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Mechanical Analysis of the String Deformation of the Horizontal Well Packer String during Setting and Fracturing

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Abstract

Under the two working conditions of setting and fracturing of the horizontal well packer string, the deformation reasons and load force distribution of the string will change with the different working conditions. In order to guarantee the packer string under the two conditions of safety and the safety of underground work in horizontal well packer string as the research object, using the string mechanics, material mechanics, Melanie formula and the generalized hooke's law theory knowledge, analyzes the packer string in setting and horizontal well fracturing string under two kinds of working condition of deformation and stress distribution. When the packer string is set, its axial deformation is mainly affected by piston effect and bulging effect. When the packer string is fractured, axial load is mainly caused by the effect of swelling, temperature and friction. According to the string of piston effect, ballooning effect, friction effect, temperature effect, obtained the corresponding effect of the corresponding string under the axial stress, axial force and deformation calculation method, the calculation results of packer string when setting and fracturing deformation and axial load distribution of a detailed description of the horizontal well of packer string downhole safety operation has some basis for action.

Keywords

horizontal well; pipe string; deformation analysis; mechanical analysis; setting and fracturing.

1. Introduction

The goal of horizontal Wells is to drill as much oil as possible to increase production per well and injection (water injection, steam injection, etc.) to achieve higher recovery.However, the horizontal well pipe string needs to be connected with multiple packers downhole to realize the segmenting stratification of oil and gas well, so as to achieve the goal of oilfield stimulation.When the horizontal well packer is set downhole, due to the influence of the packer setting process, axial deformation of the string will occur when the packer is set downhole [1].However, when the horizontal well packer string is fractured, it will be converted into axial load due to the fixed action of packer without axial deformation.Axial deformation and increased axial load on the string may cause packer seal failure and affect string strength.Therefore, it is necessary to theoretically analyze and understand the deformation and stress of the packer string during setting and fracturing to ensure the safety of the packer string downhole.

As a revolutionary technology in oil and gas field development, horizontal well technology has been studied by domestic and foreign experts and scholars since 1950s, and some achievements have been made.In the 1960s, Lubinski[2] used Hooke's Law and spiral buckling theory to study the axial deformation of a single packer string under four effects.In the 1980s, Hammerlind[3-4]further studied the stress and deformation of the double packer string.In

2001, Li Qindao et al.[5]made a systematic analysis and discussion on the stress and deformation of the single packer string.In 2009, Ma Desheng[6] took the stress state of fracturing string in horizontal well under the hole as the research object, and studied the calculation of stress and deformation of fracturing string when fracturing fluid is injected.In 2014, Lu Zhanguo [7] took the horizontal well packer string and hydraulic compression packer as the research objects and studied the influence of each packer on the stress and deformation of the string when it is set.In 2016, Liu Kaiqiang[8]took the multi-packer string of horizontal Wells as the research object, and applied the theory of material mechanics to analyze the stress of the string when the intermediate packer moves in a limited way.In 2018, Cao Yinping et al.[1]took the horizontal well double packer string and hydraulic compression packer as research objects, and deduced the calculation formula of axial force and axial stress of the packer on the string under the action of wellhead pressure, as well as the calculation formula of deformation of the string without packer constraint.In 2018, Dong Rizhi[9]studied the string entry, packer setting, fracturing construction and other processes of double sealing and single card fracturing of horizontal Wells.

In the process of setting and fracturing, the horizontal well string will be affected by different effects, resulting in deformation of the string and increasing axial load.According to the force exerted on the string during setting, the formula of the effect of piston effect and bulging effect on the deformation is obtained at this stage.Under the influence of swelling, temperature difference and friction effect, the deformation of the string will be converted into the axial load of the string. The formula of the axial force and axial stress of the packer on the string at this stage is deduced.

