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Fluid-Structure Interaction Analysis of Carbon Dioxide Injection Strings

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Abstract: Pressure fluctuations induced by fluid flow within CO_2 injection strings can lead to vibrations, which may severely compromise the operational stability of the string. To ensure stable operation, a detailed investigation into the dynamic characteristics of CO_2 injection strings was conducted. The finite element simulation software ANSYS was employed to simulate and compare the effects of different CO_2 coupling conditions, as well as the influence of wall thickness and pipe length on the natural frequency of the string. Additionally, the mechanical response of the string under axial tensile and compressive loads resulting from internal pressure generated during CO_2 fluid injection was calculated. The results indicate that compared with an empty string, both liquid-solid coupling and supercritical CO_2 coupling reduce the natural frequency—by 9.8% and 7.1%, respectively. The natural frequency of the string decreases with increasing wall thickness, and the natural frequency of the tubing decreases with increasing pipe length. Under the action of CO_2 fluid pressure, as tensile and compressive loads increase, the stress on both the pipe body and the threaded connections increases accordingly. Once the stress reaches a certain threshold, the operational stability of the string can be compromised, potentially leading to failure of the CO_2 injection string. These findings provide a valuable reference for subsequent research.

Keywords: Fluent Simulation; Fluid-Structure Interaction; Natural Frequency; Tubular String Stress; Threaded Connection.

1. Introduction

Amidst the urgent global energy transition and national support for the development of new energy sources, Carbon Capture, Utilization, and Storage (CCUS) technology is experiencing rapid advancement. However, significant challenges remain. During the downhole injection of carbon dioxide, pressure fluctuations can lead to unstable flow velocities, thereby inducing vibrations in the injection string. Such vibrations have the potential to impair or even damage the string, compromising both its structural integrity and operational safety. Consequently, as a critical conduit for this engineering process, it is imperative to conduct in-depth research into these phenomena.

In recent years, research on oil and gas pipelines has progressively expanded. Regarding fluid-structure interaction in pipelines, a developmental process from non-existence to establishment has been observed, accompanied by extensive investigations into the various impacts of fluid-induced changes on pipelines. Firouz-Abadi combined structural dynamics with flow field equations for analytical studies, deriving modal shapes and natural frequencies of tubular strings, thereby providing a foundational reference for subsequent research [1]. Lucas P et al. developed a model to analyze the interaction between fluid flow within a single pipe segment and the segment's structural vibration. This model elucidated the influence of varying fluid pressure on pipe displacement and established the correspondence between pipe stress and displacement under different vibration modes[2]. Hansson and Sandberg established a tubular string model to investigate the interaction between fluid and solid phases, with analytical results indicating that fluid effects impact the structural stability of the string[3]. Bagchi et al. conducted experimental studies on the influence of gas flow velocity and pressure on pipe vibration. Their experiments demonstrated that the frequency of internal pressure pulsations aligns with the natural structural vibration frequency of the pipe when the pipe itself does not undergo overall oscillation[4]. Yuchuan Bai et al. integrated analytical models with numerical simulations to analyze the dynamic characteristics of axially conveying fluids with varying densities in clamped and cantilevered pipes[5]. German researchers developed a novel finite element method to address coupled problems involving interactions between multiple fluids and solids[6]. Xie Cuili et al. investigated the vibration characteristics of L-shaped bends under gas-liquid two-phase flow via fluid-structure interaction studies, calculating the correlation between fluid-induced vibrations and the pipe's natural frequency[7]. Cao Yinping et al. employed the virtual mass method and finite element analysis to calculate the effect of fluid-structure interaction on the natural frequency of tubular strings, revealing that liquid-solid coupling reduces system frequency more significantly than gas-solid coupling[8]. Jiang Fan et al. utilized bidirectional fluid-structure interaction simulations to demonstrate that pipe wall deformation exacerbates the instability of oil-water annular flow at small ball valve openings and recommended rapid transition through small opening stages during valve operation[9].

