The effect of axial loading on drill string deformation

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Abstract. A practical method for calculating the axial load of a string through the load on a hook is presented and the flotation capacity of elements for different well trajectories is provided. It was found that the traditional simplified method for calculating the buoyancy factor, which is used to calculate the axial load on a string and axial tension, can only be used in vertical wells with a freely suspended pipe string, since in this state buoyancy acts only on the lower part of the string. If the string is constrained by downhole tools such as a packer or an anchor, buoyancy cannot be considered a simple weight loss. In directional wells, buoyancy changes the axial load of the string and causes shear stresses in the cross section of the string. When calculating the effect of fluid on the string, it is necessary to take into account the sequence of operations and stresses from wellhead and downhole tools.

1. Introduction

In complex wells, such as high pressure-high temperature (HPHT) wells, deep wells and directional wells, it is important to predict and control the tubing axial load and axial deformations in order to ensure operational safety [1-4]. Errors made at the design stage can cause troublesome operations, even accidents. There are many factors affecting string deformations, including temperature, fluid pressure, tool weight, friction, well trajectory, string deformation, etc. [5-8]. The most common one is the effect of fluid pressure on string deformations. The effect of fluid pressure on pipes is versatile. Firstly, the fluid pressure causes a sharp jump in the axial force at the bottom of the string and conical stages of the string due to the piston effect. Secondly, pressure of the fluid causes axial deformations due to the swelling effect. Thirdly, in directional wells, fluid pressure causes shear stresses in the cross section of the string, which increases bending deformations. Finally, fluid pressure causes a virtual axial load on the string, causing pipe bending, while pipe bending results in string shortening, contact loads and borehole friction.

Simple and practical methods for calculating the effect of fluid pressure can be found in various technical manuals. But the applicable conditions for the methods are not limited; therefore, when using them, mistakes are often made [9-12]. A method for calculating the axial force of a well string using the hook load to the bottom is presented. The change in fluid pressure and its effect on string deformations are described. The results will be of great engineering importance for complex strings.

2. Materials and methods

At any depth of the well, the internal pressure and external pressure of the fluid on the string’s surface are equal, and the buoyancy acting on the string is
\[ F_f = \gamma_0H\pi(b^2 - a^2) = \gamma_0HA_s \]  

where \( A_s = \pi(b^2 - a^2) \) — the cross-sectional area of the pipe wall.

Equation (1) shows that the buoyancy acting on the string is equal to the mass of fluid that it displaces and that is directed upward. Despite the fluid pressure applied to any point on the surface of the string, the actual buoyancy acts on the bottom of the string in a summation of forces. Let \( \gamma_i \) be the density of steel, the suspended weight (hook load) of the string is:

\[ W = (\gamma_s - \gamma_0)HA_s. \]  

Taking the wellhead as the origin of coordinates, the coordinate system is set along the depth of the well, and the axial force (positive tension, similarly here and below) of the entire string at any depth of the well is

\[ F_x = W - \gamma_sxA_s = [(\gamma_s(H - x)) - \gamma_0H]A_s. \]  

Then

\[ x = H, F_x|_{x=H} = -F_f = -\gamma_0HA_s. \]

Namely, the buoyancy acts on the lower end of the string in vertical wells.

The total buoyancy is:

\[ F_f = \gamma_0H\pi b^2 - \gamma_iH\pi a^2 = \gamma_0HA_0 - \gamma_iHA_i, \]

where \( \gamma_i \) — fluid density, \( A_i = \pi a^2 \) and \( A_0 = \pi b^2 \) — inner and outer cross-sectional areas of the string, respectively.

