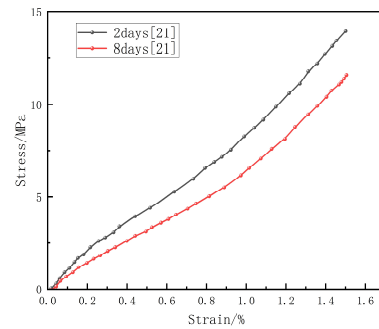
(a) Effect of corrosion phase state



(b) Effect of corrosion temperature



(c) Effect of H2S environment



(d) Effect of corrosion duration

Figure 3. Stress-strain curves of HNBR under different corrosion environments.

2.2.2 Hyperelastic Constitutive Model of HNBR under Different Corrosion Factors

HNBR is a typical hyperelastic material whose mechanical behavior cannot be accurately described by traditional linear elastic parameters such as Young's modulus and Poisson's ratio; therefore, a hyperelastic constitutive model is adopted in this paper. Experimental data of HNBR after 2 days of corrosion was selected to perform a comparative fitting of various constitutive models, as shown in Figure 4.

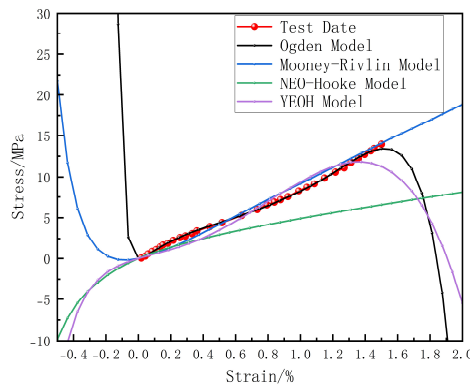


Figure 4. Comparison of hyperelastic models.

The fitting results indicate that the Yeoh model exhibits the highest correlation with the experimental data and can better describe the mechanical response of HNBR under large deformation conditions. Consequently, the Yeoh hyperelastic model is employed in this study to characterize the stress-strain

relationships of HNBR under various corrosion factors. Furthermore, a user-defined material subroutine is implemented within the finite element software to describe the time-dependent degradation of the material's mechanical properties following corrosion.

2.3 Comparative Analysis of Sealing Performance under Multi-Dimensional Corrosion Factors

Based on the established finite element model and the Yeoh hyperelastic constitutive model, a systematic simulation analysis of the sealing performance of the HNBR packer element was conducted in Abaqus under various corrosion environments.

2.3.1 Mechanical Properties of HNBR After Corrosion under Different Factors

In CCUS injection wells, the upper section of the packer may be exposed to the gas phase (pure supercritical CO₂ without formation water), whereas the lower section undergoes prolonged immersion in CO₂-saturated formation water (liquid phase). As illustrated in Figure 5, the comparative simulation results indicate that the liquid-phase corrosion environment exerts a significantly more severe deteriorative effect on the element compared to the gas-phase condition.

Following liquid-phase corrosion, the equivalent stress of the element increased by 80.47%, axial displacement rose by 2.3%, and the contact stress between the element and the casing increased by 52.56%. In the liquid-phase environment, the dissolution of CO₂ in water creates a weak carbonic acid environment that accelerates ion penetration and chemical hydrolysis. This process leads to more severe disruption of the rubber polymer chain structure, resulting in a significant reduction in both the ultimate strength and maximum elongation of the material. Consequently, the load-bearing capacity of the element diminishes, and the elevated equivalent stress increases the risk of material rupture.

