

Thermo-Mechanical Coupled Analysis of Wellbore Integrity in Perforated Underground Gas Storage Wells During Injection

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Abstract

Aiming at the severe alternating loads and failure risks faced by the perforated wellbore section under the cyclic high-rate injection and production conditions of underground gas storage (UGS), this paper conducts a thermo-mechanical coupled analysis of wellbore integrity during the gas injection process. A 3D fully thermo-mechanical coupled finite element model of the perforated casing-cement sheath-formation system was established, accurately reconstructing the 3D geometric morphology of spiral perforations. Based on the verification of the model's computational accuracy, the sensitivity laws of injection temperature and pressure on the stress and deformation characteristics of the casing and cement sheath were systematically investigated. The results indicate that the injection temperature is the most critical parameter controlling the casing strength. The "cold shock" effect below 80°C causes the local equivalent stress of the P110 casing to exceed its yield limit (reaching 820.5 MPa), simultaneously increasing the risk of cracking and failure in the cement sheath. Furthermore, the elevation of injection pressure intensifies the radial expansion of the casing, pushing it toward the yield limit. Although the local tensile stress of the cement sheath decreases due to the confining pressure effect, its equivalent strain surges dramatically (up to 1.009×10^{-1}), substantially elevating the risk of interfacial micro-annulus formation. This study reveals the damage mechanisms of the perforated wellbore section under multi-field coupling. It is recommended that on-site gas injection operations should co-optimize temperature and pressure parameters to avoid the superposition of extreme low-temperature and high-pressure conditions, providing quantitative theoretical support for the long-term safe operation of UGS and the optimization of gas injection schemes.

Keywords

Underground gas storage (UGS); Wellbore integrity; Thermo-mechanical coupling; Perforated casing; Finite element analysis (FEA)

1. Introduction

As core infrastructure for seasonal peak shaving and strategic reserves, underground gas storage (UGS) operates under cyclic high-rate injection and production. The gas injection phase is crucial for fulfilling reserves and imposes the most severe loading on the wellbore. During this phase, highly pressurized, low-temperature gas enters the wellbore, continuously exchanging heat with the high-temperature formation. This intense "cold shock" induces significant thermal contraction in the casing. The superposition of axial tensile stress from the temperature drop and circumferential tensile stress from high injection pressure severely threatens the wellbore's structural integrity [1].

Recent studies have extensively explored wellbore mechanical responses and integrity. Regarding thermo-mechanical coupling, Zhang et al. [2] derived analytical stress solutions for the cement sheath, emphasizing temperature and pressure variations as critical factors. Liu et al. [3] coupled a thermodynamic gas flow model within a phase-field framework, revealing a depth-dependent cement failure law. Focusing on complex structures, Zhao et al. [4] and Mu et al. [5] evaluated the weakening effect of perforation geometric defects on the casing's ultimate bearing capacity and yield strength through 3D modeling and experiments.

While multi-field coupling research in UGS wells predominantly targets unperforated casings, studies on 3D perforated structures rarely reflect the severe superimposed conditions of intense "cold shock" and high-pressure injection. Due to the complex 3D geometry and thermo-mechanical interactions, systematic studies on the mechanical evolution of perforated UGS sections under actual injection conditions remain scarce. The stress distribution around perforations and the deformation mechanisms of the casing-cement sheath-formation system are still unclear, restricting full-life-cycle safety evaluations.

To bridge this gap, this paper establishes a 3D thermo-mechanical coupled finite element model of the perforated casing-cement sheath-formation assembly. After verifying the model's accuracy, the sensitivity of the perforated section's stress and deformation characteristics to injection temperature and pressure is systematically investigated. This study aims to reveal the damage mechanisms of perforated UGS wellbores under cold shock and high-pressure loads, providing a quantitative theoretical basis for optimizing injection parameters and evaluating long-term integrity.

2. Finite Element Model Construction

The finite element (FE) method effectively handles complex geometries and multi-field coupling, making it widely applied in wellbore mechanical analysis. Compared to analytical methods, the FE method authentically reconstructs 3D perforation morphologies, accurately captures near-hole stress concentrations, and provides a fully coupled solution for temperature and stress fields to reflect thermo-mechanical load interactions.