2. Analysis of String Deformation during Horizontal Well Setting

2.1. Analysis of String Deformation Caused by Piston Effect in Horizontal Well Setting

During the horizontal well setting process, the ball valve at the bottom of the string is closed under the action of the pressure inside the string.During the setting operation, the pressure inside the string increases gradually. Due to the difference between the internal pressure (pressure inside the tubing) and the external pressure (pressure in the annulus), the pressure difference inside and outside the tubing will generate pressure difference, and the pressure difference between the internal and external pressure of the packer string will generate piston force.The phenomenon of string elongation or shortening due to this piston force is called piston effect [10].When the setting load increases continuously, the internal and external pressures of the horizontal well packer string will also change constantly, and the increase of the internal and external pressure difference will lead to the increase of piston force, and the axial deformation of the string under the action of piston force will also be intensified [11].

In Figure 1, A_i is the cross-sectional area of the inside diameter of the pipe string, A_1 is the cross-sectional area of the outside diameter of the pipe string, A_0 is the cross-sectional area of the packer's sealing cavity, Po is the annulus pressure of the packer's upper part, and P_i is the pressure of the packer's lower part.

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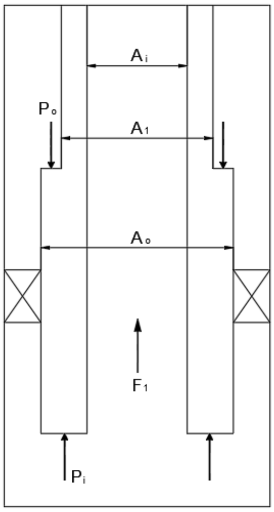

Fig.1 Schematic diagram of piston Effect of horizontal well packer string

As shown in FIG.1, the downward piston force generated by annular pressure and the upward piston force generated by pressure inside the string are respectively:

$$F_{po} = P_o(A_o - A_1) = P_o \frac{\pi}{4}\left(D_o^2 - D_1^2\right) \tag{1}$$

$$F_{pi} = P_i(A_o - A_i) = P_i \frac{\pi}{4}\left(D_o^2 - D_i^2\right) \tag{2}$$

Let the upward force (compression force) be positive and the downward force (tension) be negative. and the resultant force generated by the piston effect is $F_P=F_{Pi}-F_{Po}$, then the piston force of F_P is:

$$F_p = F_{pi} - F_{po} = \frac{\pi}{4}\left[P_i\left(D_o^2 - D_i^2\right) - P_o\left(D_o^2 - D_1^2\right)\right] \tag{3}$$

Within the online elastic range, the calculation formula of the string length deformation caused by piston force variation can be obtained by Hooke's law, $\triangle L_P$ is the string deformation of horizontal well packer caused by piston effect, and the calculation formula of $\triangle L_P$ is:

$$\Delta L_p = -\frac{F_p L}{EA_n} = \frac{\pi L}{4EA_n}\left[P_o\left(D_o^2 - D_1^2\right) - P_i\left(D_o^2 - D_i^2\right)\right] \tag{4}$$

In the formula, F_P is the axial load generated by piston effect, N; L is the length of the packer string, m;E is the elastic modulus of the packer string, MPa; A_n is the effective cross section area of the string, m^2.

When the axial deformation of the string $\triangle L_P$ is positive, the string will extend axially; Similarly, when $\triangle L_P$ is negative, the string will contract axially.

2.2. Analysis of String Deformation Caused by Bulging Effect during Horizontal Well Setting

Before and after the horizontal well packer is set, the internal pressure of the string increases continuously. When the internal pressure is greater than the external pressure, the string expands radially outward. This phenomenon is called the positive swelling effect of the string. When the internal pressure is less than the external pressure, the string shrinks in the radial direction, which is called the counter-bulging effect of the string.Fig.2 (a) shows the positive bulging effect of the string, and (b) shows the reverse bulging effect of the string.

