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Research article

Mechanical and mathematical models of multi-stage horizontal fracturing strings and their application☆

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Abstract

Multi-stage SRV fracturing in horizontal wells is a new technology developed at home and abroad in recent years to effectively develop shale gas or low-permeability reservoirs, but on the other hand makes the mechanical environment of fracturing strings more complicated at the same time. In view of this, based on the loading features of tubing strings during the multi-stage fracturing of a horizontal well, mechanical models were established for three working cases of multiple packer setting, open differential-pressure sliding sleeve, and open ball-injection sliding sleeve under a hold-down packer. Moreover, mathematical models were respectively built for the above three cases. According to the Lame formula and Von Mises stress calculation formula for the thick-walled cylinder in the theory of elastic mechanics, a mathematical model was also established to calculate the equivalent stress for tubing string safety evaluation when the fracturing string was under the combined action of inner pressure, external squeezing force and axial stress, and another mathematical model was built for the mechanical strength and safety evaluation of multi-stage fracturing strings. In addition, a practical software was developed for the mechanical safety evaluation of horizontal well multi-stage fracturing strings according to the mathematical model developed for the mechanical calculation of the multi-packer string in horizontal wells. The research results were applied and verified in a gas well of Tahe Oilfield in the Tarim Basin with excellent effects, providing a theoretical basis and a simple and reliable technical means for optimal design and safety evaluation of safe operational parameters of multi-stage fracturing strings in horizontal wells.

Keywords: Multi-stage fracturing; Fracturing string; Horizontal well; Mechanical model; Mathematical model; Hold-down packer; Sliding sleeve; Tarim Basin; Tahe oilfield

In order to enhance the recovery of low-permeability gas reservoirs and shale gas reservoirs, ball-injection sliding sleeve multi-stage fracturing for horizontal wells has been developed since 2007 [1,2]. Nowadays, multi-stage fracturing and multi-stage repeated volume fracturing in horizontal wells are the hot topics [3−10] in this field. However, in the application of these technologies, downhole tools and fracturing strings will be subject to complex stress environment, harsh mechanical condition. In view of the complicated mechanical issue, it is necessary to do safety evaluation of the multi-stage horizontal fracturing string. In 1962, Lubinski et al. [11] had initiated the study on downhole packer-string mechanics, and built mechanical-mathematical models for bulging effect, piston effect, temperature effect and helical buckling effect caused by pressure or temperature changes or various working conditions. Soon afterwards, Hammerlindl [12,13], Mitchell et al. [14] delved deeper into the study on the single packer and double-packer mechanical-mathematical models of vertical wells and buckle deformation of fracturing

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string, which laid the classical mechanical foundation for safety evaluation of fracturing strings. In China, Gao Deli [15], Li Zifeng [16], Lian Zhanghua and Ding Liangliang [17,18] conducted research on mechanical behavior and safety of oil well strings under different working conditions on the basis of previous studies and made some progress in conventional string mechanics study [11−16]. But the previous studies focus mainly on vertical wells with single packer, and there are few literature about the mechanics of horizontal well fracturing strings [17], especially under the working condition of multi-packers and multi-stage horizontal fracturing.

In view of the complicated mechanical issue, we developed the mechanical models and mathematical models for multi-stage horizontal fracturing strings in four kinds of working condition, packer setting, opening differential pressure sliding sleeve, opening ball sliding sleeve, and fracturing, mathematical models for these mechanical models, and developed practical software for mechanical safety evaluation of the strings.

1. Mechanical and mathematical models of the fracturing strings and packers

The fracturing string will contract or extend due to the changes of wellhead operation pressure in the fracturing process, creating tensile or compressive force on the packers. Therefore, the packer will generate an axial tensile or compressive force on the fracturing string. The mechanical model of multi-packer fracturing string in openhole horizontal wells is shown in Fig. 1, which shows the fracturing string with multi-packer location and its mechanical model. In Fig. 1a, point A is the wellhead location, and point D is the deflection point, AD is the vertical well section, DPC is the building up section, and BC is the horizontal section. Point P is the hold-down packer, P_1-P_{n0} are the openhole packers of horizontal interval, S_1 is differential pressure sliding sleeve and S_2-S_{m0} are the ball sliding sleeves.