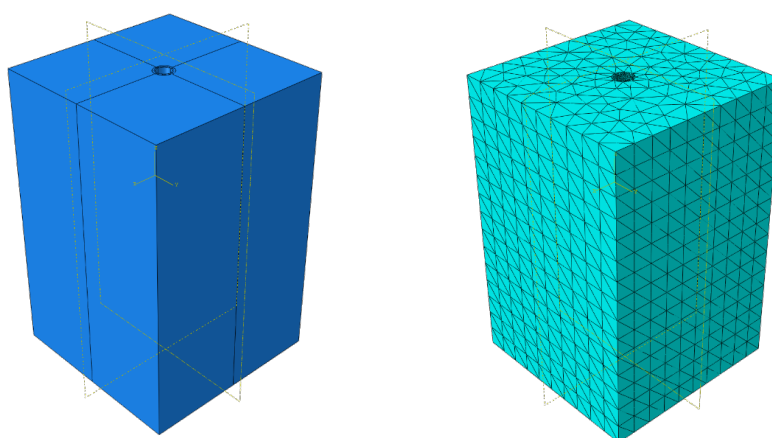
2.1. Geometric Modeling and Mesh Generation

The geometric model was established using SolidWorks. Dimensions include a casing outer diameter of 177.8 mm (thickness 10.36 mm), a cement sheath outer diameter of 215.9 mm (thickness 19.05 mm), and a formation block of 2 m × 2 m × 3 m. The formation size satisfies Saint-Venant's principle, eliminating boundary interference in the near-hole region. Penetrating spiral perforations were modeled with a 10 mm diameter, 90° phase angle, and 16 shots/m density. For the target layer at a 4000 m depth, the original formation temperature is 160 °C, with overburden and lateral confining pressures of 95.61 MPa and 41.23 MPa, respectively. The established 3D model was then imported into Abaqus for FE analysis, as shown in Figure 1(a).

A variable-density meshing strategy was adopted to balance accuracy and computational efficiency. Local mesh refinement (minimum size ~1 mm) was applied around the perforations to capture stress gradients accurately. A medium-density mesh was used for the cement sheath, while the formation mesh gradually coarsened radially outward. Fully coupled thermo-mechanical solid elements, possessing both displacement and temperature DOFs, were selected to enable simultaneous field solutions. The meshing results are shown in Figure 1(b).

2.2. Geometric Modeling and Mesh Generation

According to elasticity theory, displacement continuity is enforced at all interfaces of the casing-cement-formation assembly. The displacements at the casing-cement and cement-formation interfaces are governed by the superposition of pressure and temperature effects. However, treating the formation as an infinite elastic body with a constant temperature, the thermal effect on the formation's inner diameter is negligible; thus, its displacement is driven solely by pressure.



(a) Finite element model

(b) Meshing

Figure 1. Finite element model and meshing of the casing-cement sheath-formation assembly

$$\sigma_{\theta} = \frac{p_i r_{ci}^2 - p_o r_{co}^2}{r_{co}^2 - r_{ci}^2} + \frac{(p_i - p_o) r_{ci}^2 r_{co}^2}{r_{co}^2 - r_{ci}^2} \cdot \frac{1}{r^2} \quad (1)$$

$$\sigma_r = \frac{p_i r_{ci}^2 - p_o r_{co}^2}{r_{co}^2 - r_{ci}^2} - \frac{(p_i - p_o) r_{ci}^2 r_{co}^2}{r_{co}^2 - r_{ci}^2} \cdot \frac{1}{r^2} \quad (2)$$

Where: r is the radial distance from a given point on the casing wall to the casing center, m.

Since this model adopts the plane strain assumption, the strain of the casing along

the axial direction is zero $\varepsilon_z = 0$. Based on this condition, the axial principal stress of the casing can be derived using the generalized Hooke's law, and its expression is as follows:

$$\sigma_z = \mu(\sigma_r + \sigma_{\theta}) - E\alpha\Delta T \quad (3)$$

Where: σ_z is the axial principal stress of the casing, MPa; μ is Poisson's ratio, dimensionless; E is the elastic modulus, MPa; α is the coefficient of thermal expansion, °C-1; and ΔT is the temperature change of the casing, °C.

According to the fourth failure theory of mechanics of materials (the Von Mises yield criterion), by comprehensively considering the circumferential stress, radial stress, and axial stress applied to the casing, the expression for the equivalent stress at any given point within the casing is given by:

$$\sigma_i = \frac{\sqrt{(\sigma_r - \sigma_{\theta})^2 + (\sigma_{\theta} - \sigma_z)^2 + (\sigma_z - \sigma_r)^2}}{\sqrt{2}} < \sigma_s \quad (4)$$

Where: σ_i is the equivalent stress of the casing, MPa; σ_s is the yield strength of the casing, MPa.