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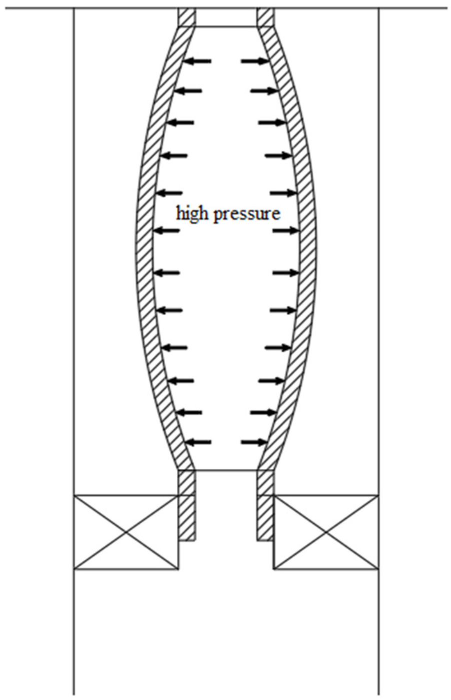
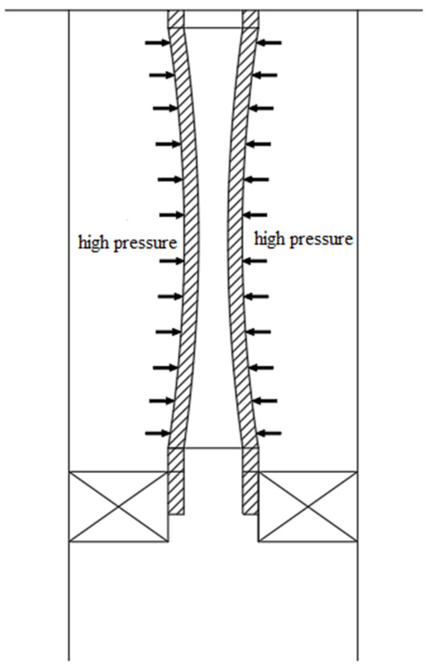


(a) is the schematic diagram of positive swelling effect of the string



(b) is the schematic diagram of the anti-bulge effect of the string

Fig.2 Schematic diagram of string swelling effect of horizontal well packer

When the horizontal well packer string is set, when the pressure inside the packer string section is higher than the external pressure (annulus pressure), the radius of the string will increase due to the positive bulging effect of the string, resulting in axial bulging force and axial deformation of the string.

Based on the material mechanics knowledge and thick-walled cylinder theory, it can be concluded [12] that when the horizontal well string is set, the radial and annular stresses on the string are as follows:

$$\sigma_r = \frac{d^2P_i - D^2P_o}{D^2 - d^2} + \frac{D^2d^2(P_o - P_i)}{r^2(D^2 - d^2)} \tag{5}$$

$$\sigma_\theta = \frac{d^2P_i - D^2P_o}{D^2 - d^2} + \frac{D^2d^2(P_i - P_o)}{r^2(D^2 - d^2)} \tag{6}$$

In the formula, P_o is the external pressure of the bottom hole string, MPa; P_i is the pressure inside the well bore string when setting the packer, MPa, $P_i=P+\gamma h$, P is the well head pressure when setting the packer, γ is the liquid specific gravity of the horizontal string, h is the vertical depth from the horizontal section of the string to the wellhead, m; d and D are the inside and outside diameters of the string respectively, m; r is the radius of any point in the inner cross section of the string, m.

Under the action of the above radial and annular stresses, the string will produce radial deformation, which will cause axial deformation of the string. Since the horizontal string is not bound by the packer during setting, i.e., when the string is not subjected to axial force, free deformation occurs. The axial stress $\sigma_X=0$ for the horizontal string.

According to the general Hooke's theorem in material mechanics, the formula for calculating the ε_X of the axial strain of a horizontal pipe string is as follows [13]:

$$\varepsilon_x = \frac{1}{E}[\sigma_x - \mu(\sigma_r + \sigma_\theta)] = -\frac{\mu(\sigma_r + \sigma_\theta)}{E} \tag{7}$$

In the formula, E is the elastic modulus of the string, MPa; μ is the Poisson's ratio of the string, generally taken as μ=0.3; σ_X is the axial stress of a horizontal string, MPa.