Li Qing applied a one-way fluid-structure coupling method to analyze the effects of static pressure and flow velocity on the natural frequency of oil transmission bends, concluding that internal fluid pressure exerts a far greater regulatory effect on frequency than flow velocity variations[10]. Kang Zhilei et al., based on a four-equation fluid-structure interaction model, analyzed the severe vibration characteristics of completion strings in high-yield gas wells during transient valve-opening conditions, identifying gas production rate, wellhead pressure, and gas density as key factors influencing lateral deformation of the string[11] . Cao

Yinping et al., after comparing the effects of different CO_2 phase states on fluid-structure interaction vibration characteristics, concluded that liquid CO_2 significantly reduces the natural frequency of tubular strings. They also calculated the regulatory effects of axial force, internal pressure, and wall thickness on the dynamic behavior of the string[12]. Ma Zhonglin elucidated the vibration mechanisms of pipe bends from dual perspectives of flow-induced excitation and acoustically induced vibration, noting that flow-induced excitation dominates low-frequency resonance at low flow velocities, while high-frequency acoustic resonance requires attention to higher-order natural frequencies[13]. Zhang Kaixuan et al. employed bidirectional fluid-structure coupling to analyze the vibration characteristics of double-inlet single-outlet tee pipes, revealing the effects of pressure pulsation amplitude and pipe outer diameter on vibration response, thereby providing references for vibration reduction design in gas transmission stations[14]. Yu Hao et al. established a two-dimensional finite element model to evaluate the sealing performance of premium threaded connections in ultra-deep well tubing under coupled tensile, compressive, and internal pressure loads. Their study introduced detailed leakage analysis methods for full-thread length, half-thread length, and shoulder areas, revealing differences in leakage risk under various sealing lengths. Results indicated that even when overall thread sealing meets requirements, leakage may still occur at the shoulder under most operational conditions. This research provides a refined evaluation basis for thread connection selection and structural optimization under complex working conditions[15][16][17].

Early research predominantly focused on the vibration modes and frequency responses of oil and gas production strings, or utilized water as the displacement medium to analyze the vibration behavior and stress variations in tubular strings. Compared to water, CO_2 exhibits significant advantages in supplementing reservoir energy and enhancing sweep efficiency, with CO_2 flooding demonstrating approximately 40% higher displacement efficiency than water flooding. Furthermore, the sequestration of CO_2 is environmentally benign. Consequently, considerable research potential exists regarding CO_2 fluid behavior, particularly in areas such as the intrinsic properties of the fluid itself, as well as the effects of parameters like wall thickness and pipe length, which have received limited attention. Additionally, studies on the stress state of tubular strings under specific loads, such as tension and compression, remain relatively scarce. This study investigates the vibration characteristics and mechanical response of tubular strings following CO_2 injection. A fluid-structure interaction model is established to evaluate the influence of key factors on the vibration frequency of the string and to analyze the stress variations at the threaded connections under different loading conditions.

Establishment of the Mathematical Model and Vibration Equations

2. Establishment of the Mathematical Model and Vibration Equations

(1) Governing Equations for CO_2 Flow

As a compressible continuous-phase fluid, the flow of CO_2 within the tubular string can be described by the Navier-Stokes equations, which adhere to the laws of mass conservation and momentum conservation.

