3D Finite Element Analysis on Mechanical Behavior of Completion Tubing String for Extra-Deep High Temperature Gas Well

Shuang Liu¹, Xinpu Shen²*, Junyan Liu¹, Guoxiao Shen², Qiang Xu¹ and Dongdong You²

¹Tarim Oil Company CNPC, Xinjiang, China;
²China University of Petroleum (Huadong), Shandong, China

*Corresponding author email: 20180011@upc.edu.cn

Abstract. 3D Finite Element model was built for analysis of mechanical behavior of tubular system. Factors of wellbore trajectory deviation and frictional contact behavior between tube and casing are considered in the model. Loads of packer setting, hydraulic fracturing, and gas production are included. Numerical solutions of stress and displacement distribution along the tubing are presented. Principal results are: 1) Displacement distribution along the whole length of tubing. 2) Distribution of axial stress and von Mises stress along the whole length of tubing. 3) Distribution of displacement and stress along the tubing section below expansion pipe, as well as frictional contact stress and frictional force in this section.

Keywords: Completion tubing; Testing; High pressure high temperature; Plastic deformation; Buckling; Numerical simulation; Expansion pipe.

1. Introduction
Mechanical behavior of completion tubing string for extra-deep high temperature gas well was an important topic in petroleum industry. In the past, most of researchers performed mechanical analysis of tubing string with theoretic methods[1-4]. In the recent years, 3D numerical method such as Finite Element method has got more and more applications on this topic[5-9].

In this paper, three-dimensional finite element numerical analysis was carried out on the mechanical behavior of pipe string, including fracturing transformation and production testing, and numerical solutions of various mechanical quantities such as displacement and stress of the pipe string were obtained. On this basis, the static strength safety factor and fatigue safety factor of the pipe string were calculated.

2. Finite Element Model

2.1. Structural Model
Table 1 gives the geometric parameters of the casing and tubing in the tubular structure. Also, Table 1 gives the depth of the selected points to be simulated in the finite element model and their corresponding closing distance changes. Figure 1 shows the pipe structure.
Table 1. Values of tubing parameters

| Lower depth [m] | Innermost layer of casing | Tubing | Clearance |
|-----------------|---------------------------|--------|-----------|
|                 | external diameter [mm]    | wall thickness [mm] | external diameter [mm] | wall thickness [mm] | internal diameter [mm] | |
| 0               | 196.85                    | 12.7   | 171.45    | 114.3 | 12.7 | 88.9 | 28.575 |
| 196.85          | 12.7                      | 171.45 | 1500      | 114.3 | 12.7 | 88.9 | 28.575 |
| 196.85          | 12.7                      | 171.45 | 3600      | 88.9  | 9.52 | 69.86 | 41.275 |
| 196.85          | 12.7                      | 171.45 | 88.9      | 7.34  | 74.22 | 41.275 |
| 196.85          | 12.7                      | 171.45 | 88.9      | 7.34  | 74.22 | 41.275 |
| 5215            | 206.38                    | 17.25  | 171.88    | 88.9  | 7.34 | 74.22 | 41.275 |
| 5590            | 145.6                     | 15.4   | 114.8     | 5590  | 88.9 | 7.34 | 74.22 | 41.275 |
| 145.6           | 15.4                      | 114.8  | 5680      | 93    | 10   | 73   | 39.44  |
| 5730            | 145.6                     | 15.4   | 114.8     | 5730  |      |      |        |

The change of closure distance with depth is shown in Fig. 1. The deviation of closure distance is considered in the model. Also, Figure 1 gives the depth of the selected points to be simulated in the finite element model and their corresponding closing distance changes.

![Figure 1. Distribution curve of closing distance with depth](image1)

Fig. 2 is a three-dimensional finite element tubular model diagram. The total length of the string is 5730 m and the packer is located at a vertical depth (TVD) of 5590 m. There could be up to 24 stress points on the pipe section in the figure. In order to improve efficiency in this analysis, only 9 representative stress points are selected to output stress and analyze.

![Figure 2. 3D finite element model of pipe string](image2)
2.2. The Mesh of the Model
3821 nodes and 1910 pipe32H which is 2nd order pipe element were used in the whole tubing string. 3787 contact elements were set between tubing and casing to simulate the possible contact friction between tubing and casing. Friction coefficient is 0.25.

2.3. Material Model
The steel grade of the casing is BT-S13Cr110 which a special alloy, and the material in the finite element model was the elastoplastic model, and the parameter values are shown in Table 2. The coefficient of thermal expansion is: 1.05e-5 °C.

| Yield strength[psi(MPa)] | Tensile strength[psi(MPa)] | Elastic properties |
|------------------------|---------------------------|-------------------|
| Maximum | Minimum | Maximum | Minimum | Young's modulus[ksi(MPa)] | Poisson's ratio |
| 125,000 (862) | 110,000 (758) | 120,000 (828) | 31,290 (215,700) | 0.3 |
| 130,000 (896) | 109,000 (750) | 129,000 (890) | 31,290 (215,700) | 0.3 |

2.4. Boundary Conditions
The string model includes displacement constraints at the wellhead and displacement constraints at the packer, and other places are force boundaries.