The string hook load is

\[ W = \gamma_sHA_s - (\gamma_0HA_0 - \gamma_iHA_i). \]

The axial load at any well depth is

\[ F_x = \gamma_sHA_s - (\gamma_0HA_0 - \gamma_iHA_i) - \gamma_sxA_s. \]  

In many cases, there are packers at the bottom of the string, and sometimes the packer allows the axial movement of the lower end of the string, or a sliding joint is used to effect this movement. Only the case when the axial movement of the lower end of the column is impossible is studied. Buoyancy does act on the bottom of the string. Since the packer has been installed, the buoyancy effect is blocked by the packer, and the axial load of the string is not directly related to the fluid pressure under the packer. If the temperature and pressure do not change before and after the packer has been installed, equation (3) and equation (6) can be used. But this is not a common case. In fact, both temperature and pressure can change; therefore a new calculation method should be developed. Suppose that the hook load \( F_0 \) is known, the distribution of the axial load of the string along the well depth is:

\[ F_x = F_0 - xy_sA_s. \]  

There is an unavoidable relationship between the hook load and the floating mass. If the hook load cannot be obtained directly, the axial load of the string can be calculated by the initial string length, temperature and pressure change before and after the packer is set. And the floating method could not be used in this process.

When using tapered strings, pressure drops occur inside and outside the string due to changes in the cross-sections. The resulting axial force which is called the piston force results in an abrupt change in the axial load of the string. In fact, the piston force is part of the buoyancy. With tapered strings, let \( A_{ou} \) and \( A_{ou} \) be for the inner and outer cross-sectional areas of the upper column, respectively, and \( A_{id} \) and \( A_{id} \) be for the inner and outer cross-sectional areas of the bottom string, respectively. Therefore, the force of the piston at this point (upward is positive, similarly below) is equal to:

\[ F_p = (A_{ou} - A_{od})P_0 - (A_{iu} - A_{id})P_i. \]  

If a control valve is used, when the valve is closed, the fluid pressure above and below it will be different, and therefore the piston force is:
\[ F_p = A_i (P_{id} - P_{iu}) \]  \hspace{1cm} (9)

where \( P_{iu} \) and \( P_{id} \) – fluid pressure above and below the valve, respectively.

When a simple string is under the simple constraint, buoyancy is equal to the weight of the fluid displaced by the string. In fact, buoyancy is the resultant force of fluid pressure and should not be described as a displaced mass of fluid. In oil and gas wells, almost all strings can experience fluid pressure changes. These changes can be caused by surface production, formation pressure, thermal stress, different fluid densities, etc. Thus, when calculating the effect of fluid pressure on the stress and strain of the string, all factors and constraints must be taken into account. For example, if wellhead pressure or annular pressure is present, the string load derived from the fluid pressure should not be calculated based on the buoyancy.

According to the relationship between axial stress and deformation, the axial deformation of the string can be calculated. As a rule, the axial load of the string is not constant; therefore an integral method is required to determine axial deformations. In any well with depth \( x \), intercepted by an infinitely small section \( dx \), its axial elongation is equal to:

\[ d(\Delta l) = \varepsilon_x dx = \frac{F_x}{A_i E} dx, \]  \hspace{1cm} (10)

where \( \varepsilon_x \) – axial deformation; \( E \) – Young’s steel modulus. This is the basic formula for calculating the axial elongation. Total axial deformation can be calculated by integration along the column. The calculation can be simplified using the axial force at the midpoint of the string.

Fluid pressure can cause axial deformations, a swelling effect. According to the basic theory of elasticity, the swelling effect can be calculated using the following formula:

\[ \varepsilon_x = \frac{2\mu}{E} \left( P_0 R^2 - P_i \right) \]  \hspace{1cm} (11)

where \( \mu \) – Poisson’s ratio of steel, \( R \) – \( OD/ID \) ratio. This formula is obtained in accordance with the plane stress hypothesis (the string can expand freely in the axial direction). The axial deformation caused by the swelling effect can be calculated using formula (11).

Bending is a common phenomenon of oil and gas well string deformation. The influence of fluid pressure on string bending is as follows: the axial load of the string and the virtual axial load. The effective axial load of string \( F_e \) (positive compression) at any well depth \( x \) is

\[ F_e = -F_x + P_i A_i - P_0 A_0. \]  \hspace{1cm} (12)

If the column is long enough, then the axial bending condition is:

\[ F_e \geq F_{cr}, \]  \hspace{1cm} (13)

where \( F_{cr} \) – critical bending force. The well size and the string limit are different, \( F_{cr} \) have different values. On the other hand, the bulge shape of the pillar is different. Column bending has two consequences: column shortening and friction.

