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Reliability analysis of elastic graphite packer in heat injection well during oil shale in-situ conversion

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Abstract:
Heat injection is essential for oil shale in-situ conversion technology. The downhole of the heat injection well reaches temperatures above 400 °C during the process of heat injection, and part of the high-temperature gas dissipates through the wellbore annulus. Consequently, in addition to causing energy loss, the dissipation causes thermal damage to the casing and wellhead. To avoid dissipation, components that are suitable for high-temperature environments should be sealed and used during heat injection while mining. Therefore, this study presents the design of a packer composed of elastic graphite rubber and a high-temperature-resistant material. The influence of numerous factors, such as downhole temperature, working load, and height of rubber, on the reliability of the packer was analyzed. Subsequently, the numerical simulation analysis of the packer reliability in in-situ conversion mining under high temperature and pressure environments was performed. The results indicate that when the operating temperature is stable, the operating load has the most obvious influence on the sealing reliability of the packer, whereas the change in the height of the rubber has the least significant effect on the maximum contact stress between the casing and rubber. The change in the operating temperature has the least significant effect on the overall sealing performance of the packer. Moreover, the rise of the temperature will increase the sealing reliability of the packer, and on the contrary, the drop in the temperature will decrease it.

1. Introduction

Oil shale is an organic sedimentary rock with a high ash content and is an unconventional oil gas resource (Chasib, 2020; Puthiya et al., 2021). The rich kerogen organic matter is in the immature oil shale stage, which can produce pyrolysis oil and gas under heating conditions (Kang et al., 2020; Wang et al., 2021). In underground oil shale in-situ conversion mining, an underground oil shale reservoir is directly heated to generate high temperatures for converting the oil shale inside the solid kerogen into useful oil gas via pyrolysis (Bondarenko et al., 2017; Zhao et al., 2020). Accordingly, a ground mining method via a specific process is required for the industrial development of oil shale. The heat injection process is the integral link in the oil shale in-situ conversion (Lemineur et al., 2020). Generally, heat injection methods include surface and bottom heat injection (Sun et al., 2019) (Fig. 1). Surface heat injection involves the use of high temperature heaters to generate high-temperature heat carriers, and the heated gas is used as input to the target formation for heating via gas

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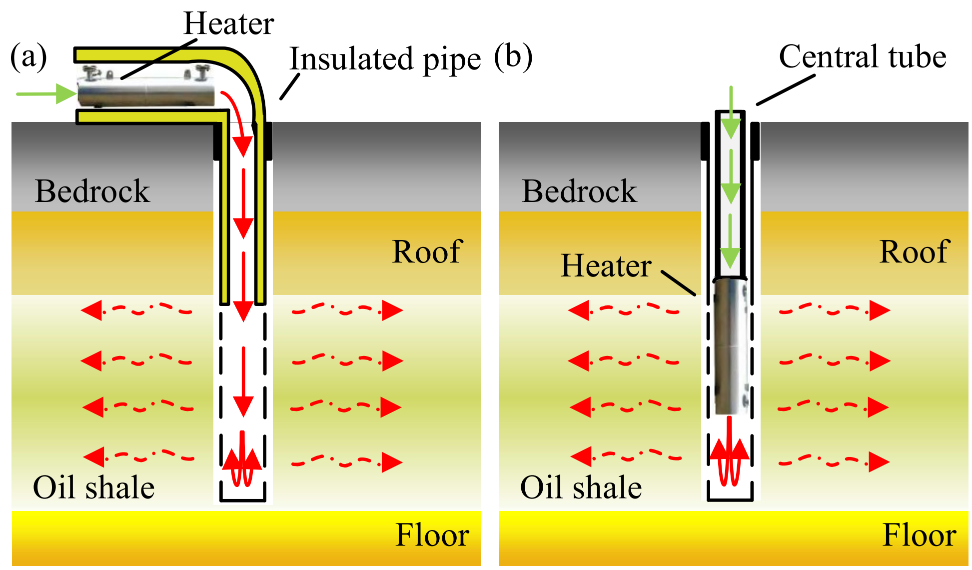

Fig. 1. (a) Surface heat injection and (b) Bottom-hole heat injection.

pipelines (Heldt et al., 2021). Bottom-hole heat injection refers to using a high-temperature heater to directly generate heat carriers that heat the target formation to obtain the required oil and gas (Hu et al., 2019).

During the in-situ conversion of oil shale, temperature (heat) is an instrumental factor (Sun et al., 2021a). In the actual process, the high-temperature gas enters the oil shale, and part of the gas is lost through the wellbore annulus (Guo et al., 2020; Wang et al., 2020), which not only wastes energy but also causes thermal damage to the casing and wellhead (Liu et al., 2020). The loss of high temperature gas affects the conversion process. Hence, a sealing component that prevents high temperature gas loss in the operation and mining with underground heating technology is necessary.

In addition to reducing the loss of energy in the annulus space of the central tube and casing, setting the packer in the heat injection well reduces the thermal damage from the casing and the central tube caused by thermal stress. Additionally, the efficiency of energy utilization of the heater is improved, and the pyrolysis of oil shale in the pyrolyzing zone is accelerated (Fig. 2). To better pyrolyze the organic matter in the oil shale into the required gas, the temperature of the exhaust gas generated by the operation of the general heater should be considerably greater than 400 °C; therefore, the packers used in conventional situations are not applicable. Therefore, selecting a packer that can withstand ultra-high temperatures in the oil shale in-situ conversion mining is crucial.

