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Performance Influencing Factors and Research Progress of Packer Rubber under HPHT and Corrosive Downhole Conditions

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Abstract

The packer is an indispensable sealing tool in oil and gas well completion and intervention operations; its sealing performance directly affects down hole safety and efficient hydrocarbon production. As the core sealing component of the packer, the packer rubber must maintain stable performance in extreme downhole environments characterized by high temperature, high pressure, strong corrosion, and long service life. This paper systematically reviews, from the perspectives of material properties, aging behavior, stress relaxation, corrosion effects, and structural design, the key factors affecting packer rubber sealing performance. It also analyzes recent domestic and international advances in the design and development of high-performance packer rubbers. Studies show that high-performance elastomers such as AFLAS and FKM exhibit superior mechanical strength and chemical stability in high-temperature, high-corrosion environments compared to conventional HNBR. During service, however, rubber materials tend to undergo stress relaxation, causing a significant drop in contact stress and a concomitant decline in sealing performance. Furthermore, downhole fluid corrosion leads to rubber embrittlement and strength degradation, which in turn can trigger seal failure. On the structural side, optimizing compression ratios, controlling interface friction, and introducing anti-"shoulder extrusion" features all effectively enhance sealing reliability. Under multiphysics coupling, numerical simulations combined with experimental validation are currently the prime means of improving service-life prediction accuracy and design optimization efficiency. In summary, improving packer rubber performance requires coordinated optimization of material selection, structural compatibility, and mechanical behavior control. The findings in this review provide important guidance for designing packer sealing elements under complex well conditions and offer key technical support for intelligent completions and green, efficient oilfield development.

Keywords: packer rubber; high temperature and high pressure; sealing performance; stress relaxation; corrosive environment; elastomer materials; structural optimization; multiphysics coupling.

1. Introduction

Since their first application in the twentieth century, packers have been widely used as core isolation devices in petroleum, natural gas, and geothermal wells. With ever-growing global energy demand—especially for deep, ultra-deep, and shale gas reservoirs—the downhole environment has become increasingly severe: temperatures can exceed 150 °C, and pressures may reach hundreds of megapascals [1, 2]. At the same time, wellbore architectures and completion methods have grown more complex (e.g., multistage casing strings, high-pressure acidizing, and chemical flooding) [3, 4]. Under these demanding conditions, the packer rubber (elastomer sealing element) must maintain reliable sealing for extended periods, directly influencing zonal isolation efficiency, operational safety, and overall resource recovery [5–7]. Therefore, a comprehensive, systematic investigation into the factors that affect packer rubber performance has significant theoretical and practical engineering value.

2. Importance of Packer Rubber Performance

2.1 Ensuring Effective Zonal Isolation

The packer rubber is the core component that realizes both sealing and isolation within the packer. During completion, zonal production, hydraulic fracturing, and other downhole operations, the rubber must radially expand between casing-to-casing or casing-to-tubing annuli so that it closely adheres to the wellbore. This ensures effective fluid isolation between different intervals. Such zonal isolation is critical for preventing crossflow, gas migration, or water invasion between adjacent reservoir layers. Without a reliable seal, high-pressure fluids could migrate up the wellbore or through the casing, leading to surface equipment overpressure or even blowouts. Moreover, a reliable seal also prevents harmful substances (e.g., H_2S, CO_2) from leaking into surrounding formations or to the surface, thereby protecting the environment [8, 9]. Consequently, the sealing reliability of packer rubber is one of the key factors in ensuring safe well operations, precise reservoir control, and compliance with environmental requirements [10].

2.2 Adaptation to High-Temperature, High-Pressure Conditions

As oil and gas exploration moves into deeper and unconventional reservoirs, downhole conditions often present high temperatures, ultra-high pressures, and near-critical CO_2 states. In such extremes, the packer rubber must endure high compression forces from the casing and thermal stresses from downhole fluids, preserving mechanical strength and elasticity. For example, in wells deeper than 4,000 m or in HPHT (High-Pressure, High-Temperature) wells, temperatures can reach or exceed 150 °C, and pressures may surpass 130 MPa. These conditions place extraordinary demands on the elastomeric material. If the rubber undergoes thermal aging, elasticity reduction, or excessive swelling, the seal will fail. Therefore, there is a pressing need to develop elastomer formulations with excellent heat resistance, pressure stability, and dimensional constancy. Composite materials or high-temperature-resistant formulations are used to maintain sealing performance while ensuring long-term service under HPHT conditions [11, 12].

2.3 Service Life and Cost Considerations

As a wear-prone component, packer rubber's service life directly affects the packer system's stability and reliability. If the rubber degrades—due to aging, stress relaxation, fatigue, or corrosion—its sealing function will be lost, and the entire packer must be pulled out. This not only interrupts ongoing downhole operations but also incurs significant manpower, equipment, and time costs to fish out the packer or re-complete the well. In deep or offshore operations, a single packer replacement can be extremely costly. Therefore, enhancing the rubber's anti-aging properties, mechanical strength, and cyclic-use life not only extends the packer's operational lifespan and improves efficiency, but also significantly reduces maintenance expenses and economic losses. Long-life, high-reliability packer rubbers have become a core objective in modern packer design [13].

