Study on the Interaction Mechanism of Packer Slips and Thick Wall Casing

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Abstract: The slips should go into casing for certain depth to set the packer when well testing, but the casing may be damaged seriously if the setting force is too large. To make known the interaction mechanism of packer and casing, and then provide basis for the choice of hanging load of casing and shape optimization of slips, the maximum hoop stress of casing in the inner wall was deduced by the thick wall theory and the limited setting force was obtained by the strength theory. The changes of the limited setting force of casing with the variable length of packer and the face angle of slip teeth were discussed taking the general packer and casing as example. It was found that the limited setting force of casing increased with the length of slip when the packer and casing kept the same. The shorter the slip, the faster the force grows. Also, the limited setting force of casing increased non-linearly with the face angle of slip teeth. The smaller the angle, the faster the force grows.

1. INTRODUCTION

To set the packer when well testing, the slips should go into casing for certain depth, but the casing may be damaged seriously if the setting force is too large. In recent years, there have been many accidents such as a collapse of casing inside slips of packer, fracture of slips, sealing failure of rubber, cut of hydraulic anchor, creep of downhole string, leakage of well hole in oilfields when the packer was set [1]. Qualitative analysis shows that the forces applied on casing and slips increase with the depth of well, which may make the bearing capacity and stability of casing inside slips reduce, so it's necessary to make clear the interaction of casing and slips. Research on slips of packer focus on the analysis of contact stress between slip and casing, structure optimization design of new slips, simulation of casing damage due to cut of slips in laboratory.

Yuangang Zhao analyzed the mechanics of slip packer with material mechanics [2]. Zhanguang Liu calculated the hoop stress and axial buckling force of casing due to the setting of slip supported packer, and then discussed the effect of pressure difference of casing on the strength based on the static force equivalent method [3]. Shuhua Kan analyzed the mechanics of the friction shoe type slip using the internationally famous finite element method software, ANSYS, and obtained the maximum fracturing pressure the slip can withstand [4]. Junliang Zhang conducted a stress analysis of variable tooth inclination, tooth angle, inner-tooth width and slip cone angle by the method of stress transient characteristic analysis and corresponding experiment verification [5]. Dai Geng, *et al.* carried out the friction and wear experiments for a casing specimen against different slip specimens which were on the Schwingung Reibung Verschleiss reciprocating-sliding tribometer equipped with a cylinder-on-disc-line contact testing system lubricated by crude oil, and studied the wear mechanisms from SEM and EDS observations [6]. Dong Yang *et al.* analyzed the mechanics of packer and tubing string when acid fracturing to seek the reason and the solution of loss of seal in high temperature, high pressure and deep well with RTTS packer and Christmas tree as example [7]. Tianliang Liu *et al.* made simulations of casing damage due to slips when setting in laboratory [8-10].

Although some useful conclusions can be drawn from the early study, the choice of whether the casing should be taken as thin-wall cylinder or thick-wall cylinder relies on the steel grade as well as the ratio of diameter of the casing and thickness. It was necessary to conduct further study on the interaction of packer and casing [11, 12]. To make known the interaction mechanism of packer and casing, and then provide basis for the choice of hanging load of casing and shape optimization of slips, the maximum hoop stress of casing in the inner wall was deduced by the thick wall theory, and the limited setting force was obtained by the strength theory. The changes of the limited setting force of casing with the variable length of packer and the face angle of slip teeth were discussed taking the general packer and casing as example.

2. MECHANICS OF CASING INSIDE SLIPS OF PACKER USED IN WELL TESTING

The schematic diagram of casing inside slips of packer used in well testing is shown in Fig. (**1**), where, d_c, D_c,

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t_c are the inner diameter of casing, outer diameter of casing, thickness of casing respectively, and l is the length of the slips of casing. When setting, casing bears axial setting force and radial pressure of slips. The mechanical model of thick wall casing subjected to assumed uniform contact stress was established in Fig. (**2**).