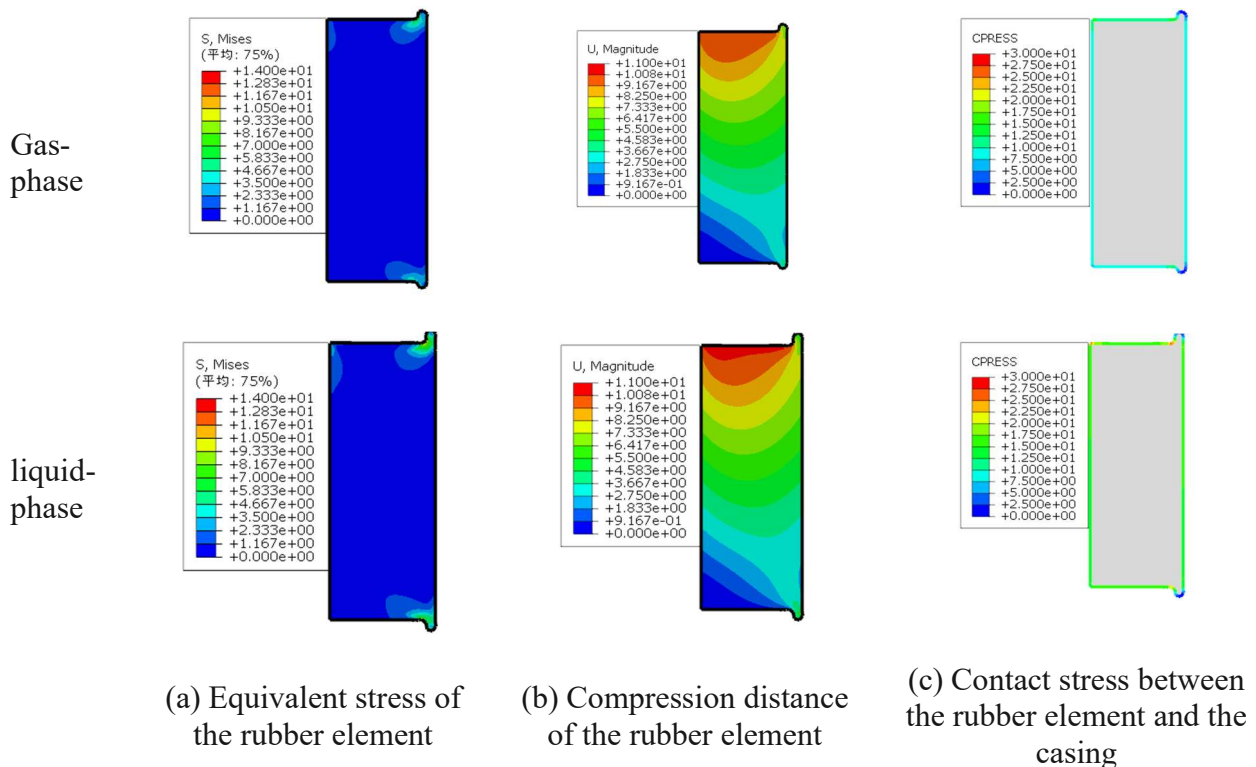


Figure 5. Simulation comparison of HNBR after corrosion in gas-phase and liquid-phase environments.

2.3.2 Analysis of Sealing Performance of HNBR after Corrosion at Different Temperatures

Recommended Translation)"Temperature acts as a critical variable influencing the kinetics of supercritical CO₂ corrosion. As illustrated in Figure 6, the simulation results reveal a distinct disparity

in sealing performance between the 80°C and 160°C operating conditions. Compared to the 80°C scenario, the element at 160°C exhibits a surge in equivalent stress of 165.81%, an increase in axial displacement of 3.07%, and a rise in contact stress of 130.33%. However, despite the increase in contact stress, an integrated analysis with the material properties in Figure 3(b) indicates that the ultimate strength of HNBR declines significantly after high-temperature corrosion. A critical conflict arises between the surging equivalent stress (induced by thermal expansion) and the deteriorating material strength. This imbalance directly increases the susceptibility of the element to exceed its structural limits, thereby leading to failure.