3. Key Factors Influencing Packer Rubber Performance

3.1 Material Properties

Wen-Jian Lan et al. [14] employed ABAQUS to perform numerical optimization and experimental validation on packer rubbers made from two materials (HNBR and AFLAS). By identifying weak points in conventional packer rubber structures and iteratively optimizing the geometry, they found that three metal-protected rubber designs still posed failure risks under HPHT conditions. Ultimately, an optimized design combining AFLAS material with a reinforced structure exhibited excellent sealing performance during multistage hydraulic fracturing in a horizontal well.

Cheng Wenjia et al. [15] conducted research on specialty elastomer formulations and packer sealing structures. By optimizing the rubber compound and molding process, they developed two grades of special rubber with Shore A hardness 80 and 90, which demonstrated excellent physical properties, corrosion resistance, and gas-explosion resistance. Combining PTFE and metal reinforcements, they developed a composite sealing element. Both simulation and field tests verified reliable sealing at 232 °C and 103.4 MPa. The full packer passed API 11D1 V0 qualification tests, and in-field applications showed stable, leak-free performance, indicating strong potential for broader adoption.

3.2 Aging Behavior

Xu Zheng et al. [16] studied the working performance of the packer sealing system by focusing on HNBR's mechanical behavior at high temperature. They performed uniaxial, planar, biaxial tensile, and stress-relaxation experiments to establish a hyperelastic and viscoelastic constitutive model. Based on experimental data, they developed a finite element analysis method for the packer seal system, proposing evaluation indices such as compression ratio, line contact pressure, surface contact pressure, and sealing coefficient. They also analyzed how high-temperature–induced stress relaxation affects sealing performance. The optimized seal structure improved sealing performance by over 30%.

Farzaneh Hassan et al. [17] investigated the mechanical behavior of HNBR elastomers during thermal aging, revealing that aging is mainly driven by chain scission and crosslinking reactions. Aging increases material stiffness, but when temperature exceeds 150 °C, properties degrade sharply, becoming brittle and failing at low strains. DSC and FTIR analyses showed that at 175 °C, chain scission dominates the aging mechanism. Two failure modes arise from aging: (1) elastic failure, where stiffer material requires higher compression stress to maintain a seal, and (2) brittle fracture at high temperature due to embrittlement. Life-prediction results indicate that samples aged at different temperatures ultimately share similar failure patterns.

3.3 Stress Relaxation

Xu Zheng and Bin Li [18] demonstrated that a packer's sealing performance under high-temperature conditions is influenced by multiple factors. First, rated set pressure may be insufficient to ensure full contact between the seal element and the casing; they recommend increasing set pressure or optimizing structural design. Second, rising temperature significantly reduces the packer rubber's mechanical properties, causing average contact stress to drop by about 15% (up to 20%). In addition, stress relaxation induced by high temperature further weakens sealing ability: average contact stress decreases by roughly 35%, with maximum reductions exceeding 50%. To mitigate these effects, they propose introducing a temperature safety factor (≥ 1.25) and a stress-relaxation safety factor (≥ 1.56) to enhance sealing reliability.

Li Bin et al. [19], using advanced test equipment at 180 °C, conducted uniaxial tensile and stress-relaxation tests on Y344-type packer FKM rubber. They fitted a hyperelastic and viscoelastic constitutive model via least-squares regression and built a simplified finite element model. Their study showed that stress relaxation reduces maximum shear stress at the ends and within the rubber, which helps delay tear failure and extend service life.

However, contact stress, line pressure, and surface pressure between the rubber and casing all decrease due to stress relaxation—maximum contact stress fell by over 15%, and effective sealing length decreased by 16.93%. High-temperature stress relaxation thus significantly impacts packer sealing performance and must be carefully considered.

3.4 Corrosion Effects

Yue Qian-bei et al. [20] performed laboratory tests on expandable packers used in multistage fracturing with stationary tubing under various corrosive environments. Their results showed that corrosion environments markedly reduce rubber shear strength, tensile strength, and elastic modulus. They established a dynamic model of packer-to-tubing interaction and proposed a safety evaluation method for packer setting based on dynamic results. In a field application in Daqing Well Gao 182-151, although no leaks occurred in each fracturing stage, the corroded rubber at stage I had a shear safety factor ≤ 1.10, indicating a risk of tearing.

Baojun Dong et al. [21] studied corrosion mechanisms of different packer rubber materials under downhole conditions. They found that in CO_2–H_2S environments, AFLAS's mass and volume gain rates are close to those of FKM, while HNBR's mass gain rate is roughly three times that of FKM. In terms of mechanical properties, FKM shows minimal change, AFLAS shows a slight decline, and HNBR suffers significant deterioration. Regarding fracture morphology, AFLAS and HNBR exhibit brittle fracture, whereas FKM fails in a ductile manner. Comprehensive analysis indicates that FKM has the best corrosion and aging resistance, followed by AFLAS, while HNBR performs worst. Hence, HNBR is not recommended for use in CO_2–H_2S gas wells. SEM/EDS images further confirm microstructural changes before and after corrosion.