2.5. Load Conditions
The stress of the pipe model is gravity, internal and external pressure, stress caused by temperature changes, and buoyancy. The local force of THT (Three-pieces-High Temperature) hydraulic packer is neglected in the overall string model. The three curves in Fig. 3 below show the values of the tubing pressure parameters in the three different construction stages: Pre-packer-setting, stimulation, and production testing stage. Table 3 shows the formation temperature and pressure parameters. Table 4 shows the values of wellhead internal pressure and casing pressure in each stage.

Table 3. Temperature and formation pore pressure parameters.

| Working well section[m] | Depth of target layer[m] | Formation pressure coefficient | Density of kill fluid[g/cm³] | Temperature of wellhead[°C] | Local actual ground temperature |
|-------------------------|--------------------------|-------------------------------|-----------------------------|-----------------------------|--------------------------------|
| 5640-5677               | 5614                     | 1.75                          | 1.85                        | 5                           | 141.7                           |

Table 4. Wellhead internal pressure and casing pressure at each stage

| Condition                          | internal pressure[MPa] | Casing pressure[MPa] |
|------------------------------------|------------------------|---------------------|
| Displacement 3.5m³/min             | 83                     | 30                  |
| Pure gas production 00.0×10⁴m³/d   | 70                     | 0                   |

3. Results of Finite Element Analysis
Fig. 3(a) shows the distribution of the equivalent stress (sMises) along the entire length of the pipe string at 9 stress points in section of pipe string during fracturing, and it’s maximum value is 372 MPa (TVD: wellhead). According to the initial yield strength value of 758 MPa in Table 3, the stress of the pipe string is in the state of elastic stress during fracturing. The static strength safety factor Ns at this time is: Ns=758/372=2.04. Dangerous cross section is at the wellhead.

Fig.3(b) shows the distribution of the equivalent stress (sMises) along the whole length of the string at
each stress point of the cross section of the string during the well test. The maximum equivalent stress is 289MPa (TVD: wellhead). According to the initial yield strength value of 758mpa in Table 3, the stress of the pipe string is in the state of elastic stress. The static strength safety factor \( N_s \) at this time is: 
\[ N_s = \frac{758}{289} = 2.62 \]. Dangerous cross section is at the wellhead.

It can be seen from Fig.3(b) that at the bottom of the string during the production testing, elastic buckling and stress oscillation occur within 400 m above the packer. Letters loc (1-9) on figure 3 represent the location of a stress point. MD stands for Measured Depth.

![Figure 3. Distribution of von Mises stress along the tubing string: (a) for stimulation stage, (b) testing production stage](image)

Fig.4 (a) shows the distribution of the axial force (S11) of the pipe string along the entire length of the pipe string during production testing. Fig.4(b) is a partial enlarged view of the distribution of S11 along the full length of the pipe at TVD = 5000 to 5400 m. Due to the occurrence of elastic buckling behavior, the amplitude of the axial stress oscillation value at 5095 m is: 
\[ \sigma_a = 90-51.85 = 38.15 \text{ MPa} \], and the average stress \( \sigma_m = 51.85 \text{ MPa} \). Correspondingly, it can be calculated that the fatigue safety factor on the section of the pipe string corresponding to the above depth is 1.74.

![Figure 4. The axial force distribution of the pipe string along pipe string during production testing: (a) the full length view, (b) zoomed view of lower part](image)

4. Conclusions

According to the mechanical analysis results of the above finite element pipe string, the following conclusions are obtained:

1) In the reservoir stimulation stage, the maximum equivalent stress at each point of the pipe string is 372 MPa, and the static strength safety factor \( N_s \) of the pipe string is 2.04 during the fracturing stage. Dangerous cross section is at the wellhead. The distribution of axial stress (S11) has no oscillation
along the entire length of the pipe string. The string is safe during the fracturing transformation stage without risk of damage.

2) In the production test stage, the maximum equivalent stress at each point of the pipe string is 289 MPa, and the static strength safety factor $N_s$ of the pipe string is 2.166 during the fracturing stage. Weakest cross section is at the wellhead. Axial stress oscillates at a depth of 5000-5400 m.

3) During the production test, the minimum fatigue safety factor is 1.74. Under acid etching environment, the safety factor value is relatively small, and the pipe string has a certain risk of fatigue fracture. Dangerous cross-section location depth is near 5095 m. No stress oscillation during the fracturing stage, no risk of fatigue fracture.

4) It is suggested that a higher level of corrosion-resistant and high-strength alloy steel should be used for the 20 m string near the 5095 m depth to avoid possible fatigue fracture. In addition, if some measures could be taken to reduce the local stress concentration, the risk of fatigue fracture of the above dangerous sections will also be reduced.

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