As a crucial sealing component, packers are effectively used in the operation of oil gas fields. The rubber structure plays a significant role in the sealing of the packer (Ma et al., 2014). Generally, the rubber structure of a packer is made of an elastic material under appropriate working conditions. To achieve sealing, we produced radial expansion under an axial load, which results in annular circumferential contact stress between the casing and rubber. The packer controls the loss of oil, gas, and fluid overflow by sealing the annular position of the mining well during operation and can withstand large

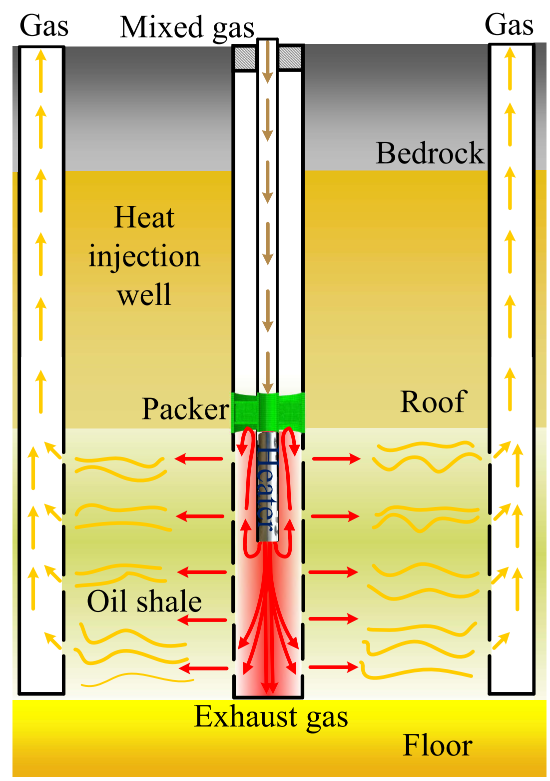

Fig. 2. Application of packer in the in-situ conversion of oil shale.

internal and external operating pressure differences to guarantee the performance of the downhole mining tools.

Global research on packers primarily focuses on the sealing mechanism, structural design, structural optimization, and materials. Dong et al. (2021) analyzed the mechanical and aging properties of three packer rubber materials in a gas corrosive environment with CO_2-H_2S coexistence; however, they did not involve a high-temperature working environment. Dong et al. (2020a) proposed a sealing structure and anti-shoulder protrusion packer that is suitable for high-pressure environment characteristics to shale gas production. It mitigates the rubber hose shoulder protrusion and bad sealing performance. Moreover, compared with conventional packers, the axial contact stress was significantly improved; however, the theory is only limited to deep geological conditions and high-pressure conditions, and there is no detailed research on shallow low-pressure working environments. Chen et al. (2019) selected three damage parameters as the analysis basis. Moreover, three damage parameters of the packer rubber matrix were obtained under various stresses and riser speeds through mechanical-property tests and the fatigue crack initiation theory. Finally, they proposed a calculation method for packer fatigue performance but did not propose a theory applicable under high temperature and pressure working environments. Liu et al. (2019) analyzed the force analysis of the packer under corrosive operation conditions and reported that the contact stress and parker compression distance with hydrogenated nitrile rubber material changed slightly and fulfilled the requirements of on-site construction; moreover, the sealing performance of the packer in the casing with the increase/decrease in the formation depth was analyzed. However, the application basis under temperature-related working conditions was not proposed in their paper. Zheng and Li (2021) examined the pressure-bearing performance of the deformation mode of the rubber honeycomb structure for the applicability of the packer. However, they did not conduct an extended analysis on the practical application effect of the packer using a rubber honeycomb structure in high-temperature working conditions. Johnston et al. (2003) analyzed the deformation stability of the packer rubber with three structures through the finite element model and proposed a concept of packer rubber stability; however, it is difficult to combine the proposed concept with practical applications. Additionally, existing literature (Shields et al., 2015; Lan et al., 2019; Dong et al., 2020b) describes packers with different structures, the stress state of the packer rubber under different working loads, and the applicable state of the packer rubber under high temperature and pressures. However, it does not involve the operation of packers under high pressure and ultra-high temperature during oil shale in-situ conversion mining.

Existing common well problems, such as heat loss, leakage, and casing damage, are related to the lack of downhole sealing (Shaikh et al., 2019). Specifically, the high-pressure and high-temperature conditions limit the use of conventional seals in extreme downhole conditions. To alleviate the existing problems, scholars (He et al., 2021; Li et al., 2021; Zhao et al., 2021) have used wellhead sand control screens, cement plugs, crusted liners, and sealing plugs for sealing or used synthetic ceramic materials to replace conventional sealing methods. However, these sealing methods are mostly located at or near the wellhead, and part of the high-temperature exhaust gas directly enters the gap between the center tube and the casing while centrally heating the oil shale layer using the heater. The air in the heat injection well forms hot and cold convection currents, causing a rapid loss in part of the energy, with the other part of the energy entering the casing (Lin et al., 2021), oil shale roof, and bedrock via heat conduction; thus, thermal damage of a larger area is due to the insulated piping and casing, which dissipates the remaining energy.