1.1. Mathematical model of pretension force on the tubing string after the setting of multi-packers

1.1.1. Case 1: under the working condition of setting multi-packers, with differential pressure ΔP_k

As is shown in Fig. 1b, the mechanical-mathematical model of string section L_k is established by statics equilibrium relationship [17]:

$$T_k = W_k \cos\theta_k \pm N_k\mu \tag{1}$$

$$N_k = \mu W_k \sin\theta_k \tag{2}$$

where, T_k is the axial force of k section fracturing string, N; W_k is buoyant weight of k section fracturing string, N; N_k is the normal force of k section fracturing string, N; θ_k is the angle of inclination at k section fracturing string, °; μ is the friction coefficient between fracturing string and borehole wall.

Substituting Eq. (1) with Eq. (2), the tension acting on any given infinitesimal section k is deduced and the equation is expressed in Eq. (3).

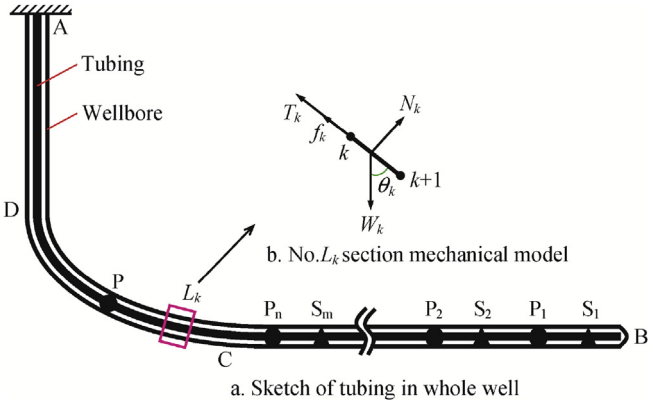

Fig. 1. Forces on the multi-stage fracturing tubing in a horizontal well.

$$T_k = W_k(\cos\theta_k \pm \mu \sin\theta_k) \tag{3}$$

The axial tension at the hold-down packer location P is the sum of T_k acting on each section of string, which is written as Eq. (4).

$$T = \sum_{k=1}^{n} T_k = \sum_{k=1}^{n} W_k(\cos\theta_k \pm \mu \sin\theta_k) \tag{4}$$

The sketch map of the fracturing string below hold-down packer P with openhole packers and sliding sleeves is shown in section BC of Fig. 1a. After setting packers, the pressure in the fracturing string increases by Δp_k, and the pretension force F_0 on the fracturing string between horizontal openhole packers is calculated by Eq. (5).

$$F_0 = \Delta p_k A_i \tag{5}$$

where, F_0 is the axial force between the openhole packers, N; Δp_k is setting pressure, MPa; A_i is internal surface area of the fracturing string, mm^2.

For the pretension force F_1 at the hold-down packer location P, tension T caused by buoyant weight of the string should be added, so the calculating model of F_1 is Eq. (6). The fracturing string will elongate when setting, in this case the friction and axial force are of opposite directions, which means minus will be applied in Eq. (6), otherwise plus sign should be applied.

$$F_1 = T + F_0 = \sum_{k=1}^{n} W_k(\cos\theta_k - \mu \sin\theta_k) + \Delta p_k A_i \tag{6}$$

1.2. Mechanical-mathematical model of open differential pressure sliding sleeve strings

1.2.1. Case 2: under the working condition of open differential pressure sliding sleeve at differential pressure $\Delta p'$

After the setting of downhole string, the differential pressure sliding sleeve S_1 will be opened to do the first stage of fracturing of P_1-B section. The mechanical model of the tubing string before opening differential pressure sliding sleeve S_1 is shown in Fig. 2a−d. Fixed at P_1, and free at B, the