According to formula (5), (6) and (7), it can be concluded that the axial deformation of the horizontal section pipe string at this time is:

$$\Delta L_x = \varepsilon_x L = -\frac{2\mu L(P_i d^2 - P_o D^2)}{E(D^2 - d^2)} \tag{8}$$

3. Axial Load Analysis of Horizontal Well Packer String during Fracturing Operation

3.1. Axial Load Analysis of String Caused by Swelling Effect during Fracturing in Horizontal

During the setting or fracturing of the horizontal well packer string, when the internal pressure of the string is greater than the formation pressure outside the string and exceeds the allowable value of bending deformation of the string, the horizontal well string will produce positive bulging deformation, as shown in Figure 3.When the pressure inside the string is less than the pressure outside the string, the counter bulging effect will occur. The pressure difference between inside and outside of frac string will cause axial load and deformation of frac string. Horizontal pipe string in the packer setting finished, because the string on the position of packer string in down hole anchoring, sealing and constraint function, the string generated by the deformation and the possibility of displacement will be converted to string axial load and stored in a string, and the string will be in accordance with the packer setting position separated into different string section [13].

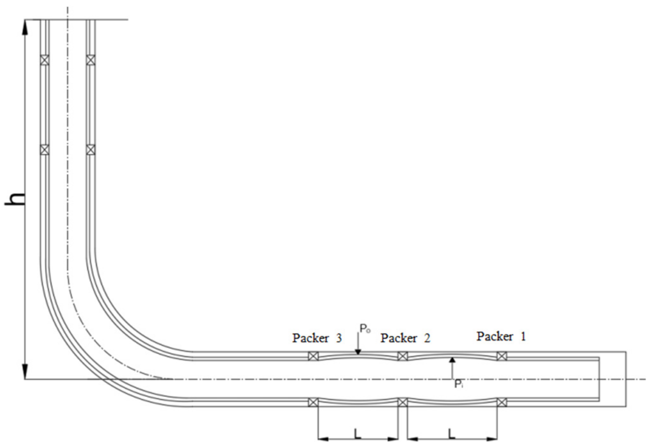


Fig.3 Schematic diagram of string swelling effect of horizontal well packer

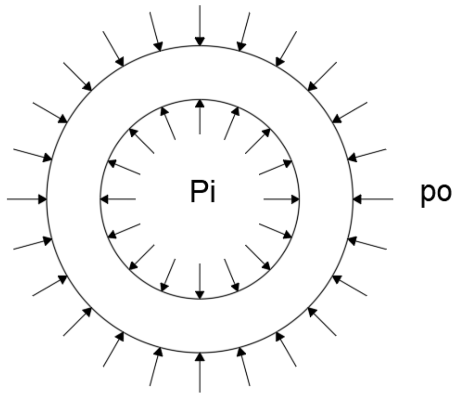


Fig.4 Force analysis diagram of horizontal well packer string

As shown in FIG. 3, when the horizontal well string is set for fracturing, the first stage of fracturing of the horizontal well string is completed by plugging the no. 1 packer from the wellhead, applying wellhead pressure P, and then injecting the string segment separated by the fracturing hydraulic fracturing no. 1 and No. 2 packer. Then, fracturing operations are carried out on the subsequent string sections of No.2, No.3, no.3 and No.4 in turn.

For the convenience of calculation, it is assumed that the length of the tubing string separated by the packer is equal and the pressure within the tubing string is evenly distributed as shown in FIG. 4. Then, according to the material mechanics knowledge and thick-walled cylinder theory, it can be concluded [14] that the radial and annular stresses on the tubing string during fracturing operations in horizontal Wells are:

$$\sigma_{r1} = \frac{d^2}{D^2 - \mathrm{d}^2}\left(1 - \frac{D^2}{r^2}\right)P_{i1} - \frac{D^2}{D^2 - d^2}\left(1 - \frac{d^2}{r^2}\right)P_o \tag{9}$$

$$\sigma_{\theta 1} = \frac{d^2}{D^2 - \mathrm{d}^2}\left(1 + \frac{D^2}{r^2}\right)P_{i1} - \frac{D^2}{D^2 - d^2}\left(1 + \frac{d^2}{r^2}\right)P_o \tag{10}$$

In the formula, P_o is the external pressure of the pipe string, MPa;P_{i1} refers to the pressure inside the well bore string when setting packer No. 1, MPa, P_{i1}=P+ηh, P refers to the wellhead pressure during fracturing, η refers to the specific gravity of fracturing fluid in the horizontal well string, h refers to the vertical depth from the horizontal section of the pipe string to the

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wellhead, m; d and D are the inside and outside diameters of the string respectively, m;r is the radius of any point in the inner cross section of the string, m.