Therefore, the reliability of the packer immediately affects the energy utilization rate of the heater during oil shale in-situ conversion mining. Combining the actual operating conditions, this paper proposes and formulates a set of reliability evaluation indicators for the advantages and disadvantages of the working effect of the packer during oil shale in-situ conversion mining. A formulated reliability evaluation index is used in oil shale in-situ conversion mining.

2. Packer structural design and finite element modeling

Rubber is an integral component in achieving the sealing effect of the packer. Therefore, rubber is a key consideration when designing the packer, while the retaining ring, center tube, and casing are auxiliary design objects, as depicted in Fig. 3, where H indicates the height of the rubber.

In addition to rubber, the central tube, casing, and retaining ring must have high-temperature resistance properties. The nickel-based superalloy GH4169 has decent physical and chemical properties as well as good processing properties at

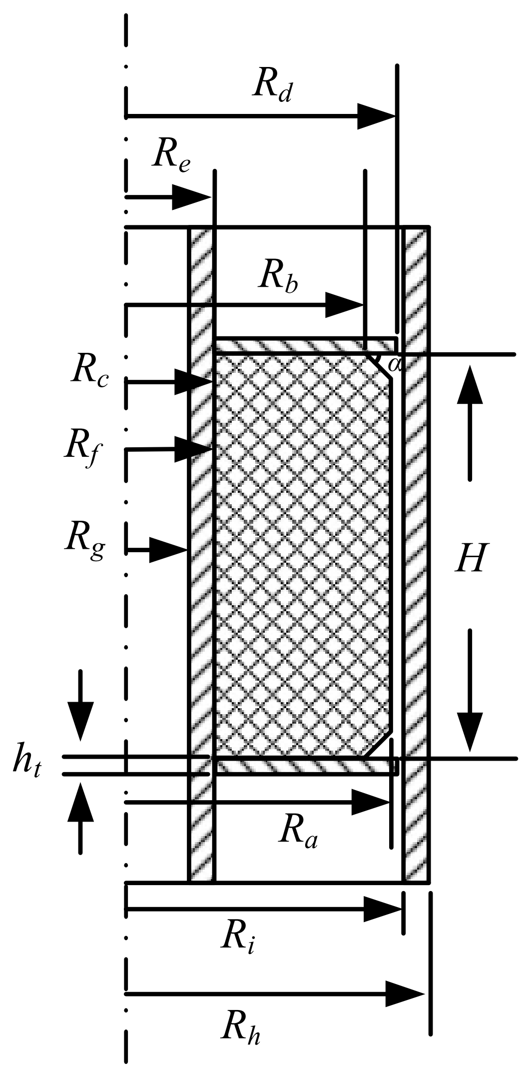

Fig. 3. Structure diagram of packer.

Table 1. Structural dimensions of packer.

Parameters	Settings	Value	Units
Outer diameter of retaining ring	R_d	217	mm
Inner diameter of retaining ring	R_e	70	mm
Thickness of retaining ring	h_t	10	mm
Outer diameter of rubber	R_a	210	mm
Bobbin diameter of rubber	R_b	205	mm
Inner diameter of rubber	R_c	70	mm
Outer diameter of center tube	R_f	70	mm
Inner diameter of center tube	R_g	60	mm
Outer diameter of casing	R_i	240	mm
Inner diameter of casing	R_h	220	mm
Inclination of end face of rubber	α	45	°

Table 2. Material properties of nickel-based superalloy and elastic graphite at different temperatures.

Parameters	Values		
Working temperature (°C)	400	450	500
Density (g/cm^3)	8.24/1.1	8.24/1.2	8.24/1.3
Poisson's ratio	0.28/0.49	0.29/0.49	0.30/0.49
Specific heat capacity (J/kg·°C)	456.2/687.2	480.4/699.8	514.8/721.9
Thermal expansion coefficient (10^{-6} °C)	13.4/110.1	14.0/112.6	14.4/115.1
Thermal conductivity (W/(m·K))	17.4/121	18.0/132	19.6/141

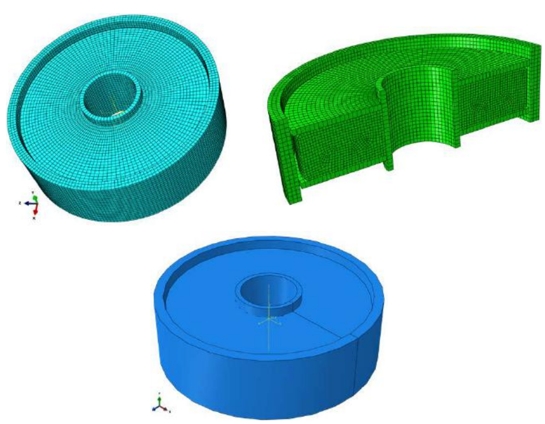

Fig. 4. Packer finite element model.

approximately 500 °C (Bayata and Alpas, 2021; Feng and Shao, 2021). Therefore, GH4169 can be used as the center tube, casing, and retaining ring material.

Upon determining the material composition of the packer structure, the structural dimensions of the designed packer are listed in Table 1.