Using the casing yield strength as the failure criterion: when the equivalent stress is less than the yield strength, the casing remains in an elastic deformation state, and the wellbore structure is considered safe; when the equivalent stress is greater than or equal to the yield strength, the casing enters a plastic state, indicating that strength failure of the casing has occurred.

To verify the established 3D thermo-mechanical FE model, it was simplified into an unperforated axisymmetric model, and the casing equivalent stress was compared with the elastic analytical solution for thick-walled cylinders. The verification conditions included an injection temperature of 80 °C and internal pressures of 50, 55, and 60 MPa.

As shown in Table 1, the FE results agree well with the analytical solutions, with a maximum relative error of only 2.21% (well below the 5% engineering limit). The FE values are slightly lower due to the differences in end constraints between the 3D solid model and the analytical plane strain assumption. These results confirm that the established FE model possesses sufficient accuracy for subsequent parametric analysis.

Table 1. Comparison of calculation results

Condition	Internal Pressure P_i (MPa)	Theoretical Calculation (MPa)	Numerical Simulation (MPa)	Relative Error (%)
Injection 1	50	224.6	220.6	1.78
Injection 2	55	236.7	232.6	1.73
Injection 3	60	248.9	243.4	2.21

3. Sensitivity Analysis of Wellbore Strength and Safety Under Gas Injection Conditions

Underground gas storage (UGS) features cyclic high-rate injection and production. During the critical gas injection phase, the wellbore endures severe thermo-mechanical loads. This study investigates the individual effects of injection temperature and pressure on the strength and stress distribution of the perforated casing and cement sheath. The findings provide a quantitative basis for optimizing gas injection schemes and evaluating the long-term integrity of UGS wells.

3.1. Effect of Temperature on Wellbore Strength and Safety

Temperature is a core factor affecting wellbore safety under UGS injection conditions. Low-temperature injected gas continuously exchanges heat with the high-temperature formation, leaving the casing in a prolonged "cold shock" state. The superimposed thermal contraction stress and injection pressure create severe stress concentration at the perforations. Keeping the injection pressure constant at 50 MPa, simulations across 60–100 °C were conducted to analyze the wellbore's mechanical responses. The variation laws of the equivalent stress and equivalent strain of the casing with injection temperature are shown in Figure 2.

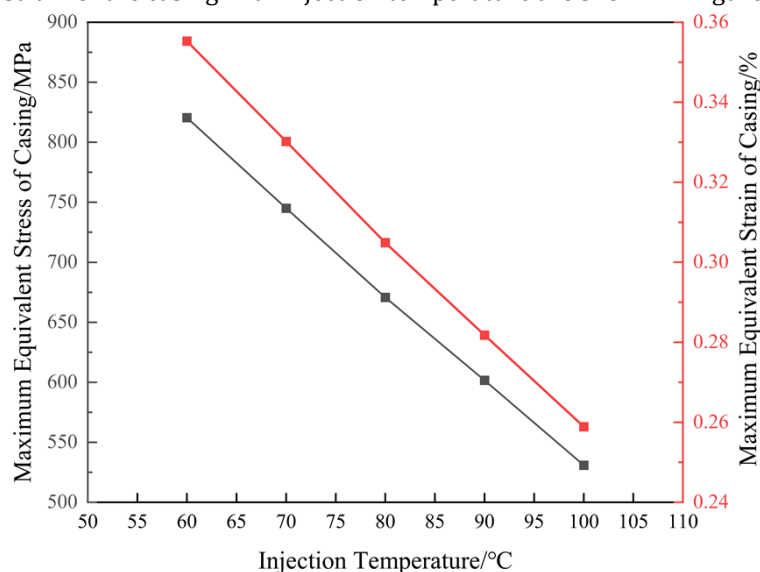


Figure 2. Variation laws of equivalent stress and equivalent strain of the casing with injection temperature

As shown in Figure 2, both metrics decrease linearly as temperature increases. Using the P110 casing yield strength (758 MPa) as a benchmark, the stress reaches 820.5 MPa at 60 °C (entering plastic deformation) and 745.1 MPa at 70 °C (dangerous critical state). Safety margins improve at 80 °C and above. Thus, injection temperature should be maintained above 80 °C to mitigate "cold shock" damage to the perforated casing.

