Academic Journal of Emerging Technologies
ISSN Print: 3104-4417
ISSN Online: 3104-4425
CD ISSN: 3104-4433
https://doi.org/10.63313/AJET.9028

Static and Dynamic Analysis of Injection -Production Tubing Under Alternating Loads

Peng Zhou
School of Mechanical Engineering, Xi'an Shiyou University, Xi'an, Shaanxi, 710065, China
Email: 1175255754@qq.com

How to cite this paper: Zhou, P. (2025). Static and dynamic analysis of injection-production tubing under alternating loads. *Academic Journal of Emerging Technologies*, 2(1), 37-45. ISSN Print: 3104-4417; ISSN Online: 3104-4425.
https://doi.org/10.63313/AJET.9028
Published: 2025-12-31

Abstract

Underground gas storage serves as a critical facility for natural gas peak shaving and strategic reserves. The injection-production string faces safety risks such as buckling, erosion, and vibration under cyclic loads, temperature variations, and complex wellbore conditions. Based on traditional dynamic analysis, this paper focuses on the dynamic effects of alternating loads by establishing a three-dimensional string dynamics model to systematically investigate vibration characteristics, stress responses, and fatigue life. The research findings aim to provide a theoretical basis for the safety evaluation and parameter optimization of gas storage injection-production strings.

Keywords

Gas Storage; Injection-Production String; Alternating Load; Dynamic Response; Fatigue Life

1. Introduction

Underground gas storage facilities are the core infrastructure for peak shaving and strategic reserves of natural gas. Their injection and production tubing strings face safety risks such as buckling, erosion, and vibration under periodic loads, temperature changes, and complex wellbore environments. In 2023, He Houfeng, Hu Xuhui, and Zhuang Yongtao [1] et al. conducted PVT parameter fitting for the low-porosity and low-permeability oil reservoir in Block A of Shengli Oilfield based on crude oil component data and constant composition expansion experiment results, and constructed a component model with seven pseudo-components. They thereby calculated the initial miscibility pressure and multiple contact miscibility pressure. The research team proposed for the first time an empirical formula for the injection rate of CO_2 flooding based on the gas channeling phenomenon as the control condition, and optimized the key parameters of reservoir engineering based on the homogeneous component model. The optimal injection and production parameters were ultimately determined as a five-spot well pattern, 250-meter well spacing, 20 tons/day injection rate, and 26.0 MPa production pressure. In 2022, Cui Chuanzhi, Su Xinkun, and Yao Tongyu [2] et al. used numerical simulation methods to analyze the injection-production coupling sweep characteristics of CO_2 miscible flooding, and clarified the gas channeling degree characterization indicators and classification standards. The results showed that injection-production coupling development could expand the sweep area, delay gas channeling, and increase recovery rate; the gas channeling stage division results calculated by the new method were consistent with the field monitoring data and could be used as a basis for identifying gas channeling stages; they also analyzed the influence of well pattern type and reservoir properties on the gas channeling stage, such as the longer oil production without gas stage and the delayed gas channeling development stage under the five-spot well pattern with higher porosity. In June 2019, Cao Yinping, Guo Lu, and Dou Yihua [3] took oil and gas well tubing as the research object and deeply explored the influence of fluid-solid coupling on the vibration characteristics of the tubing. They established the vibration equations of the tubing considering and not considering fluid-solid coupling, and used ANSYS Workbench software to build a three-dimensional finite element model of the tubing. They compared and analyzed the natural frequencies and vibration mode characteristics under three working conditions: empty tubing, gas-solid coupling tubing, and liquid-solid coupling tubing. The research results showed that when fluid-solid coupling was taken into account, the natural frequency of the tubing was lower than that of the empty tubing without fluid-solid coupling, and the frequency drop was more significant under liquid-solid coupling conditions. In addition, they systematically investigated the variation laws of the natural frequency of the tubing with vibration order and tubing length, as well as the specific influence of fluid-solid coupling on the vibration mode. The relevant conclusions can provide important references for the structural design and safe operation of oil and gas well tubing. In June 2019, Yan Xing, Yan Yifei, and Yan Xiangzhen [4] took the tubing of underground gas storage wells as the research object and studied its nonlinear vibration characteristics using the wavelet multi-scale transformation method. In May 2018, Luo Jianan [5] studied the vibration characteristics and sealing performance of underground gas storage injection and production tubing under complex working conditions. He established a mathematical model of gas-solid coupling vibration of underground gas storage well tubing and analyzed the vibration form and vibration mechanism of the tubing through the Hamilton principle.

In response to the above issues, this paper focuses on the dynamic effects of alternating loads on the basis of traditional dynamic analysis. By establishing a three-dimensional tubing dynamic model, the vibration characteristics and stress response of the tubing under alternating loads are systematically studied. The research results can provide a theoretical basis for the safety assessment and parameter optimization of underground gas storage injection and production tubing.