Based on the structural dimensions listed in Table 1, the packer model is established on ABAQUS 6.12. Considering the actual operating conditions, the packer should be able to block high temperature and pressure exhaust gas diffused from escaping the annular space. Therefore, the operating loads should be set for the retaining ring under the model, and a temperature field should be established to add temperature-related variables. Accordingly, the rubber, central tube, casing, and retaining ring are divided by the C3D8H eight-node linear hexahedron element. The elastic modulus of elastic graphite rubber (superelastic) and nickel-based superalloy (206,000 MPa) will not change as the temperature changes, when designing material properties, the cohesive constitutive and Mooney-Rivlin constitutive models are considered, and the mechanical and thermal parameters related to temperature are included, as shown in Tables 2 and 3. The established model is depicted in Fig. 4.

Table 3. Friction coefficient between packer structures under different working temperature (400/450/500 °C).

Parameters	GH4169	Elastic graphite
GH4169	0.1/0.1/0.1	0.66/0.68/0.7
Elastic graphite	0.66/0.68/0.7	-/-/-

3. Theoretical design of packer reliability

Packers are integral components for ensuring ensure production efficiency in modern oil and gas production (Jiao et al., 2021; Zheng et al., 2022). The reliability of a packer directly affects the efficiency of oil shale mining and oil and gas

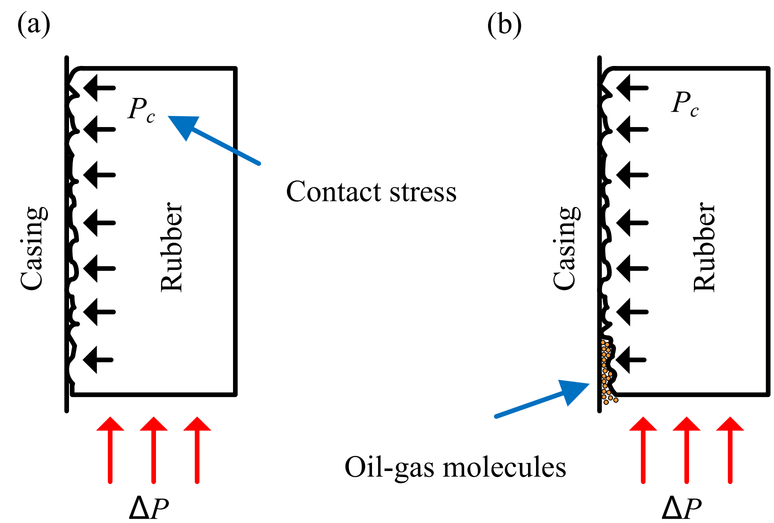

Fig. 5. Microscopic sealing mechanism of the rubber. (a) Schematic of the irregular microscopic surface of the rubber and (b) Oil-gas molecules squeeze into the gaps on the surface of the rubber.

production. At present, there are no studies formulating a set of evaluation indicators suitable for assessing packer reliability in downhole heaters in oil shale in-situ conversion mining. Therefore, this study establishes a set of reliability evaluation criteria based on sealing performance and theoretical and fatigue life analyses.

3.1 Sealing reliability design

The sealing reliability of the packer is primarily based on the rubber. Therefore, we performed stress analysis on the rubber, and the macro and micro sealing mechanisms of the sealing process were determined (Hu et al., 2020; Zhang et al., 2021b). Subsequently, the sealing performance coefficient is introduced to evaluate the sealing capacity of the rubber.

Rubber sealing mechanism: Under the working pressure difference, the rubber is subject to axial compression and radial expansion, allowing it to form the main sealing surface with the casing and central tube. To achieve the sealing effect, the minimum contact stress on the contact surface should be greater than the pressure of the fluid medium. The rebound force of the rubber, maximum deformation of the casing, and the gap between the outer diameter of the rubber determine the contact stress (Nguyen et al., 2011). The minimum sealing gap between the rubber and adjacent sealing surface is such that the fluid medium cannot pass through because of the extrusion of the fluid medium or manufacturing errors (Fig. 5). The fluid viscosity, the pressure difference of the working fluid, and size of the fluid molecules determine the minimum gap that can be passed (Bica et al., 2022):

$$K=\int_{s_2}^{s_1} P_c ds \tag{1}$$

Sealing performance coefficient: Once the rubber is stably sealed, the sealing performance of the rubber cannot be solely evaluated by the contact stress. Thus, it is necessary to introduce the sealing performance coefficient K (Zhang et al., 2019, 2021a) to quantify sealing performance. The integral of the curve between the contact stress P_c and the axial position s on the side of the rubber denotes the sealing performance coefficient K (Eq. (1)):

3.2 Damage reliability design

The sealing reliability is only an evaluation index after the stability of the packer. The fatigue life value of the packer under complex conditions is also a crucial indicator for analyzing its reliability. As the main sealing component of the packer rubber, the damage and service limit due to stress concentration and creep in the high temperature and pressure process form the basis for analyzing the fatigue life of the packer (Gehrmann and Muhr, 2020; Champy et al., 2021).

In this study, the packer fatigue durability analysis model is established using FE-SAFE 2016 software combined with ABAQUS 6.12. In defining the fatigue algorithm, the sinusoidal load spectrum was set, the loading frequency was set to once per second, and the loading frequency range was defined as 10^7–10^8 times; then, the output results were observed.

3.3 Theoretical verification of reliability design

Once the packer rubber is pressurized, contact stress is generated between the casing and rubber (Ren et al., 2011; He et al., 2017). If the pressure is too low, the oil gas molecules enter the gap between casing and rubber, causing the seal to fail. Therefore, calculating the minimum contact stress that can seal the casing and rubber through pressing the rubber is crucial for evaluating the sealing reliability of the packer rubber.