Investigating the effect of buoyancy in deviated wells is a more laborious task than in vertical wells. In most cases, accurate calculation is impractical, therefore theoretical analysis is necessary. To trace this problem, let’s take a curved section of the casing, Figure 1, a), where the internal fluid pressure is ignored.
For such a section, it is difficult to accurately calculate the effect of fluid on axial load and deformation, and this is not necessary. The simplified calculation is practical. In the process of simplification, attention should be paid to the concepts of fluid distribution and resultant forces.

Suppose the hook load $W$ is known. Then the axial distribution of the string force can be calculated as follows: divide the string into finite segments along the well path, then compute them from top to bottom using a recursive algorithm.

For a vertical segment of the AB string, fluid pressure is distributed symmetrically and the resulting force is zero in any axial micro-segment. The axial force is

$$ F_x = W - \gamma x A_s. $$

The weight of the string is the only load. This formula can be used for the end of a vertical section.

If the curved section is close to an arc of a circle, then the calculation will be more convenient. As it shown in Figure 1, $s$ - a curvilinear coordinate variable. Axial string force $F_{s0}$ - the initial point of the curved coordinate, $\alpha_b$ - the angle between the axis of the string and the direction of gravity (slope); $\alpha_e$ - a slope of the string at the end of the arc segment ($s = S$). Then the radius of curvature is:

$$ \rho = \frac{s}{\alpha_e - \alpha_b}, $$

The bend at any arc length is:

$$ \alpha_s = \alpha_b + \frac{s}{\rho}. $$

Let $P_{s0}$ be fluid pressure. Let us intersect a string segment of length $s$, as shown in Figure 1, b), then its forces from gravity and fluid pressure are buoyancy $sA_0 \gamma_0$ (upward) and gravity force $sA_s \gamma_s$ (downward). The resulting forces in the upper and lower sections of the hydrostatic pressure are $P_{s0} A_0$:

$$ [P_{s0} + \gamma_0 \rho (\sin \alpha_s - \sin \alpha_b)] A_0 = F_s A_0, $$

respectively, along the pipe axis. In fact, the forces at the top and bottom of the element are not fluid pressure, but axial forces $F_{s0}$ and $F_s$ respectively. By equilibrium, they have the following relationship:

$$ [F_{s0} + sA_0 \gamma_0 - sA_s \gamma_s] \cos \alpha_s - F_s - [P_{s0} + \gamma_0 \rho (\sin \alpha_s - \sin \alpha_b)] A_0 = 0, $$

from which the axial force $F_s$ is:

$$ F_s = (F_{s0} + P_{s0} A_0 + sA_0 \gamma_0 - sA_s \gamma_s) \cos \alpha_s - [P_{s0} + \gamma_0 \rho (\sin \alpha_s - \sin \alpha_b)] A_0. $$

Similarly, the shearing force at a variable curvilinear coordinate $s$:

$$ Q_s = (F_{s0} + P_{s0} A_0 + sA_0 \gamma_0 - sA_s \gamma_s) \sin \alpha_s. $$
Thus, the fluid pressure can cause a shear force in the curved line, the force pointing in a direction like a radial arc. These two equations can be used up to the end of the arc section BC, and thus $F_t$ and $Q_\ell$ can be obtained at point C. If the curvature changes, the section should be divided into several parts; with each part the method described above should be used.

The method for analyzing the deflected section is similar, but simpler than the curved section, as shown in Figure 1, a and c). Where $t$ is the rectilinear coordinates, the slope of the curved section is $\alpha_e$. Let $F_{t0}(=F_0), Q_{t0}(=Q_s), P_{t0}$ for the axial force, shear force and fluid pressure at the starting point ($\ell = 0$) respectively. Then the axial force and the shear force in any position $\ell$ is equal to:

$$F_t = F_{t0} - \ell A_s y_s \cos \alpha_e, \quad (17)$$

$$Q_\ell = Q_{t0} + \ell[A_o y_0 - A_s y_s] \sin \alpha_e. \quad (18)$$

Both efforts involve the bending of the string.