3.5 Friction Effects

Peng-Cheng Wang et al. [22] developed a finite element stress-strain modeling method for elastomeric packers after mechanical set to analyze sealing performance under HPHT downhole conditions. Using experimentally measured uniaxial tensile data, they selected the Ogden model that best fits the material behavior. Their results show that the interface friction coefficient has a significant effect on the contact stress distribution and von Mises stress concentration between the packer rubber and casing: higher friction coefficients yield lower average contact stress, with stress distributed as a gradient along the contact length. Meanwhile, variations in internal and external groove profiles and support ring structures induce local bulging deformation, which helps form a stable seal. This research emphasizes the need to account for interface friction and structural parameters when designing packer rubber, and it proposes combining experimental data, simulations, and machine learning to optimize fracturing packer rubber design in the future.

Shao-Qi Chen et al. [23] showed that for the Y341-114 compression packer, the Yeoh model effectively simulates rubber deformation behavior. Finite element results indicate that rubber compression amount and the contact stress against the casing increase with larger setting loads; moreover, the three rubber elements do not contact the casing simultaneously, with the lower rubber element deforming the most. Simulation analysis under 20–28 MPa injection pressure revealed a maximum von Mises stress of 25.45 MPa—below the rubber's compressive strength—demonstrating safe operation. The maximum contact stress between rubber and casing exceeds formation fluid pressure, indicating good sealing capability. Friction helps prevent the rubber from shifting. Contact-stress analysis shows that at the onset of setting, the rubber's midsection contacts the casing first; during injection, stress concentrates at the rubber's shoulder region, especially the lower shoulder, which is prone to "shoulder extrusion." To extend packer life, it is recommended to reinforce both ends of the rubber or introduce anti-"shoulder extrusion" features in the design.

4. Conclusions

As the core downhole sealing and isolation component, packer rubber's performance directly influences the safety, economics, and environmental compliance of oil and gas operations. With development shifting toward deep, ultra-deep, and unconventional reservoirs, packer rubbers face extreme, coupled challenges—high temperatures (> 150 °C), high pressures (> 130 MPa), and multiphysics interactions (chemical corrosion, dynamic friction, stress relaxation). In recent years, significant progress has been made in understanding and improving packer rubber performance:

1. Material Optimization: High-temperature elastomers such as AFLAS and FKM, as well as composite materials, have significantly enhanced thermal and corrosion resistance. For example, AFLAS combined with an optimized structure performs exceptionally under HPHT conditions, while FKM shows superior corrosion resistance in CO_2–H_2S environments compared to HNBR.
2. Aging and Stress Relaxation Studies: Research has revealed that high-temperature aging is controlled by chain scission and crosslinking, while stress relaxation reduces contact stress. Temperature safety factors (≥ 1.25) and stress-relaxation safety factors (≥ 1.56) have been proposed to guide design and life prediction.
3. Structural Design: Combining finite element modeling with experimental validation has driven structural optimization. For instance, anti-"shoulder extrusion" features and optimized support-ring layouts effectively mitigate stress concentrations, while controlling interface friction helps maintain stable sealing.
4. Corrosion Protection: Studies show that different rubbers respond very differently in corrosive environments. FKM's ductile fracture behavior makes it advantageous in acidic environments, whereas HNBR's mechanical degradation under corrosion warrants caution.

Despite these advances, existing research has limitations: most studies focus on single factors (e.g., temperature or pressure) rather than a comprehensive multiphysics coupling analysis (thermal–mechanical–chemical–time). Laboratory and numerical simulations often do not fully replicate actual downhole conditions. Moreover, standardized methods for life-cycle reliability evaluation and service-life prediction of packer rubbers remain underdeveloped.

5. Future Outlook

Future research on packer rubbers should target the following breakthroughs:

1. New Material Development:
   – Develop smart elastomer composites with resistance to temperatures > 200 °C and pressures > 200 MPa, such as nanoreinforced rubbers, self-healing elastomers, or functionally graded materials, to meet the needs of ultra-deep and geothermal wells.
2. Multiphysics Coupling Mechanisms:
   – Establish constitutive models that couple thermal, mechanical, chemical, and time-dependent factors. Integrate in situ monitoring technologies to reveal failure mechanisms under dynamic loads (e.g., acid-fracturing shocks).
3. Life Prediction and Reliability Assessment:
   – Develop data-driven, machine-learning-based packer rubber life-prediction algorithms that integrate material aging, stress relaxation, and fatigue damage models to build a comprehensive life-cycle performance evaluation system.
4. Intelligent Structural Design:

– Explore adaptive sealing structures (e.g., shape-memory alloy–rubber composites) and leverage digital twin technology to dynamically match rubber structure to downhole conditions.
5. Standardization and Environmental Improvement:

– Promote unified test standards for packer rubbers under HPHT and corrosive environments. Develop biodegradable or low-carbon rubber materials to reduce environmental impact from discarded rubbers. Advancing packer rubber technology will require interdisciplinary innovation—integrating materials science, mechanical simulation, artificial intelligence, and green chemistry—to support efficient oil and gas resource development and ultimately contribute to carbon-neutral goals.

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