2. Static Analysis

2.1. Gravitational Effect

During the operating cycle of a gas storage facility, the tubing string continuously experiences axial tensile forces due to its own weight. These loads can cause plastic deformation of the tubing. Since the material of the tubing undergoes irreversible yielding during the deformation process, this deformation does not recover when the load is removed. As a result, the axial tensile force persists throughout the entire injection and production cycle.

2.2. Piston Effect

The piston effect primarily occurs at locations where the diameter of the tubing changes. This is because the internal pressure within the tubing and the external annular pressure act jointly on the positions of sudden diameter change in the tubing as well as on the end faces of the sealing tubes. Due to differences in the stressed areas at these locations, the effective area subjected to pressure changes accordingly, which in turn induces axial deformation of the tubing string.

After the packer is set, if operating parameters or wellhead pressure are adjusted, corresponding changes will occur in both the internal tubing pressure and the annular pressure. Such pressure fluctuations further lead to variations in the piston force. The dynamic changes in piston force directly cause alterations in the length of the injection/production tubing string, thereby affecting the overall stress distribution and structural stability of the tubing. According to Hooke's law in material mechanics, there is a clear quantitative relationship between the magnitude of change in piston force and the magnitude of change in tubing length. As shown in **Figure 1**.

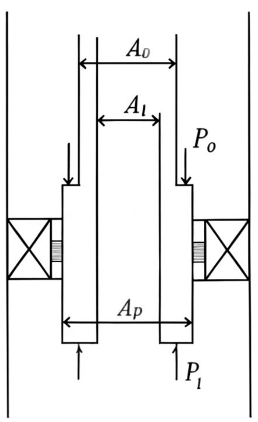

Figure 1. Example of a figure caption (figure caption).

2.3. Bulging Effect

When the internal pressure of the injection/production tubing string is higher than the external pressure, the pressure acting radially inward on the inner wall of the tubing in the horizontal direction causes the tubing to expand radially—resulting in an increase in diameter—while simultaneously contracting axially and shortening in length. This phenomenon is referred to as the positive bulging effect. Conversely, if the annular pressure exceeds the internal tubing pressure, the tubing will experience radial contraction (a decrease in diameter) and axial elongation (an increase in length). This phenomenon is known as the reverse bulging effect. As shown in **Figure 2**.

The bulging effect generates an axial force within the tubing string, the magnitude of which depends on the variation of the internal–external pressure differential and the cross-sectional area of the tubing. Because the length change of the tubing induced by the bulging effect disrupts its original geometric configuration, it alters the stress distribution of the tubing within the wellbore, thereby further affecting its structural stability and service life.

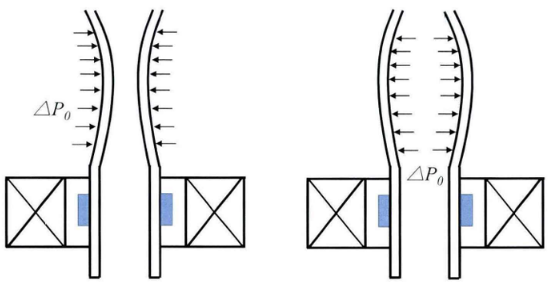

Figure 2. Example of a figure caption (figure caption).

2.4. Temperature Effect

The temperature effect refers to the thermal expansion and contraction of the tubing string caused by changes in ambient temperature or the temperature of the fluid inside the wellbore. For tubing strings equipped with packers, before the packer is set, the tubing can expand and contract relatively freely within the wellbore; under such conditions, the deformation resulting from temperature variations has little impact on the axial stress of the tubing. Therefore, during the pre-setting stage, length changes due to thermal expansion or contraction are usually not taken into account.

During normal production operations, fluid flow inside the wellbore leads to a nonlinear temperature distribution along the well depth. To accurately calculate the temperature effect, the tubing string should be divided into several infinitesimal segments, and the thermal expansion or contraction of each segment should be computed based on its average temperature change, so as to obtain the overall deformation.

The temperature effect induces axial deformation of the tubing, the magnitude of which is related to the material's coefficient of thermal expansion, the tubing length, and the temperature change. Expansion and contraction of the tubing may cause loosening of connections with other components or generate additional stresses, thereby affecting the tubing's sealing performance and overall structural integrity. Under multi-cycle alternating loading, the deformation caused by the temperature effect accumulates over time, accelerating fatigue damage to the tubing.

3. Modal Analysis

Using the finite element analysis software ANSYS, modal analysis was performed on the tubing string, and the first ten orders of vibration frequencies were calculated. The results show that the tubing string's first-order natural frequency is 0.001 Hz, and as the vibration order increases, the frequencies exhibit an upward trend, reaching 0.0149 Hz at the tenth order.