Continuity Equation:

$$\frac{\partial \rho_g}{\partial t}+\frac{\partial\left(\rho_g u\right)}{\partial x}+\frac{\partial\left(\rho_g v\right)}{\partial y}+\frac{\partial\left(\rho_g w\right)}{\partial z}=0 \quad (1)$$

In the equations, ρ_g: density of CO_2, u, v and w: the flow velocities of CO_2 in the x y and z

Momentum Equation:

$$\begin{aligned}
&\frac{\partial}{\partial t}(\rho_g u)+\mathrm{div}(\rho_g u\vec{V})=-\frac{\partial p_g}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+F_x\\
&\frac{\partial}{\partial t}(\rho_g v)+\mathrm{div}(\rho_g v\vec{V})=-\frac{\partial p_g}{\partial x}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+F_y\\
&\frac{\partial}{\partial t}(\rho_g w)+\mathrm{div}(\rho_g w\vec{V})=-\frac{\partial p_g}{\partial x}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+F_z.
\end{aligned} \quad (2)$$

(2) Establishment of the Fundamental Equations for Fluid-Structure Interaction Vibration

In analyzing the dynamic vibration model of the tubular string, a method was employed to simplify the continuous string, which possesses infinite degrees of freedom, into a discrete system with finite degrees of freedom[12][15]. The governing differential equation for tubular string vibration under fluid-structure interaction can be expressed as follows, with solutions typically obtained using the direct integration method or the modal superposition method.

$$\left(M+M_f\right)y''+(K+K_f)y=0 \quad (3)$$

M: Total mass matrix; y'': Vector acceleration; y': Vector velocity; y: Displacement vector; M_f :Fluid mass matrix; K_f: Fluid stiffness matrix.

(3) Theoretical Formulation for Tubing Vibration Modes

The foundation of structural vibration analysis lies in the mastery of modal theory, which enables the determination of structural mode shapes, effective weights, and natural frequencies, among other parameters. The general form of the vibration differential equation is expressed as follows [17]:

$$\begin{aligned}
&[M]\{\ddot{X}\}+[K]\{X\}=\{0\}\\
&\{x\}=\{X\}e^{i\omega t}
\end{aligned} \quad (4)$$

$\{X\}$ represents the amplitude vector at the corresponding points; $e^{j\omega t}$ denotes a complex exponential signal, with j being the imaginary unit, ω a constant, and t the variable.Further calculation of Equation (4) yields:

$$\left([K]-\omega^2[M]\right)\{X\}=\{0\} \quad (5)$$

By solving Equation (5) and selecting the unique non-zero solution, the natural frequencies ω_r of the system at each order are obtained.

$$\omega_1<\omega_2<\omega_3<\omega_4<\cdots<\omega_n \quad (6)$$

Substituting the square of ω_r into Equation (6) yields:

$$\left([K]-\lambda^2[M]\right)\{\phi\}_r=\{0\},\quad r=1,2,3,\ldots,n \quad (7)$$

ϕ: Parameter column vector; r: Modal order.

3. Variations in CO_2 Fluid Parameters

After CO_2 is injected into the tubular string, energy transfer occurs due to thermal interactions among the tubing, annulus, and the surrounding environment. Consequently, parameters such as temperature and pressure of CO_2 within the tubular string undergo changes. The physical properties of CO_2 are highly sensitive and exhibit significant variations under different temperature and pressure conditions, while simultaneously influencing the distribution of temperature and pressure. The variations in the physical properties of CO_2 under different temperatures and pressures, as obtained through the REFPROP property query software developed based on the NIST database, are illustrated in the figure below.