Because the mechanical properties of the elastic graphite rubber are similar to those of elastic rubber, the relationship between the bulk modulus Q and shear modulus G of the rubber and the elastic modulus E and Poisson's ratio v of the elastic graphite rubber are as follows (Uyanik, 2019):

$$G=\frac{E}{2(1+v)} \tag{2}$$

$$Q=\frac{E}{3(1-2v)} \tag{3}$$

After the rubber withstands the working load pressure, it reaches a stable sealing state. The height of the rubber H_1 changes from the original height to H. According to the theory of rubber compression and linear elasticity (Sun et al., 2021b), the height of the compressed rubber is as follows:

$$H_1=\left[1-\frac{2R_i(R_i-R_a)}{R_i^2-R_c^2}\right]H \tag{4}$$

where R_i denotes the inner diameter of the casing, mm; R_a indicates the outer diameter of the rubber, mm; R_c indicates the inner diameter of the rubber, mm.

To better connect the axial load and contact stress P_c of the rubber, the body deformation coefficient γ must be introduced (Bazkiaei et al., 2021):

$$\gamma=H_1\sqrt{\frac{8G(\ln R_i-\ln R_c)}{Q\left[\left(R_i^2+R_a^2\right)\left(\ln R_i^2-\ln R_a^2\right)-\left(R_i^2-R_a^2\right)\right]}} \tag{5}$$

Therefore, when the rubber is subjected to axial load to stabilize the sealing specific pressure P_0, the contact stress P_c at which the rubber can achieve sealing is as follows (Zhang et al., 2018):

$$\begin{aligned}P_c=&10^{-6}P_0\left\{\cosh\left[\tanh^{-1}\left(\tanh\frac{\gamma}{2}\right)\right]\right.\\&\left.-\tanh\frac{\gamma}{2}\sinh\left[\tanh^{-1}\left(\tanh\frac{\gamma}{2}\right)\right]\right\}\end{aligned} \tag{6}$$

The sealing specific pressure P_0 of the rubber is generated by high-temperature oil and gas. Therefore, the seal specific pressure P_0 can be calculated using the Clapeyron equation (Karim et al., 2022; Walker et al., 2022):

$$P_0V=nRT \tag{7}$$

where V indicates the equivalent oil and gas volume (approximately estimated by the size of the rubber before and after compression), m^3; n denotes the number of moles of gas, mol; R indicates the universal gas constant, J/mol·K; T is the oil and gas temperature, K.

Based on the above formula, when the oil gas temperature is constant, the minimum contact stress between the casing and rubber can achieve a sealing effect, which provides a basis for judging the sealing reliability of the packer.

4. Simulation analysis of packer reliability

During oil shale in-situ conversion mining, along with the use of downhole heaters, packers are used in high temperature and pressure environments. In this study, using ABAQUS 6.12 software and according to the experimental support provided in the literature (Sun et al., 2018; Shuai et al., 2020; Wang et al., 2022), the working of the packer was simulated for downhole temperatures of 400, 450, and 500 °C; the corresponding working loads were 6, 7, and 8 MPa, respectively; and the heights of the rubber were 50, 60, 70, and 80 mm, respectively. Subsequently, the sealing and damage reliabilities of the packer under constant-temperature and varying-temperature working conditions were analyzed and verified by the reliability design theory. The final results are used to guide actual oil shale in-situ conversion mining.

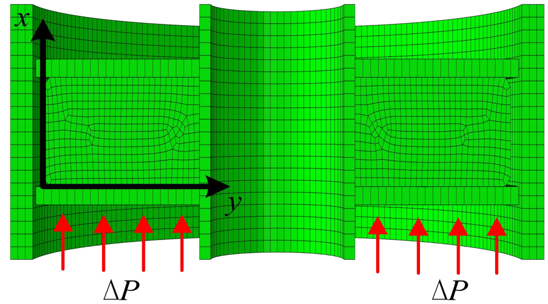

Fig. 6. Schematic of the contact stress between the axial position of the casing and rubber.

4.1 Research on reliability of packer under constant temperature

When the downhole working temperature is stable at 400, 450, and 500 °C, and the lower retaining ring is subjected to working loads of 6, 7, and 8 MPa, respectively, the relationship between the axial position and contact stress of the side of the casing and the rubber for different heights of the rubber is shown in Figs. 6 and 7.

Fig. 8 indicates that the greater the working temperature and load, the greater the density of the rubber material, the smaller the elastic modulus, the rougher the surface of the rubber, the greater the friction coefficient between the casing, rubber, and central tube, and the greater the maximum contact stress between the casing and rubber. Meanwhile, the change in the height of the rubber does not have an obvious influence on the maximum contact stress. The factors influencing the maximum contact stress are in the following order of increasing influence: Height of rubber and working temperature and load.

The experimental results in Fig. 7 obtained through MATLAB (R2020b) are substituted into Eqs. (1) and (6), and the minimum contact stresses at which the packer rubber and casing can achieve sealing under the working temperatures of 400, 450, and 500 °C were calculated as 2.58, 2.78, and 2.97 MPa, respectively. Therefore, when calculating the sealing performance coefficient, data whose contact stress is less than the minimum contact stress when sealing is achieved must be ignored.

Through the post-processing function of ABAQUS 6.12, the maximum contact stress of the rubber when it reaches the sealed state under nine working conditions was extracted. A graph of the maximum contact stress between the casing and rubber under different working conditions was plotted, as shown in Fig. 8.