The resulting force of fluid pressure on the vertical section of the string is zero, and on the curved section of the column is:

$$F_{fc} = S A_o y_0 + P_{s0} A_o \cos \alpha_b - P_s A_o \cos \alpha_e. \quad (19)$$

where

$$P_s = P_{s0} + \gamma_0 \rho (\sin \alpha_e - \sin \alpha_b).$$

At $\alpha_b = 0$:

$$F_{fc} = S A_o y_0 + P_{s0} A_o - (P_{s0} + \gamma_0 \rho \sin \alpha_e) A_o \cos \alpha_e. \quad (20)$$

$$F_f = L A_o y_o \quad (21)$$

Although in vertical wells the deformation state of the string differs from that in deviated wells, the buoyancy that the string receives is equal to the mass of fluid displaced by the string.

In the absence of relative movement between the pipe string and the packer, the fluid pressure at the lower end of the string is held by the packer, the buoyancy acting on the string is equal to:

$$F_{ft0}^2 = T A_o y_0 + P_s A_o \cos \alpha_e. \quad (22)$$

If $P_T = P_s + \gamma_o T \cos \alpha_e$, we have:

$$F_{ft}^2 = T A_o y_0 \sin^2 \alpha_e \quad (23)$$

The total buoyancy is

$$F_f = S A_o y_0 + P_{s0} A_o - (P_{s0} + \gamma_0 \rho \sin \alpha_e) A_o \cos \alpha_e + T A_o y_0 \sin^2 \alpha_e$$

When $\alpha_e = \pi/2$, the results of formula (23) and formula (21) will be the same, or will differ in the following cases. The vertical section of the string does not receive the net buoyancy force from the fluid pressure; the effect of the fluid is transmitted to it in the form of an axial load from the string bottom. The internal forces are different in deviated and vertical wells. Firstly, the resulting buoyancy force is different, therefore the axial force distribution is different. Secondly, in deviated wells there is a shear force in the string, but in vertical wells, it is absent. The contact forces of the string with borehole walls are not taken into account. Internal fluid pressure is also ignored to reduce complexity.

3. Results and Discussion
In a thermal recovery well, casing prestressing is an effective method to improve safety of the casing. While cement is hardening, it is necessary to maintain pump pressure in the casing until a cement sheath has formed. As a result of increased pressure, the piston effect lengthens the string and the swelling effect shortens the casing, but the net effect is that the casing is elongated. After the wellhead has been set and the pump has been depressurized, the elongation becomes axial prestressing. The following parameters are given: casing outer diameter is 177.8 mm, wall thickness is 9.19 mm, casing length is 600 m, Young’s elastic modulus is $1.98 \times 10^5$ MPa, Poisson’s ratio is 0.3, pump pressure is 16 MPa. The calculation results are: The axial prestress of the casing by the pump-pressure is 26.3 MPa.

When testing high HPHT wells, permanent packers are often used. This packer allows the lower end
of the string to slide freely, but separates the annular fluid pressure from the formation pressures below. At various stages, the axial force and deformation of the string are not linked. Only the shut-off stage is taken into account. The internal valve located at the bottom of the tubing string is closed to separate the internal pressure from the formation pressure. The parameters are: the outer and inner diameters of the main pipe are 88.9 mm and 68.33 mm, the outer and inner diameters of the sliding pipe are 99.06 mm and 73.71 mm, the depth of the packer is 2800 m, the reservoir pressure is 60 MPa, the density of the fluid in the annular space is 1.5 g cm$^{-3}$, the density of the fluid in the string is 0.001 g / cm$^3$.

Calculation results: the piston effect shortens the string by 0.69 m, while the deflection effect shortens the string by 0.064 m. If the gate in the valve is at the wellhead, there will be a swelling effect that shortens the string by 0.66 m.

4. Conclusion
The influence of fluid pressure on the string depends on two factors: pressure distribution determined by the working medium and the operation stage and its spatial state and limitations. The methods for calculating string stresses and strains described in the technical manuals do not deal with these issues. When calculating stresses and strains in the string, a method and a formula must be carefully selected. It has been established that the traditional simplified method for calculating the buoyancy factor, which is used to calculate the axial force of the string and the axial elongation, can be used only for vertical wells with a freely suspended tubing, since in this case the buoyancy acts on the bottom of the string. If the string is bounded by downhole tools such as a packer or an anchor, the buoyancy cannot be considered in a traditional aspect. In a directional well, the buoyancy changes the axial force of the string and causes shear stress in the cross section. Examples from oilfield engineering show that when calculating the effect of fluid on the string, the sequence of operations and restrictions imposed by the wellhead and downhole tools should be taken into account.