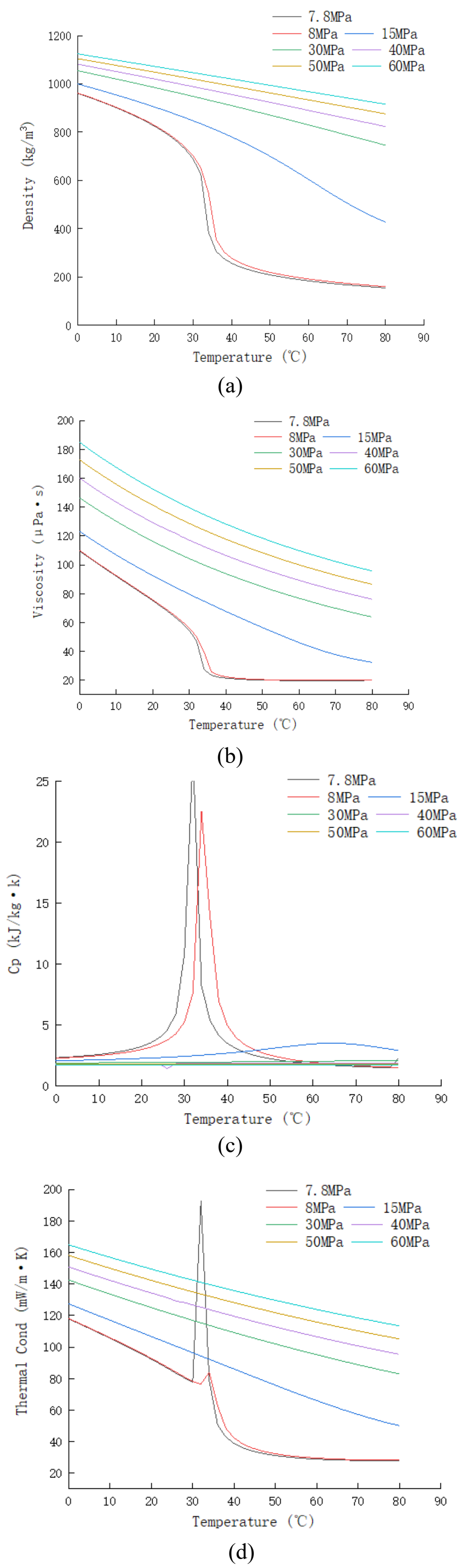

Figure 1. Variation Diagram of Carbon Dioxide Physical Properties

4. Influence of Pipe Length and Wall Thickness on Tubular Strings under Fluid-Structure Interaction

CO_2 flooding reservoirs are typically located at depths ranging from 600 to 4,000 meters underground, resulting in tubular strings extending several kilometers in length. Under limited computational resources, establishing a full-scale model of such elongated strings presents significant calculation challenges. Therefore, it is common practice to select a representative segment of the string for analysis. This study adopts a P110 tubing section with a length of 10 meters and specifications of Φ88.9 mm× 6.45 mm as the fundamental analytical model. The tubular segment is filled with fluid, and modeling is performed using the Design Modeler (DM) module in ANSYS. The material properties of the tubing are defined as follows: density ρ = 7850 kg/m³, Poisson's ratio μ = 0.3, and elastic modulus E = 206 GPa. The first ten natural frequencies are calculated and compared for three distinct conditions: empty tubing, tubing filled with liquid CO_2, and tubing filled with supercritical CO_2. As illustrated in Figure 2, the variations in natural frequencies due to fluid-structure interaction under these different operational conditions are presented.

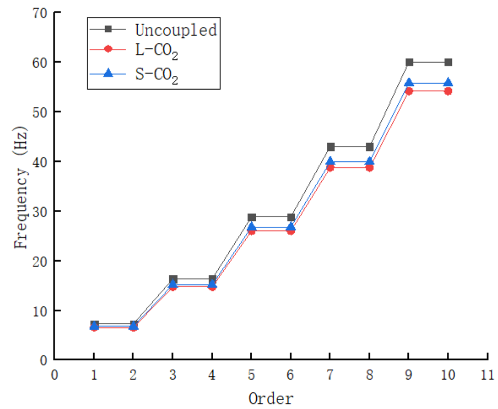

Figure 2. Variation of Natural Frequencies under Fluid-Structure Interaction for Different Operational Conditions.

As illustrated in Figure 2, when the coupling effect between the fluid and the tubular string is considered, the natural frequency of the string coupled with liquid CO_2 decreases by 9.8% compared to that of the empty string. Similarly, the natural frequency under supercritical CO_2 coupling decreases by 7.1%. Therefore, it is essential to account for the influence of the fluid when analyzing the natural frequency of tubular strings.