The forces acting on single slip and casing are shown in Fig. (**3**). From equilibrium equation of force, we can get the following equations in the vertical and horizontal directions.

$$F_1 \sin\alpha + f_2 \cos\alpha = f_1 = \frac{Q}{n} \quad \text{(in the vertical direction)} \qquad (1)$$

$$P^* = F_1 \cos\alpha - f_2 \sin\alpha \quad \text{(in the horizontal direction)} \qquad (2)$$
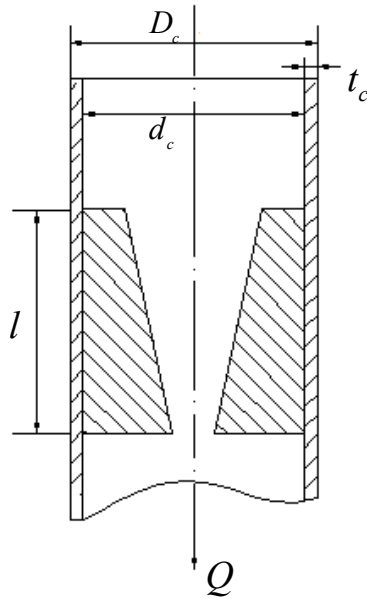

Fig. (1). Schematic diagram of casing inside slips of packer.
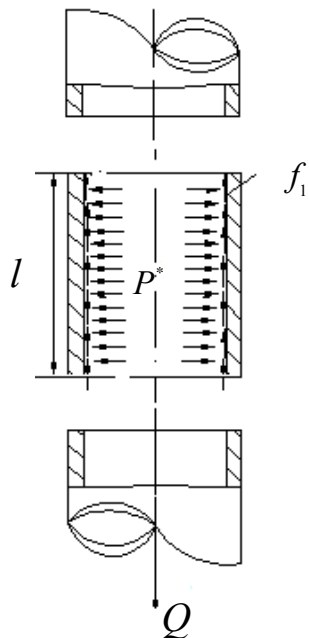

Fig. (2). Mechanical model of thick wall casing.

From the law of friction, we can get

$$f_1 = \mu_1 \cdot P^* \qquad (3)$$

$$f_2 = \mu_2 \cdot F_1 = \tan\varphi \cdot F_1 \qquad (4)$$

where, F_1 is the pressing force on the slope of slip, α is the wedge angle of slip, f_1 is the friction between slip and casing, f_2 is the friction on the slope of slip, Q is the axial force of packer, n is the number of the pieces of slips, P^* is the radial force on inner wall of casing from single slip. μ_1 is the friction coefficient between slip and casing, 0.05~0.5 in general, but 0.4~0.6 for slip base with large trapezoidal hole. μ_2 is the friction coefficient between slip and the wedge of packer, 0.22 in general, and φ is the friction angle between slip and the wedge of packer [13].
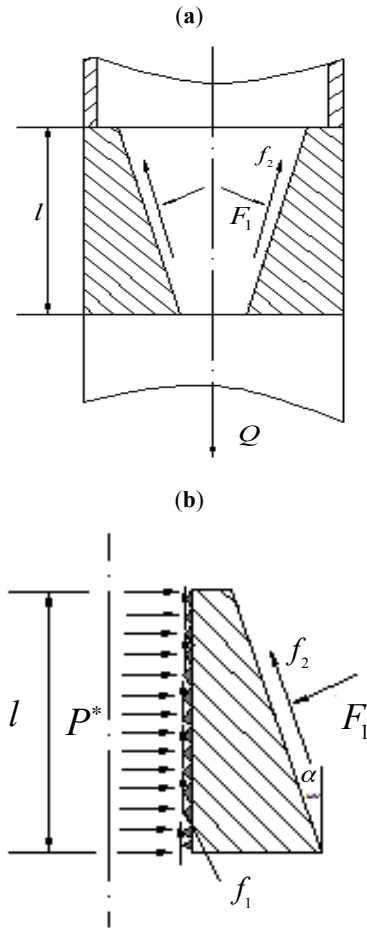
(a)

(b)

Fig. (3). Forces acted on single slip and casing.

By combining equation 1 to equation 4, we get:

$$f_1 = \frac{Q}{n} \qquad (5)$$

$$P^* = \frac{Q}{n \cdot \tan(\alpha + \varphi)} \qquad (6)$$

Then, to meet the equilibrium of slip, there should be

$$\mu_1 \geq \tan(\alpha + \varphi) \tag{7}$$

The contact arc length of slip tooth with casing wall is $d_c \cdot \sin\beta_k$, and the area of the bottom of slip tooth is $S = d_c \cdot \sin\beta_k \cdot l$. The radial pressure between slip tooth and inner wall of casing p_r can be expressed as follows with the assumption of P^* being uniform in the inner wall of casing.

$$p_r = \frac{P^*}{S} = \frac{Q}{nld_c \tan(\alpha + \varphi)\sin\beta_k} \tag{8}$$

where, p_r is the radial pressure between slip tooth and inner wall of casing, β_k is half the angle of the tooth surface of slips.