References
[1] Nikolaev N I and Kozhevnikov E V 2014 Enhancing the cementing quality of the well with horizontal profile Bulletin of PNRPU. Geology. Oil & Gas Engineering & Mining 11 29–36 DOI: 10.15593/2224-9923/2014.11.3
[2] Polyakov V N, Chizhov A P, Kotenev Yu A, and Mukhametshin V Sh 2019 Results of System Drilling Techniques and Completion of Oil and Gas Wells IOP Conference Series: Earth and Environmental Science (IPDME 2019 – International Workshop on Innovations and Prospects of Development of Mining Machinery and Electrical Engineering) 378 (1) 1–7 DOI: 10.1088/1755-1315/378/1/012119
[3] Dmitriev A Yu 2008 Fundamentals of drilling technology Tomsk: TPU 216 p
[4] Mukhametshin V V 2018 Bottomhole formation zone treatment process modelling with the use geological and geophysical information IOP Conference Series: Earth and Environmental Science (IPDME 2018 – International Conference on Innovations and Prospects of Development of Mining Machinery and Electrical Engineering) 194(2) 1–5 DOI: 10.1088/1755-1315/194/2/022024
[5] Zeigman Yu V, Mukhametshin V Sh, Khafizov A R and Kharina S B 2016 Prospects of Application of Multi-Functional Well Killing Fluids in Carbonate Reservoirs SOCAR Proceedings 3 33–39 DOI: 10.5510/OGP20160300286
[6] Polyakov V N 1983 Requirements to the integrity and strength of the well in the process of completion of wells in the fields of Bashkortostan Oil economy 2 27–28
[7] Kuleshova L S, Mukhametshin V V and Safiullina A R 2019 Applying information technologies in identifying the features of deposit identification under conditions of different oil-and gas provinces Journal of Physics: Conference Series (ITBIT 2019 – International Conference "Information Technologies in Business and Industry") 1333(7) 1–5 DOI: 10.1088/1742-6596/1333/7/072012
[8] Batalov S A, Andreev V E, Lobankov V M and Mukhametshin V Sh 2019 Numerical simulation of oil formation with regulated disturbances. Oil recovery quality simulation Journal of Physics: Conference Series (ITBI 2019 – International Conference "Information Technologies in Business and Industry") 1333(3) 1–6 DOI: 10.1088/1742-6596/1333/3/032006

[9] Polyakov V N, Kuznetsov Yu S, Sagidullin I A, Shulgina N Yu, Dubrovskiy V S, Khusainov V M, Khaminov N I, Akhmetzyanov R G, Vildanov A A and Starov O E 2005 The solving of problems of tailing-in and wells operation in abnormal thermodynamic conditions Oil Industry 5 104–110

[10] Andreev V E, Chizhov A P, Chibisov A V and Mukhametshin V Sh 2019 Forecasting the use of enhanced oil recovery methods in oilfields of Bashkortostan IOP Conference Series: Earth and Environmental Science (International Symposium «Earth sciences: history, contemporary issues and prospects») 350 (1) 1–6 DOI: 10.1088/1755-1315/350/1/012025

[11] Akhmetov R T, Mukhametshin V V, and Kuleshova L S 2019 Simulation of the absolute permeability based on the capillary pressure curves using the dumbbell model Journal of Physics: Conference Series (ITBI 2019 – International Conference "Information Technologies in Business and Industry") 1333 (3) 1-8 DOI: 10.1088/1742-6596/1333/3/032001

[12] Akhmetov R T, Mukhametshin V V, and Kuleshova L S 2019 Simulation of the absolute permeability based on the capillary pressure curves using the dumbbell model Journal of Physics: Conference Series (ITBI 2019 – International Conference "Information Technologies in Business and Industry") 1333 (3) 1-8 DOI: 10.1088/1742-6596/1333/3/032001