4.1. Influence of Tubing Length on the Natural Frequency of the Pipe

The vibration characteristics of a tubular string are influenced by its intrinsic parameters, among which the length of the string is a non-negligible factor. Taking a 4000-meter deep well in the field as an example, the pressure acting on the CO_2 injection string varies with well depth. When the wellhead pressure is 18 MPa, the bottom-hole pressure can reach 40 MPa. For analysis, the internal pressure of the string may be set to 35 MPa, with both ends of the string assumed to be fixed supports. The figure below illustrates the first ten natural frequencies corresponding to different string lengths under the same pipe diameter.

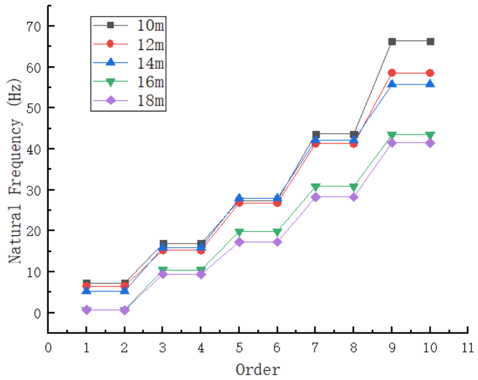

Figure 3. Comparison of Natural Frequency Variation Curves of the Tubular String with Respect to Pipe Length.

4.2. Influence of Wall Thickness on the Natural Frequency of the Pipe

Wall thickness is also a critical factor that cannot be overlooked when analyzing the vibration characteristics of a tubular string. For this study, tubular strings with wall thicknesses of 5.49 mm, 6.45 mm, 7.34 mm, 9.53 mm, and 11.21 mm were selected. Based on the computational data obtained from the CO_2 fluid-structure interaction analysis, the internal pressure of the string was set to 30 MPa, and both ends of the string were defined as fixed supports. Modal analysis was then conducted to extract the first ten natural frequencies as a function of wall thickness. Furthermore, a comparative analysis was performed to evaluate the variations in natural frequency and deformation patterns across different orders under the selected wall thicknesses.

The results, as shown in Figure 4, indicate that the wall thickness of the CO_2 injection string has a notable influence on its natural frequency. As the wall thickness increases, both the natural frequency and deformation magnitude of the string decrease, while its load-bearing capacity improves. The primary reason for this is that with increased wall thickness, the forces exerted by the internal fluid on the string are more effectively distributed. This reduces the stress per unit area and enhances protective effects. Therefore, under practical operational conditions, increasing the wall thickness of the CO_2 injection string can effectively mitigate vibration-induced damage and prolong the service life of the string.

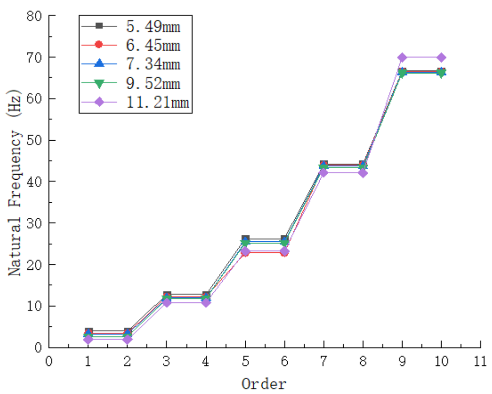

Figure 4. Comparison of Natural Frequency Variation Curves with Respect to Wall Thickness.

5. Influence of Fluid-Structure Interaction on Tubular String Connections and the String Itself

Under the stress induced by fluid flow during fluid-structure interaction in CO_2 injection strings, the operational lifespan of the string can be adversely affected, particularly at the pipe coupling sections. Under the influence of internal CO_2 fluid and combined with other applied loads, if the stress exceeds the maximum allowable stress at the pipe connections, the sealing integrity of the threaded joints may be compromised due to variations in vibration-induced stress. Therefore, it is essential to evaluate whether the threaded joints are at risk of structural failure by analyzing stress variations. Particular attention should be paid to whether extensive high-stress zones develop at the pipe connections and whether these stresses surpass the material's yield limit. This study primarily analyzes the stress distribution in the tubular string under the combined effects of tensile and compressive loads along with fluid-induced stresses, with a specific focus on the threaded joints.