When fracturing the first section of the string, packer No. 1 and No. 2 fix the string position, so that packer No. 1 exerts an axial constraint on the string, so no axial deformation can occur in this section of the string, that is, the axial strain is 0.According to the general Hooke's theorem in material mechanics, the axial strain calculation formula of the pipe string can be obtained as follows:

$$\varepsilon_{x1}=\frac{1}{E}\left[\sigma_{x1}-\mu\left(\sigma_{r1}+\sigma_{\theta 1}\right)\right]=0 \tag{11}$$

In the formula, E is the elastic modulus of the string, MPa; μ is the Poisson's ratio of the string, generally taken as μ=0.3; σ_{x1} is the axial stress of a horizontal string, MPa.

According to formula (11), the axial stress on the horizontal section pipe string is:

$$\sigma_{x1}=\mu\left(\sigma_{r1}+\sigma_{\theta 1}\right)=\frac{2\mu\left(P_{i1}d^2-P_oD^2\right)}{\left(D^2-d^2\right)} \tag{12}$$

According to material mechanics knowledge and formula (12), it can be concluded that the axial force on the string is:

$$F_{x1}=\sigma_{x1}A_x=\frac{\mu\pi\left(P_{i1}d^2-P_OD^2\right)}{2} \tag{13}$$

In the formula, A_X is the cross-sectional area of the horizontal segment pipe string, m^2.

Similarly, from the derivation process of the above formula, it can be concluded that when the horizontal well string performs fracturing on the string section of N and N +1 packer, the axial stress and axial force on the string section are as follows:

$$\sigma_{xn}=\mu\left(\sigma_{rn}+\sigma_{\theta n}\right)=\frac{2\mu\left(P_{n1}d^2-P_oD^2\right)}{\left(D^2-d^2\right)} \tag{14}$$

$$F_{xn}=\sigma_{xn}A_x==\frac{\mu\pi\left(P_{n1}d^2-P_OD^2\right)}{2} \tag{15}$$

3.2. Axial Load Analysis of String Caused by Temperature Effect in Horizontal Well Fracturing Operation

In level of packer string section of horizontal well fracturing operations, because of the need to inject a large number of fracturing fluid in the tubing string within which to the formation of rock cracks, under the influence of the injected fluid packer string will be a sharp drop in temperature, the temperature change will change the length of the string (heat bilges cold shrink, when string elongation is restricted, the string on the packer setting makes horizontal well string location is fixed, tubing string stress and deformation caused by temperature change and cannot effectively, will be in between the packer string within the period of an axial load), the phenomenon known as temperature effect.

When the horizontal well packer string is fracturing, the temperature of the string will drop sharply due to the injection of a large amount of fracturing fluid into the string. According to the thermal stress calculation formula in material mechanics, the axial strain caused by temperature effect can be written as follows:

$$\varepsilon = \alpha \Delta T = \alpha (T - T_0) \tag{16}$$

In the formula, α is the thermal expansion coefficient of the string material (generally 1.26×10^{-5}m/℃);ΔT is temperature changes for the string value; T_0 is the initial temperature of the string, namely the formation temperature, °C; T is the string temperature when there is fracturing fluid in the string, °C.

The axial stress σ_{xT} of horizontal well string due to temperature effect is:

$$\sigma_{xT} = \varepsilon E = \alpha E (T - T_0) \tag{17}$$

According to formula (17), the axial force F_T of the horizontal well string caused by temperature effect can be written:

$$F_T = A_T \sigma_{xT} == \frac{\pi\alpha E (D^2 - d^2)}{4} (T - T_0) \tag{18}$$

In the formula, A_T is the effective cross-sectional area of the string, m²;E is the elastic modulus of the string, MPa;D and d are the outer diameter and inner diameter of the string respectively, m.