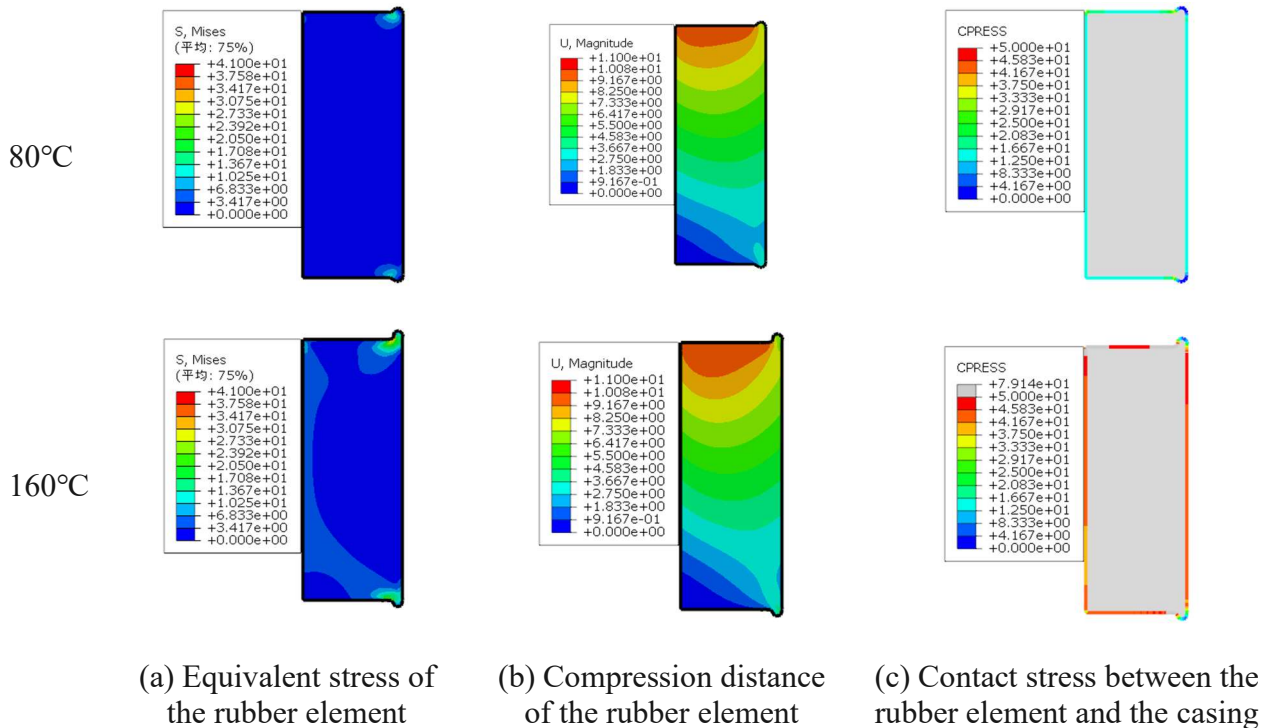


Figure 6. Simulation comparison of HNBR after corrosion at different temperatures.

2.3.3 Analysis of Sealing Performance of HNBR after Corrosion in Environments with and Without H₂S Gas

The comparative simulation results are presented in Figure 7. The failure mechanisms differ distinctly between liquid-phase supercritical CO₂ corrosion environments containing H₂S and those without H₂S. Data indicate that, compared to the pure CO₂ environment, post-corrosion in the H₂S-containing environment results in a decrease of 35.12% in equivalent stress, a reduction of 2.3% in axial displacement, and a decay of 28.26% in the contact stress with the casing. As a highly corrosive medium, H₂S accelerates the chemical degradation and molecular chain scission of the rubber matrix. As observed in the post-corrosion stress-strain curves in Figure 3(c), the modulus of the corroded material decreases significantly, exhibiting distinct softening characteristics. This deterioration in mechanical properties weakens the rebound resilience of the element under the same setting load, rendering it unable to provide sufficient reaction force. Consequently, this leads to a substantial decline in both contact stress and sealing capability.