5.1. Finite Element Analysis of the Influence of Tensile Loads on Tubular Strings

In downhole conditions, when a tubular string is subjected to a combination of fluid pressure and tensile loads, the resulting stress variations are significantly more pronounced compared to scenarios involving only tensile loads without fluid-structure interaction. This combined loading critically affects the stable operation of the string. Figure 5 illustrates the stress contour plot under tensile loading conditions.

As shown in Figure 5, under the combined action of fluid pressure on the tubular string and axial tensile loading, the maximum stress occurs at the pipe coupling. The stress in other sections of the string is relatively low, with the highest stress concentration observed at the threads of the internal threaded connection. It is evident that as the tensile load increases, the maximum stress experienced by the string also rises, and the rate of stress escalation accelerates correspondingly with the increase in tensile load. This indicates that the stress in the string increases nonlinearly, highlighting the significant influence of tensile loading on the string's mechanical response. When the tensile load reaches 700 kN, the ultimate stress on the string attains 937 MPa, exceeding the material's yield limit. However, due to the relatively robust geometry of the threaded teeth, the string does not undergo failure. The sealing performance of the string remains intact, and the structural integrity of the string itself is preserved, ensuring stable operation under the applied loading conditions.

5.2. Finite Element Analysis of the Influence of Compressive Loads on Tubular Strings

In addition to tensile loads, CO_2 injection strings are also subjected to compressive loads. Figure 6 presents the stress nephogram under varying compressive loads in the presence of fluid pressure.

As the compressive load increases, the stress experienced by the tubular string also rises. Under the influence of compressive loading, not only does the pressure on the string itself progressively intensify, but the stress at the threaded connections also escalates. Particularly noticeable is the significant increase in stress at the first and second threads of the connection between two pipe segments. This observation indicates that compressive loading not only affects the stress distribution within the string but also demands special attention regarding the stress concentration at the threaded connections. This is critical because such stress concentrations may not only compromise the structural integrity and operational stability of the string but also adversely affect the sealing performance after CO_2 injection, potentially leading to severe consequences such as leakage.