3.1. Mode Shape

The first five mode shapes of the tubing string are shown in the figure. It can be observed that each mode shape is essentially symmetric along the well depth. At the wellhead and at the packer location, zero displacement occurs due to fixed constraints. The maximum displacements of the mode shapes are concentrated between 900 m and 1100 m depth, which is also the critical section for mechanical strength evaluation of the tubing.

3.2. Frequency Variation

As the injection and production gas volume increases, the first five orders of natural vibration frequencies of the tubing string all exhibit a gradual decreasing trend. When the gas volume reaches 200,000 m^3 per day, the rate of frequency reduction becomes significantly faster; and when the gas volume exceeds 300,000 m^3 per day, the first and second order frequencies of the tubing have dropped to zero.

The reason the first and second order frequencies almost coincide is that the tubing has a circular cross-section, so its mode shapes in the X and Y directions are theoretically identical. Under different gas volume conditions, the tubing will display different vibration patterns; therefore, optimizing the injection and production gas volume can effectively improve the vibration behavior of the tubing string. As shown in **Figure 3**.

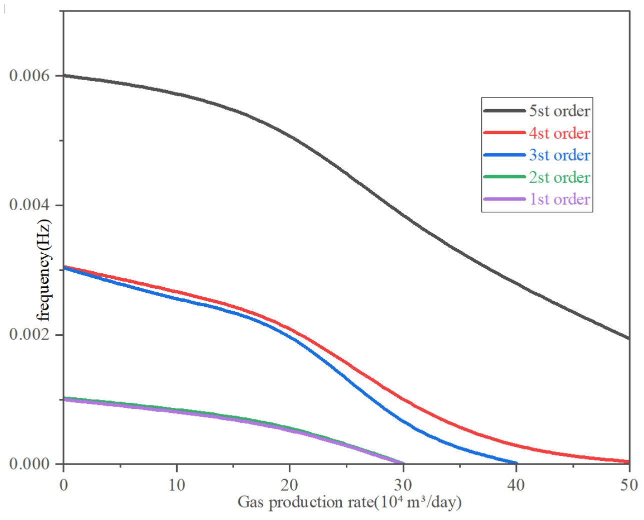

Figure 3. Example of a figure caption (figure caption).

4. Transient Dynamic Analysis

Under gas injection and production conditions, the tubing string in a gas storage facility experiences axial friction resistance due to the interaction between the gas and the inner wall. In actual operation, the tubing undergoes frequent alternation between injection and production cycles. To simulate these working conditions, a sinusoidal alternating load is applied to the tubing model.

Considering that the gas flow velocity is not constant during production and injection processes, the calculated friction resistance is approximated as a sinusoidal cyclic force and applied to the inner wall of the tubing, with the fluctuation amplitude taken as 20 % of the friction resistance. During gas injection, the friction resistance acts downward, while during gas production, it acts upward.

4.1. Vibration At Critical Points

Three critical points with relatively large modal displacement were selected from the modal analysis, located at well depths of 900 m, 1000 m, and 1100 m.

To simulate the actual operating conditions of the injection/production tubing string, an impact dynamic load corresponding to a production rate of 272,000 m^3/day was applied to the tubing, and transient dynamic analysis was conducted. The longitudinal vibration velocity and acceleration at the three depths (900 m, 1000 m, and 1100 m from the wellhead) were obtained as functions of time.

As shown in **Figure 4** and **Figure 5**.During the initial 1.5 seconds of vibration, the fluctuation amplitudes of both vibration velocity and acceleration at the same location were relatively significant; thereafter, the amplitudes tended to stabilize and exhibited periodic variation. This periodically varying vibration state subjects the tubing to long-term alternating stress, making it susceptible to fatigue failure even at relatively low stress levels.

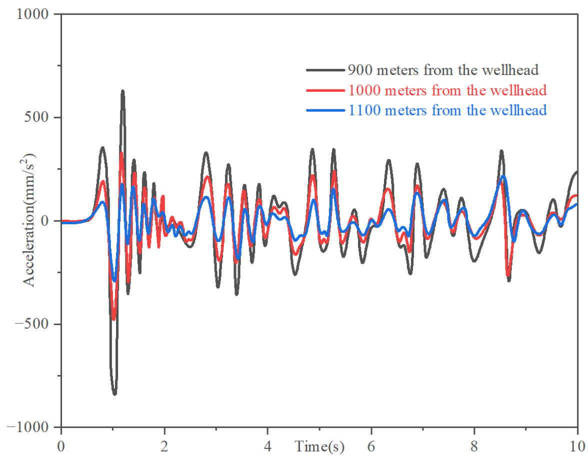

Figure 4. Example of a figure caption (figure caption).