According to the calculation results, rubber sealing failure occurs at 400 °C, 6 MPa, and 50 mm; when only considering the maximum contact stress between the casing and rubber, the rubber achieves its optimum sealing performance at 500 °C, 8 MPa, and 50 mm. When only the overall sealing performance is considered, the sealing performance of the rubber at 500 °C, 8 MPa, and 80 mm is the best. Comprehensive analysis

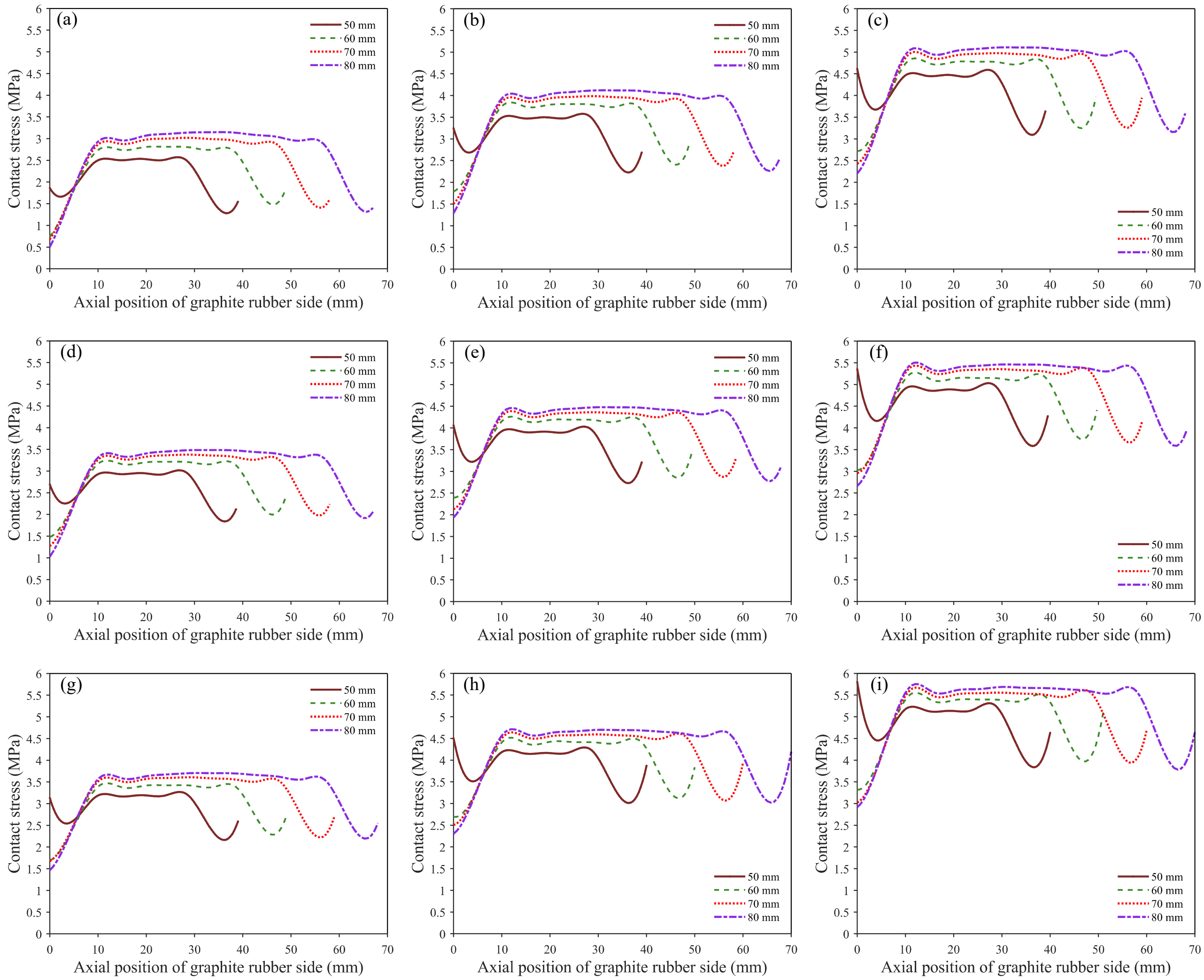

Fig. 7. Relationship between the axial position of the side of the rubber and the contact stress of the casing under three types of workloads with different rubber heights under constant temperature. (a) Working condition: 400 °C, 6 MPa, (b) Working condition: 400 °C, 7 MPa, (c) Working condition: 400 °C, 8 MPa, (d) Working condition: 450 °C, 6 MPa, (e) Working condition: 450 °C, 7 MPa, (f) Working condition: 450 °C, 8 MPa, (g) Working condition: 500 °C, 6 MPa, (h) Working condition: 500 °C, 7 MPa, and (i) Working condition: 500 °C, 8 MPa.