The temperature effect occurs over the entire string and the calculation formula of string length variation ΔL_T caused by temperature effect in horizontal Wells is as follows:

$$\Delta L_T = \varepsilon L = \alpha \Delta T L = \alpha L (T - T_o) \tag{19}$$

Formula, ΔT is temperature changes for the string value; L is the string entry length, m.

3.3. Axial Load Analysis of Pipe String Caused by Fluid Viscous Frictional Effect

String in horizontal well fracturing operation, in the process of fracturing fluid injection, the flowing fluid in the cylinder wall, as a result of the fracturing fluid viscosity, string friction resistance to the flow of fracturing fluid, and string will be reaction, thus cause the axial load and deformation of tubing string, this is called the fluid viscous friction effect.

Due to the setting of the string packer, the stress deformation on the string cannot be transmitted downward, so the axial stress deformation caused by the fluid viscous frictional effect will be stored in the string.

According to the calculation formula of hydraulic head loss along the pipeline, the head loss h_f of unit length of fluid in the string during fracturing operation of horizontal well string can be obtained as follows:

$$h_f = \frac{\lambda v^2}{2gd} L \tag{20}$$

In the formula, λ is the drag coefficient along the water head, also known as the friction coefficient, which can be determined by its empirical formula and Reynolds number Re calculation; ν for the average flow rate of liquid in the string, m/s; g is the acceleration of gravity, m/s; d is the inside diameter of the string, m; L is the string length, m.

Flow pressure drop loss ΔP in the string is:

$$\Delta P = \gamma h_f = \rho g h_f \tag{21}$$

In the formula, ρ is the density of the fracturing fluid in the string, kg/m³.

According to formula (21), the shear stress τ_m and friction resistance T_f on the inner wall of the string are respectively:

$$\tau_m = \frac{\Delta P d}{4L} = \frac{\rho g d}{4L} h_f \tag{22}$$

$$T_f = (\pi dL)\tau_{\mathrm{m}} = \frac{\rho g \pi d^2}{4} h_f \tag{23}$$

According to formula (23), the increment of axial force ΔF_m of a unit length fractured string caused by friction effect under the action of fracturing fluid flow can be calculated as follows:

$$\Delta F_m = \frac{\rho g \pi d^2}{4} h_f \tag{24}$$

In horizontal well string fracturing operation, the axial load F_m caused by friction effect between the two packers is:

$$F_m = \frac{\rho g \pi d^2}{4} h_f = \frac{\rho \pi d \lambda v^2}{8}\left(\frac{L}{2} - x\right) \tag{25}$$

In the formula, ρ is the density of fracturing fluid in the string, kg/m^3; L is the distance between two adjacent packers, m; x is the distance between a certain position on the string segment and the previous packer between two adjacent packers, m.

The axial stress σ_{xm} caused by fluid viscous friction effect in horizontal well string is:

$$\sigma_{xm} = \frac{F_m}{A} = \frac{\rho d \lambda v^2}{2(D^2 - d^2)}\left(\frac{L}{2} - x\right) \tag{26}$$

In the formula, A is the cross-sectional area of the horizontal well string, m^2.

4. The Total Axial Deformation of the Horizontal Well Packer String is Divided into Total Axial Load Analysis

4.1. The Total Axial Deformation of the String of Various Effects

Through the previous analysis, in the horizontal well packer string setting and fracturing process, its total length variation $\triangle L$ only affects the string deformation when the string is set, then the sum of the axial deformation caused by various effects on the packer string is:

$$\Delta L = \Delta L_p + \Delta L_x + \Delta L_T + \Delta L_m = \Delta L_p + \Delta L_x \tag{27}$$

In the formula, $\triangle L$ represents the total deformation of various effects, m;$\triangle L_P$ represents the string deformation caused by piston effect during packer string setting, m;$\triangle L_X$ represents the string deformation caused by the swelling effect during packer string setting, m;$\triangle L_T$ denotes the length deformation of packer string caused by temperature effect. $\triangle L_T$=0, m, during fracturing of string; $\triangle L_m$ refers to the packer string deformation caused by fluid viscous friction effect. $\triangle L_m$=0, m, when the string is fractured.