As the critical sealing medium, the cement sheath receives thermal contraction deformation transferred from the casing. Keeping pressure at 50 MPa, the maximum equivalent stress and strain of the cement sheath under various temperatures were extracted, as shown in Figure 3.

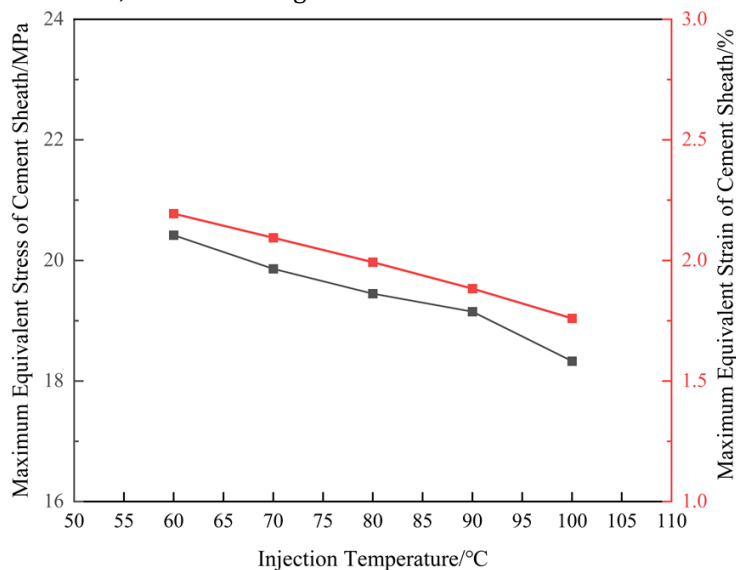


Figure 3. Variation laws of equivalent stress and equivalent strain of the cement sheath with injection temperature

Figure 3 shows cement equivalent stress ranges from 18 to 21 MPa. At 60 °C, the stress (20.42 MPa) approaches the lower limit of cement compressive strength (20–40 MPa), posing fatigue cracking risks under cyclic loading. Additionally, the strain at 60 °C (2.194×10^{-2}) significantly exceeds that at 100 °C (1.760×10^{-2}). Such large relative displacement risks interfacial debonding. Hence, sufficient attention must be paid to sealing integrity, and flexible cement systems are recommended for low-temperature injection.

3.2. Effect of Internal Pressure on Wellbore Strength and Safety

Injection pressure directly generates circumferential tensile stress, and the resulting stress concentration at perforations makes the actual stress much higher than in unperforated casings. To systematically study this effect, simulations were conducted for 50–70 MPa injection pressures while keeping the temperature constant at 80 °C. The variation laws of the equivalent stress and equivalent strain of the casing with injection pressure are shown in Figure 4.

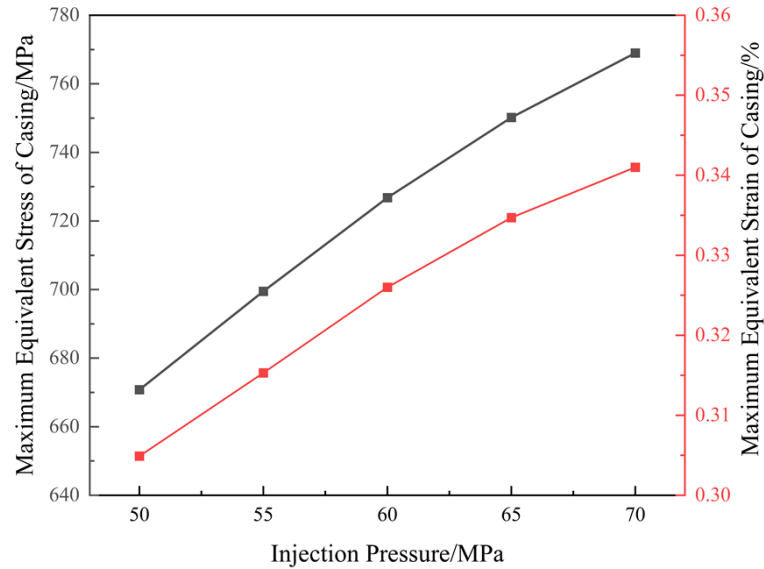


Figure 4. Variation laws of equivalent stress and equivalent strain of the casing with injection pressure

Figure 4 indicates that casing stress approaches and exceeds its yield limit (758 MPa) as pressure rises. Stress reaches 670.8 MPa at 50 MPa, 750.2 MPa at 65 MPa (critical state), and 769.0 MPa at 70 MPa (plastic deformation). Therefore, injection pressure and temperature must be jointly optimized to prevent casing strength failure under extreme combined loads.