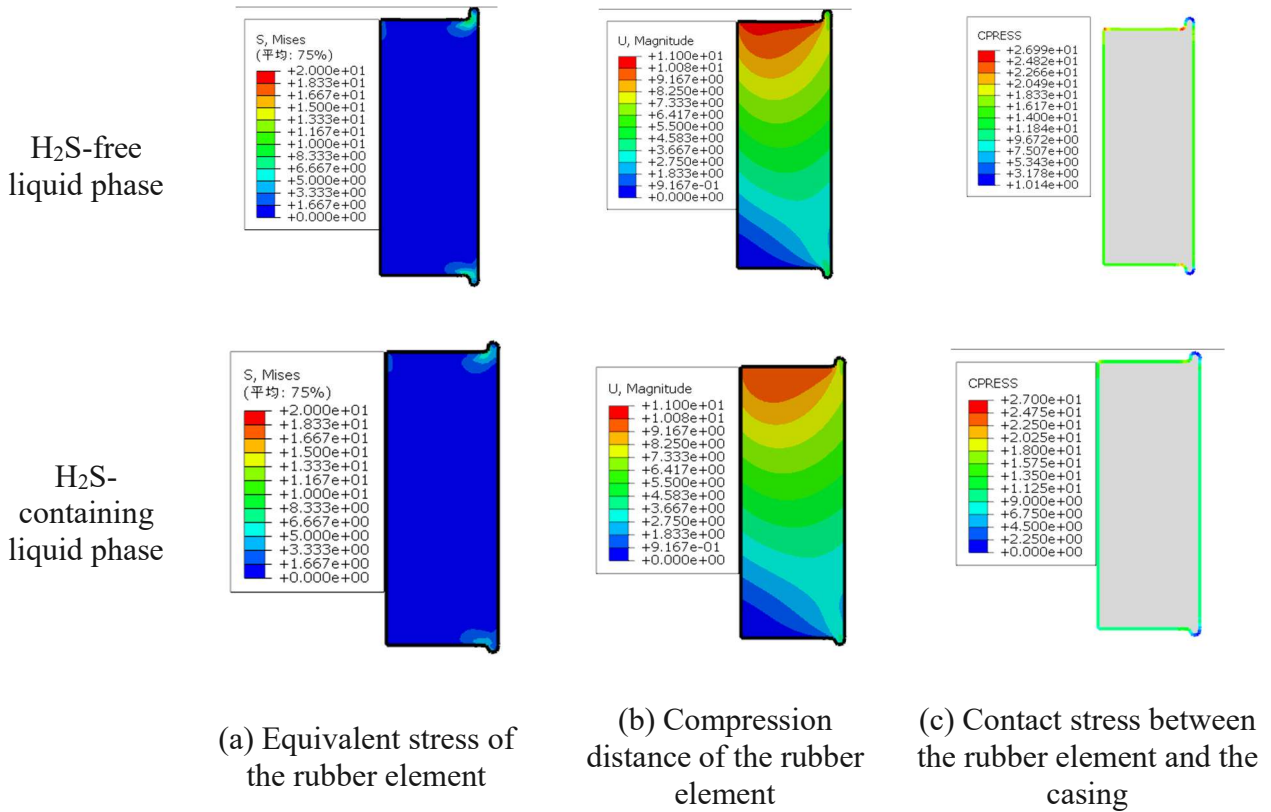


Figure 7. Simulation comparison of HNBR after corrosion in environments with and without H₂S