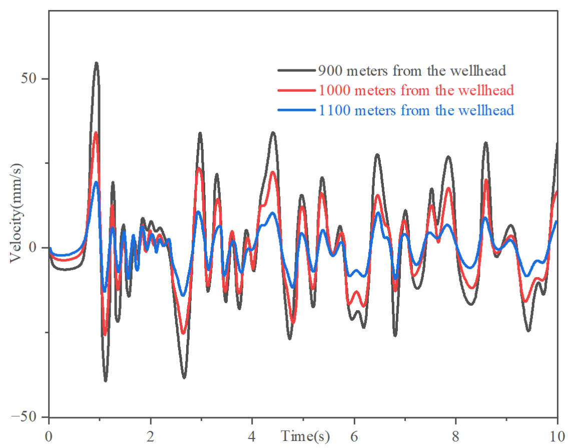

Figure 5. Example of a figure caption (figure caption).

4.2. Force Variation With Well Depth

As shown in **Figure 6** and **Figure 7**. At various moments during the tubing vibration process, the axial force and stress at the wellhead change relatively little. However, the axial force and stress along the entire tubing string are non-uniformly distributed with respect to well depth, and their distribution patterns differ markedly at different times.

In some cases, there may even be no axial neutral point inside the tubing, and the maximum axial force does not necessarily occur at the wellhead.

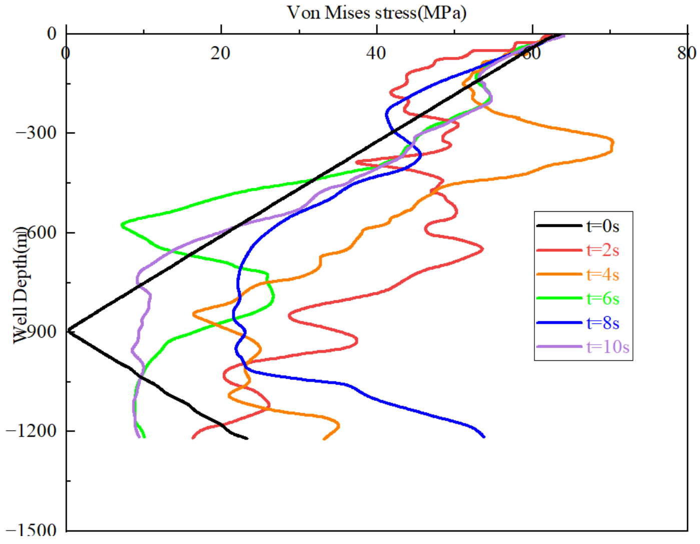

Figure 6. Example of a figure caption (figure caption).

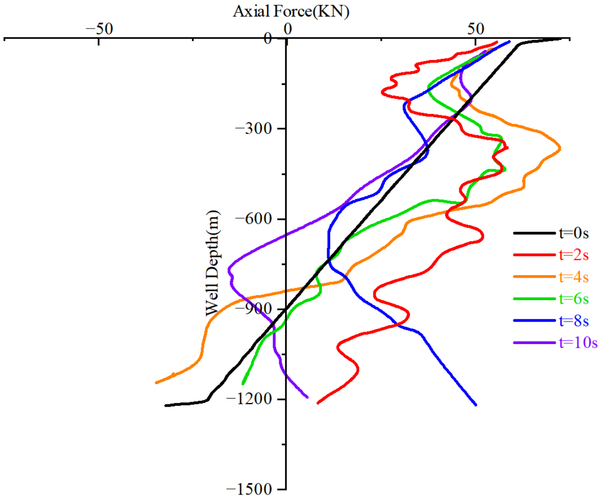

Figure 7. Example of a figure caption (figure caption).

References

[1] He H F, Hu X H, Zhuang Y T, et al. Optimization research and application of CO_2 injection and production parameters for low-permeability reservoirs: A case study of Block A in Shengli Oilfield[J]. Petroleum Geology and Recovery Efficiency, 2023, 30(2): 112-121.

[2] Cui C Z, Su X K, Yao T Y, et al. Coupling and sweep characteristics of CO_2 miscible flooding in low-permeability reservoirs and a quantitative method for dividing gas breakthrough stages[J]. Special Oil & Gas Reservoirs, 2022, 29(4): 90-95.

[3] Cao Y P, Guo L, Dou Y H. Influence of fluid-structure coupling on vibration characteristics of oil-gas well tubing strings[J]. Machinery Design & Manufacture, 2019, (6): 84-87+91.

[4] Yan X, Yan Y F, Yan X Z. Research on nonlinear vibration characteristics of gas storage

well tubing strings based on wavelet multiscale transform[J]. Journal of Vibration and Shock, 2019, 38(20): 51-60.

[5] Luo J N. Study on vibration characteristics and sealing performance of injection-production tubing strings in gas storage wells[D]. China University of Petroleum (East China), 2018.