When the total axial deformation of the string of horizontal well packer is positive, the string will be extended in the axial direction; Conversely, when $\triangle L$ is negative, the string will shrink axially.

4.2. The Total Axial Load of the String Resulting from Various Effects

During the setting and fracturing of the string of the horizontal well packer, the total axial load of the string generated by various effects is:

$$\Delta F = F_p + F_x + F_T + F_m \tag{28}$$

In the formula, F_P is the axial load of the string caused by piston effect; F_X is the axial load of the string caused by the bulging effect; F_T is the axial load of the string caused by temperature effect; F_m is the axial load of the string caused by the friction effect between the two packers.

5. Summary

(1) The reasons for the string deformation in the setting and fracturing process of the horizontal well packer string are studied and analyzed, among which the piston, swelling, temperature and friction effect are the main reasons for the string deformation and axial force.

(2) According to the deformation of horizontal section of the packer string, using the knowledge of material mechanics and elastic mechanics, horizontal well is deduced from the string of n, n + 1 packer string section setting and fracturing operation, the string section by piston effect, ballooning effect and temperature effect and the effect of friction on the string axial stress, axial force and the general expression of the axial deformation of tubing string. The research results have practical significance for understanding the comprehensive stress of the horizontal well packer string in complex deep Wells, to clarify the stress load of the packer string in the process of setting and fracturing.

(3) In the process of setting and fracturing, the length of the packer string in horizontal well is mainly affected by piston effect and bulging effect. And at the time of the fracturing packer string, because the string setting has been completed and the fracturing string is fixed, the packer string will not produce axial displacement, pipe string is affected by temperature effect and friction effect and the stress and deformation can't effectively transfer within the tubing string, would be between the packer string segment of an axial load, cause the string force change.

References

[1] Yinping Cao, Hao Li, Yihua Dou. Mechanical analysis of double packer string for horizontal well[J].Oil field machinery, 2018, 47(001): 1-5.

[2] LubinskiA,Althouse WS. Helical Buckling of Tubing Sealed in Packers[J].Journal of Petroleum Technology, 1962, 14(6) : 655-670.

[3] Hammerlindl D J. Movement, Forces, and Stresses Associated With Combination Tubing Strings Sealed in Packers[J].Journal of Petroleum Technology, 1977, 29 (2) : 195-208.

[4] Hammerlindl D J. Packer-to-Tubing Forces for Inter-mediate Packers[J].Journal of Petroleum Technology, 1980, 32(3) : 515-527.

[5] Qindao Li, Guangping Xie, Juan Zhang. Calculation of initial string compression analysis of a packer string stress analysis system discussion iii[J].Drilling process, 2001, 24(6): 48-51.

[6] DechengMa. Mechanical analysis of fracture string in horizontal well[D].Daqing Petroleum College, 2009.

[7] Zhanguo Lv. Mechanics and safety analysis of horizontal well multi-packer string[D].Xi 'an: Xi 'an Petroleum University, 2014.

[8] Kaiqiang Liu. Analysis of the influence of intermediate packer on the mechanical properties of multi-packer string in horizontal well[D].Xi 'an: Xi 'an Petroleum University, 2016.

[9] Rizhi Dong. Mechanical analysis and application of double - seal single - stuck fracturing string in horizontal well[D].Northeast Petroleum University, 2018.

[10] Qi Liu ,Jianxun Jiang, Qing Shi, et al. Calculation and analysis of stress deformation of packer string allowing free movement[J].Fault block oil and gas field, 2007(01): 61-63+93.

[11] Qin Hua. Analysis on mechanical properties of deep well test and completion packer string at HIGH temperature and high pressure[J].Mechanical research and application, 2019, 32(06): 35-38.

ISSN: 2688-9323

[12] Zhiguan Xu. A brief course on Elasticity[M].Beijing：Higher Education Press, 2013.

[13] Kaiqiang Liu. Analysis of the influence of intermediate packer on the mechanical properties of multi-packer string in horizontal well[D].Xi 'an Petroleum University, 2016.

[14] Hongwen Liu, Jianxing Lin, Manling Cao. Mechanics of materials[M].Beijing：Higher Education Press, 2011.