2.3.4 Analysis of Sealing Performance of HNBR after Corrosion for Different Durations

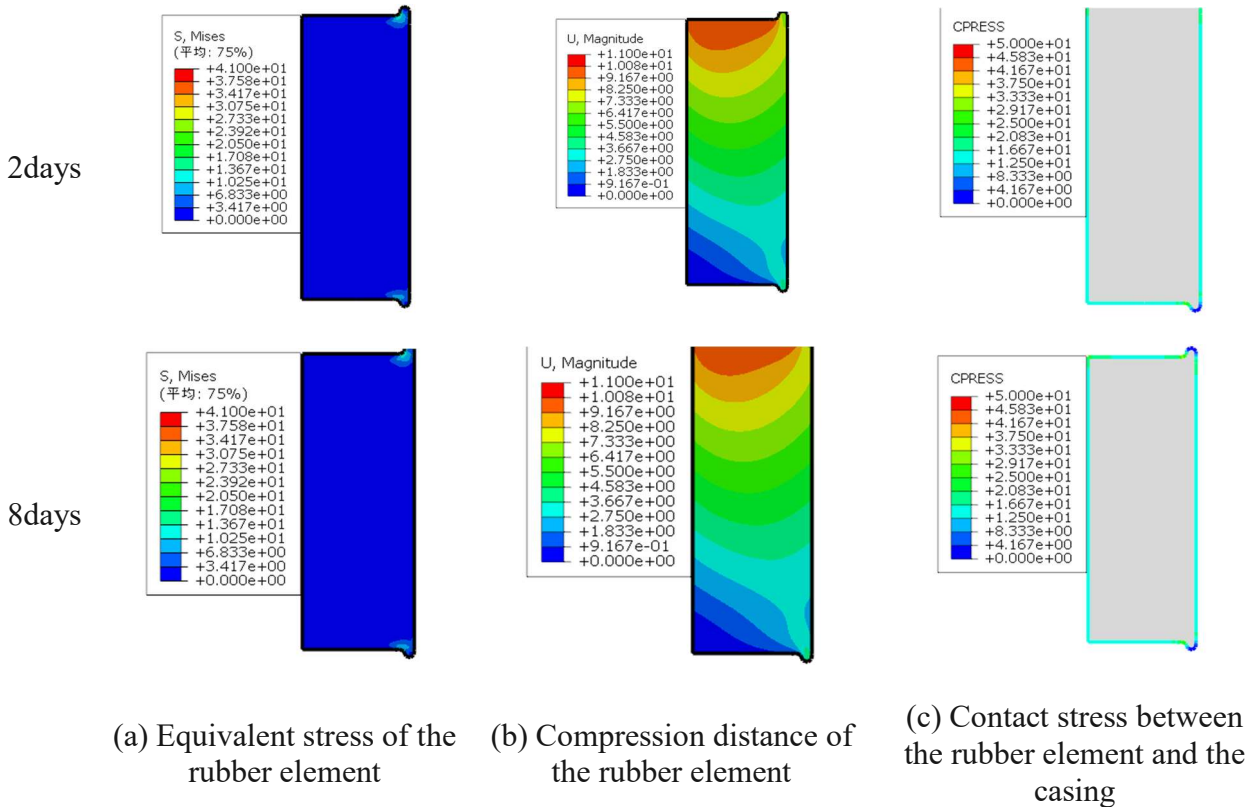


Figure 8. Simulation comparison of HNBR after corrosion for different durations.

Sealing performance exhibits a dynamic decay process over the course of service time. As illustrated in the simulation results in Figure 8, compared to the data from 2 days of corrosion, the element after 8 days of corrosion experienced a 59.2% decrease in equivalent stress, a 0.57% reduction in axial displacement, and a substantial decay of 62.92% in contact stress with the casing. This trend indicates that as the corrosion duration extends, the cumulative effect of internal material damage becomes pronounced. This accumulation leads to severe relaxation of the interfacial contact stress required to maintain the seal, thereby incrementally increasing the risk of leakage during long-term service.

3. Conclusion

In this paper, the impact of the multi-factor downhole environment in CCUS-EOR wells on the sealing performance of packer elements (HNBR) was investigated through systematic finite element analysis. The following primary conclusions were drawn:

- (1) Liquid-phase and high-temperature environments significantly exacerbate stress concentration and the risk of long-term failure. The degree of corrosion experienced by HNBR in liquid environments containing formation water or at high temperatures (160°C) is substantially higher than that in gas-phase or lower-temperature environments. Liquid-phase corrosion causes the equivalent stress at the shoulder to surge by 80.47%, while at 160°C, this surge reaches 165.81%. These conditions are highly prone to inducing shoulder tearing and bulk cracking of the element.
- (2) H₂S environments lead to material embrittlement and a comprehensive decline in sealing performance. The presence of H₂S induces a comprehensive reduction in the stress-strain properties of the rubber, resulting in a decrease in the element's rebound resilience. Macroscopically, this manifests as a 28.26% decay in contact stress.
- (3) Sealing performance undergoes continuous degradation over time. As the corrosion duration extends to 8 days, the equivalent stress decreases by 59.2%, axial displacement reduces by 0.57%, and the contact stress with the casing decays by 62.92%. This indicates that the sealing system faces sustained performance attenuation during long-term service, making time-dependent evaluation indispensable.

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