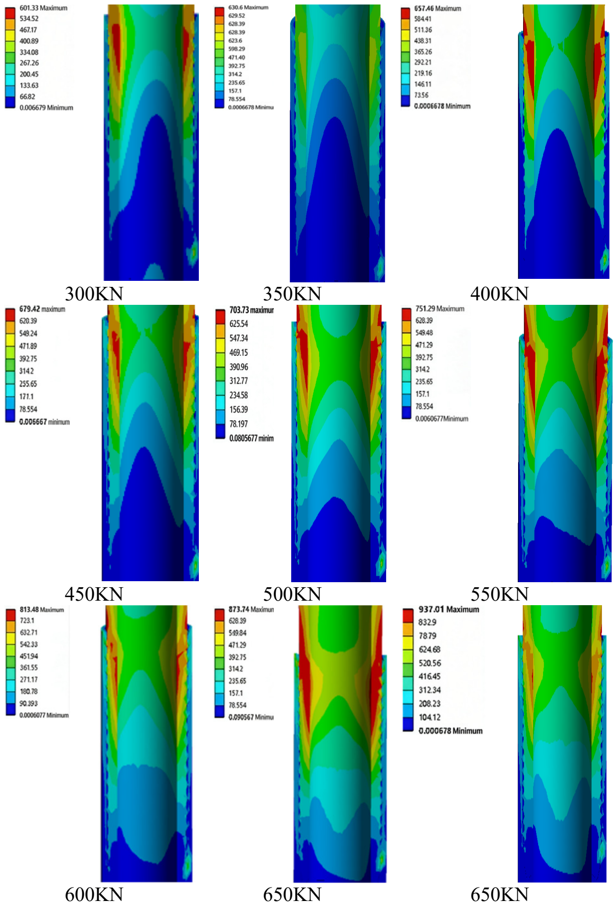

Figure 5. Stress Nephogram Under Tensile Load

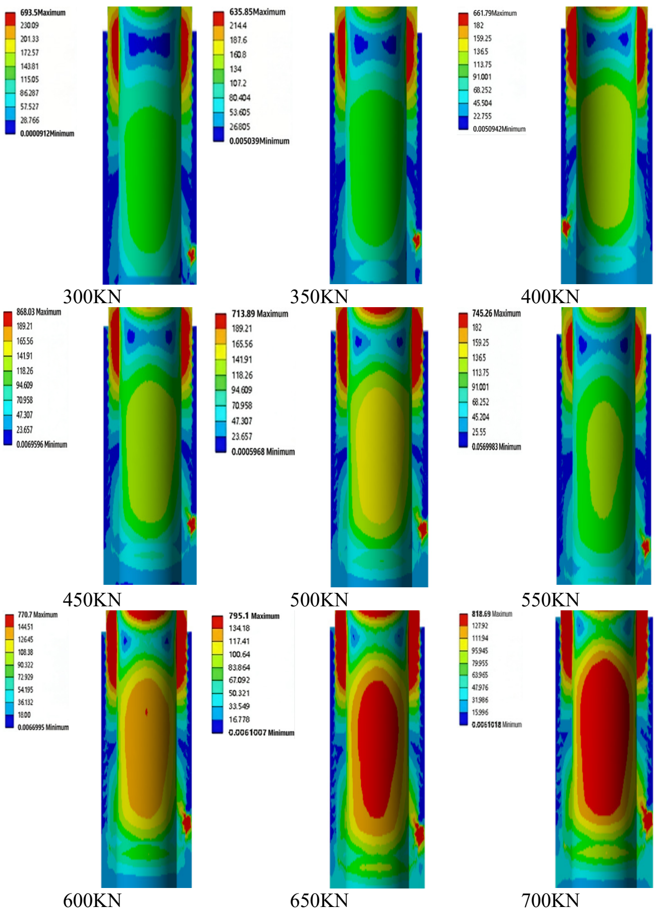

Figure 6. Stress Nephogram under Compressive Loading

6. Conclusion

Taking the supercritical CO_2 injection string as the research subject, this study conducted a comparative analysis of natural frequencies under different operating conditions considering fluid-structure interaction. The effects of varying pipe lengths and wall thicknesses on the natural frequency of the string were investigated. Additionally, the mechanical response at the string connections under axial tensile and compressive loads induced by internal pressure after CO_2 injection was calculated. The following conclusions were drawn:

(1)Under fluid-structure interaction, the natural frequency of the tubular string is reduced. Both pipe length and wall thickness exhibit an inverse relationship with the natural frequency. An increase in pipe length leads to a decrease in natural frequency, a reduction in maximum amplitude, and a more dispersed distribution of vibration modes. In practical applications, longer pipelines require focused attention on resonance risks in the low-frequency range, while shorter pipelines necessitate control over concentrated vibrations in the high-frequency range. As wall thickness increases, the natural frequency decreases. Therefore, within the constraints of actual production conditions, selecting pipelines with greater wall thickness can help mitigate potential vibration-induced damage.

(2)Under the fluid pressure generated after CO_2 injection into the tubular string, the maximum stress predominantly occurs at the threaded connections, though it may also manifest in the structural body of the string itself. However, overall, the stress magnitude on the string body is generally lower than that at the threaded connections. Therefore, during operational use of the string, special attention must be paid to the stress conditions at the connections to avoid excessive stress that could compromise sealing integrity and lead to leakage.

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