Keeping the temperature constant at 80 °C, the maximum equivalent stress and strain of the cement sheath under various pressure conditions were extracted, as shown in Figure 5.

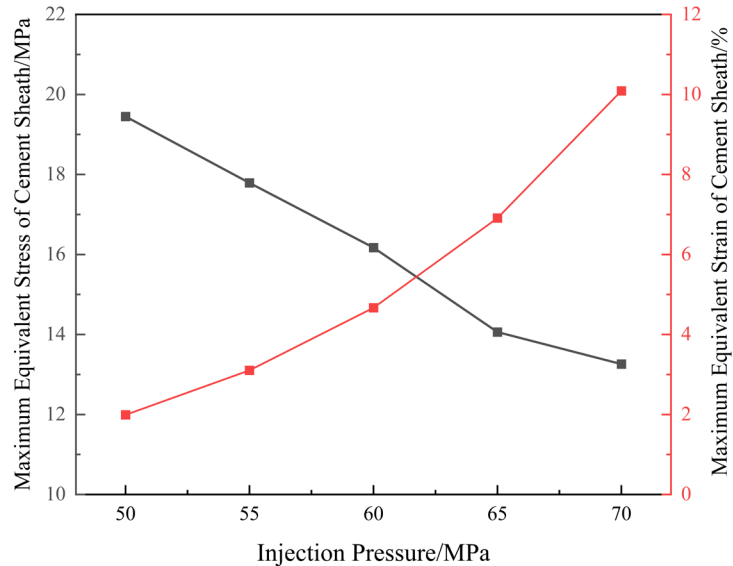


Figure 5. Variation laws of equivalent stress and equivalent strain of the cement sheath with injection pressure

Figure 5 reveals diverging trends for cement stress and strain. As pressure rises

from 50 to 70 MPa, strain surges from 1.993×10^{-2} to 1.009×10^{-1} , indicating exacerbated deformation. Conversely, stress decreases from 19.45 to 13.26 MPa (a 31.8% drop). Mechanistically, casing radial expansion increases confining pressure on the cement, reducing local peak tensile stress while aggravating overall deformation.

Although the stress remains within the safe compressive range across all tested pressures, the surging strain (reaching 1.009×10^{-1} at 70 MPa) drastically elevates the relative interfacial displacement. Therefore, crucial attention must be paid to the sealing integrity of the cement sheath interface under high-pressure injection conditions.

4. Conclusions

Aiming at UGS gas injection conditions, a 3D thermo-mechanical coupled finite element model for perforated wellbores was established to investigate the impact of temperature and pressure on wellbore strength. The main conclusions are:

The FE model exhibits high reliability and accuracy. Compared with the theoretical analytical solution for thick-walled cylinders, the maximum relative error of the casing equivalent stress is only 2.21% (well below the 5% engineering limit), verifying its applicability under complex loads.

Injection temperature dominates the safety of the perforated casing. The "cold shock" effect significantly elevates failure risks. At 60 °C, the casing equivalent stress (820.5 MPa) exceeds its yield limit, and the cement stress (20.42 MPa) nears its compressive lower limit. To ensure wellbore safety, the injection temperature should be ≥ 80 °C.

High injection pressure affects the casing and cement differently. As pressure rises, casing stress monotonically approaches its yield limit (769.0 MPa at 70 MPa). Conversely, the cement stress decreases by 31.8% due to stronger confining pressure. However, intensified casing radial expansion causes the cement equivalent strain to surge (1.009×10^{-1} at 70 MPa), substantially increasing the risks of interfacial debonding and micro-annulus formation.

UGS injection schemes require comprehensive thermo-mechanical considerations. The superposition of extreme low-temperature and high-pressure conditions must be avoided. To mitigate high-pressure and cold-shock impacts, emphasis should be placed on cement interface sealing, potentially introducing elastic-tough cement slurries to accommodate large interfacial deformations..

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