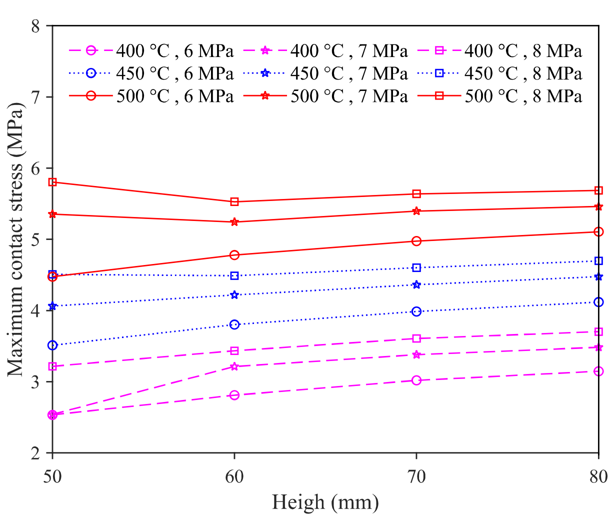

Fig. 8. Maximum contact stress between the casing and rubber under different working conditions.

indicates that the sealing reliability of the packer will be more reliable when the working temperature and load and height of the rubber increase.

The experimental results output by ABAQUS 6.12 were imported into the FE-SAFE 2016, and all the results of the analysis indicated "No damage".

The results show that no damage to the packer occurred when the number of loading cycles reached 108. As the frequency of loading is one per second, the packer does not fail after use for more than 3.17 years. Specifically, the damage reliability of the packer under different working conditions is stable.

4.2 Research on reliability of packer under variable temperature

The heat transfer process of the heater is not constant dur-

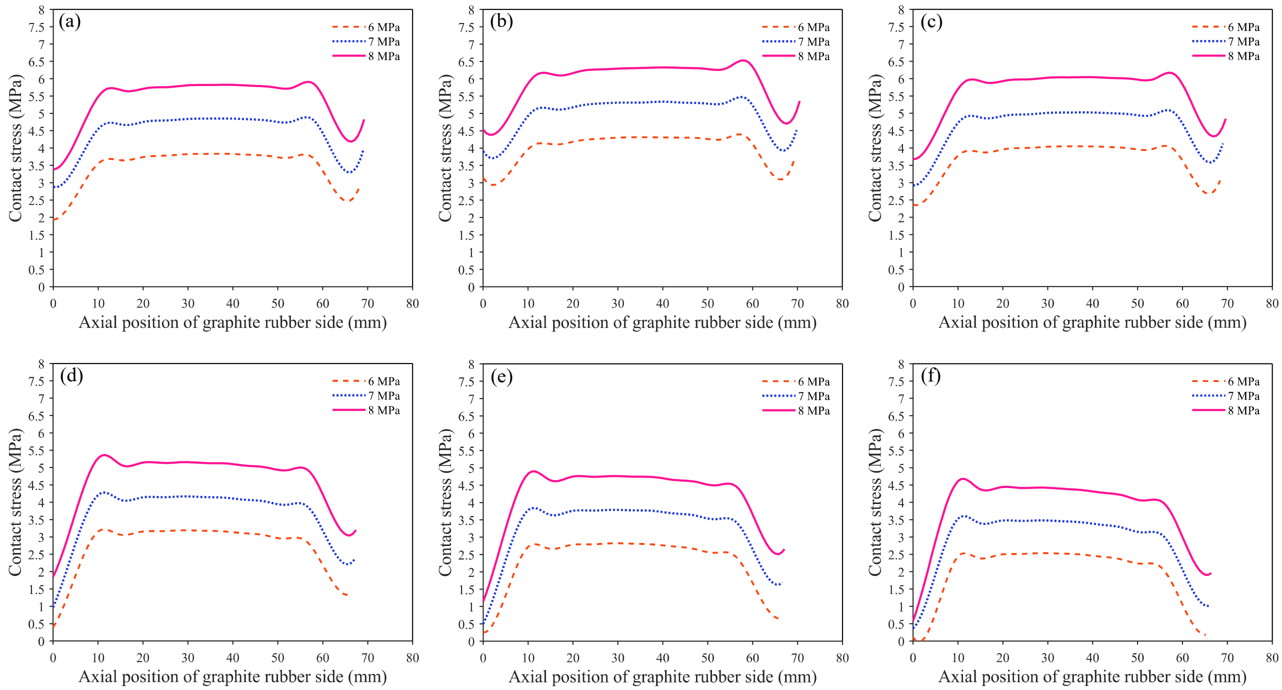

Fig. 9. Relationship between the axial position of the side of the rubber and the casing contact stress with varying working temperatures. (a) Working temperature rises from 400 to 450 °C, (b) Working temperature rises from 400 to 500 °C, (c) Working temperature rises from 450 to 500 °C, (d) Working temperature decreases from 500 to 450 °C, (e) Working temperature decreases from 450 to 400 °C, and (f) Working temperature decreases from 500 to 400 °C.

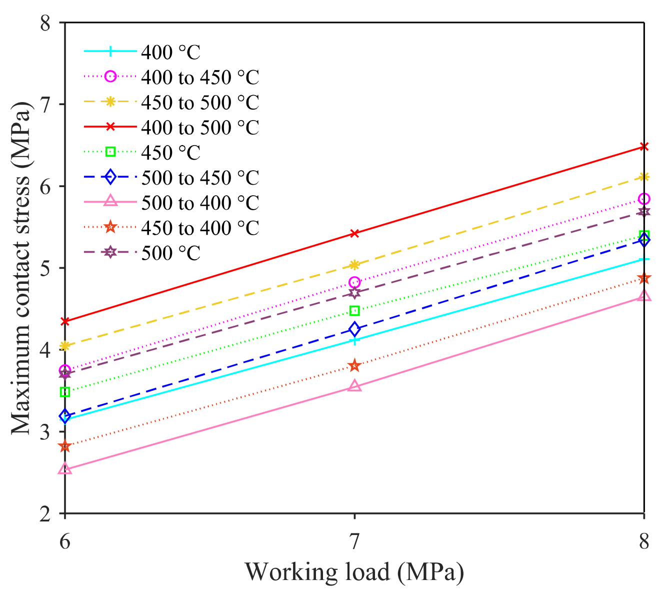

Fig. 10. Change in the maximum contact stress between the casing and rubber at various working temperatures.

ing oil shale in-situ conversion mining. Therefore, with the change in the heat transfer process of the heater, the downhole working temperature also constantly changes. The calculation results indicate that when the height of the rubber is 80 mm, the sealing reliability of the rubber is optimum; therefore, the rubber height of 80 mm is selected as the research object. When the analytical working temperature is raised from 400 to 450 and 500 °C, varied from 450 to 400 and 500 °C, and decreased from 500 to 400 and 450 °C, the relationship between the axial position of the graphite rubber side and the contact stress of casing is shown in Fig. 9, and then, the sealing reliability and damage reliability of the packer are analyzed.

Fig. 9 further analyzes the sealing performance coefficient and the maximum contact stress between the casing and rubber after the working temperature changes. A comparison chart of the maximum contact stress between the casing and rubber is created when the working temperature remains constant, as depicted in Fig. 9.

A comparison of Figs. 8 and 10 shows that the increase in working temperature increases the density of the rubber material, decreases the elastic modulus, and roughens the surface of the rubber. Specifically, the increase in the sealing performance coefficient and maximum contact stress of the rubber is due to the increase in the friction coefficient between the casing, rubber, and center tube. The decrease in working temperature reduces the density of the rubber material, increases the elastic modulus, and makes the surface of the rubber smoother. Consequently, the decrease in the sealing performance coefficient and maximum contact stress of the packer rubber is due to the decrease in the friction coefficient between the casing, rubber and center tube. When the operating temperature cools from 500 to 400 °C and the working load is 6 MPa, the rubber exhibits seal failure. Therefore, the heating process improves the reliability of the packer's seal performance, while the cooling process reduces the packer's seal reliability performance.

ABAQUS 6.12 results under the varying-temperature working conditions were imported into the FE-SAFE 2016 software, and all the results of the analysis indicated “No damage”. Therefore, the damage reliability of the packer under varying-temperature working conditions is stable within the range of cyclic loading times.

5. Conclusions

In this study, a graphite packer that can withstand high temperatures and pressures is selected and designed, and the reliability design theory of the packer is proposed. Based on this theory and considering the actual operating conditions, the reliability of the packer under constant temperature and varying temperature during oil shale in-situ conversion mining is analyzed, which provides a critical basis for the actual working condition. The results of the analysis are given below.

1) When the downhole working temperature is stable, the downhole working temperature and working load are high, the maximum contact stress between the casing and rubber is high, and the maximum contact stress is minimally affected by the rubber height. The factors influencing the maximum contact stress are in the following order of increasing influence: Height of rubber, working temperature, and working load.
2) When the downhole working temperature is stable, the working conditions correspond to a temperature of 400 °C and load of 6 MPa, and the rubber with the height of 50 mm loses its sealing effect; further, the greater the downhole working temperature, working load, and height of the rubber, the higher the overall sealing performance of the packer, and the lower the influence of a change in temperature on the packer’s overall sealing performance. The factors influencing the packer’s overall sealing performance are in the following order of increasing influence: Working temperature, height of rubber, and working load.
3) Based on the research results, when the downhole operation temperature changes, and when the operation temperature is stable, the rubber height is selected as 80 mm for the research object. The analysis results indicate that the heating process significantly increases the overall sealing performance and maximum contact stress between the casing and rubber, stabilizing the packer sealing reliability. The sealing reliability of the packer is more unstable because the cooling process significantly reduces the overall sealing performance and maximum contact stress between the casing and rubber. When the working temperature is reduced from 500 to 400 °C, and the working load is 6 MPa, the sealing of the packer fails.
4) Regardless of whether the working temperature is constant or varying, the damage reliability of the packer is stable. Specifically, the packer can be used for more than 3.17 years.

Nomenclature

R_d = Outer diameter of retaining ring, mm
R_e = Inner diameter of retaining ring, mm
h_t = Thickness of retaining ring, mm
R_a = Outer diameter of rubber, mm
R_b = Bobbin diameter of rubber, mm
R_c = Inner diameter of rubber, mm
R_f = Outer diameter of center tube, mm
R_g = Inner diameter of center tube, mm
R_i = Outer diameter of casing, mm
R_h = Inner diameter of casing, mm
α = Inclination of end face of rubber
s = Axial position, mm
H = The original height of the rubber, mm
H_1 = The changes height of the rubber, mm
P_c = Contact stress, MPa
Q = Bulk modulus, MPa
G = Shear modulus, MPa
E = Elastic modulus, MPa
P_0 = Sealing specific pressure, MPa
K = Sealing performance coefficient, MPa·mm
V = Equivalent oil and gas volume, m^3
R = Molar gas constant, J/mol·K
T = Oil and gas temperature, K
v = Poisson’s ratio, Dimensionless
γ = Body deformation coefficient, Dimensionless

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Conflict of interest

The authors declare no competing interest.

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