Equation 8 can be transformed into equation 9 as follows:

$$K = \frac{1}{\tan(\alpha + \varphi)} \cdot p_r = K \cdot \frac{Q}{nld_c \sin\beta_k} \tag{9}$$

where, K is the transverse load coefficient, d_c is the inner diameter of casing. Equation 9 is the equation of radial pressure between slip and inner wall of casing with the consideration of the shape of slip tooth. It can be used to evaluate the damage of casing from slip tooth more accurately.

3. STRESS ANALYSIS OF THICK WALL CASING INSIDE THE SLIPS

Taking the casing as thick wall cylinder, the hoop stress σ_θ caused by the radial pressure p_r can be obtained by the Lame equation.

$$\sigma_\theta = -\frac{(d_c + 2t_c)^2 \, p_r}{2t_c(d_c + t_c)} \tag{10}$$

where, t_c is the thickness of the casing.

And, the axial stress of casing inside slips of packer σ_z was

$$\sigma_z = \frac{Q}{A_c} \tag{11}$$

where, $A_c = \pi t_c(d_c + t_c)$ is the cross sectional area of the casing.

4. ANALYSIS OF THE LIMITED SETTING FORCE OF THICK WALL CASING INSIDE THE SLIPS OF PACKER

Taking the expressions of hoop stress and axial stress in equation 10 and equation 11 into the strength theory, we can get the limited setting force of casing inside slips of casing $Q_{\lim}$ as

$$Q_{\lim} = [\pi t_c(d_c + t_c)\sigma_s] /$$
$$\left\{ \sqrt{1 + \left(1 + \frac{(d_c + 2t_c)^2}{2t_c(d_c + t_c)} \cdot \frac{K\pi t_c(d_c + t_c)}{nld_c \sin\beta_k}\right)} \right.$$
$$\left. \sqrt{\left|\frac{(d_c + 2t_c)^2}{2t_c(d_c + t_c)} \cdot \frac{K\pi t_c(d_c + t_c)}{nld_c \sin\beta_k}\right|} \right\} \tag{12}$$

where, σ_s is the yield strength of the material of the casing. Equation 12 was the equation of bearing capacity of the casing with the consideration of non-uniformity of the radial stress and hoop stress of thick wall casing in radial direction.

5. EXAMPLE OF LIMITED SETTING FORCE OF THICK WALL CASING

In the example, a 5 1/2″ packer was set into the casing with an outer diameter of 139.7mm and thickness of 9.17mm and steel grade as P110. The number of slips were 6, the wedge angle was 15°, the variable length of the teeth of slips was 50mm, 80mm, 110mm, 140mm, 170mm and 200mm, and the variable face angle of the teeth of slips was 30°,40°,50°,60°,70°,80° and 90°. The curve of limited setting force of the casing, inside slips of packer calculated by the thick wall cylinder, with the length of slip, is plotted in Fig. (**4**).

From Fig. (**4**), we can see that the limited setting force of casing inside slips increases with the length of slip when the packer and casing remained the same. The shorter the slip, the faster the force grows. Also, the limited setting force of casing increased non-linearly with the face angle of slip teeth. The smaller the angle, the faster the force grows. Because large face angle of slip teeth would make stress concentrate on casing or even cause the collapse of casing. With the view of safety of the casing and shape optimization of slip, it was recommended that the face angle of slip teeth should be around 60°to decrease the contact stress of casing from slip. To keep good bearing capacity of casing, it was recommended that the length of slip be between 100mm to 140mm.
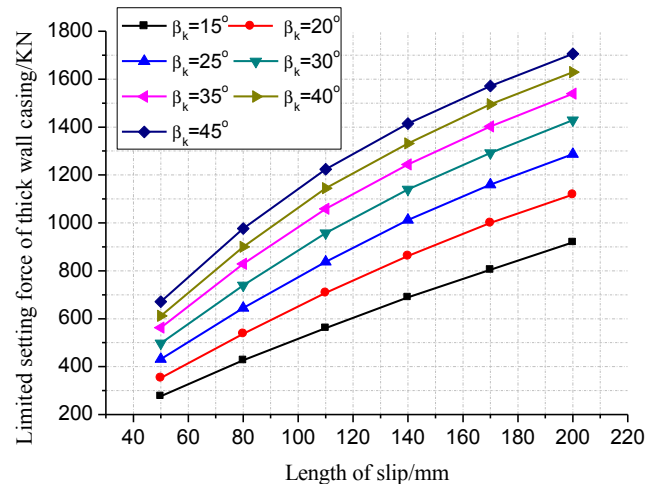

Fig. (4). Limited setting force of the thick wall casing inside slips of packer.

CONCLUSION

The maximum hoop stress of casing in the inner wall was deduced by the thick wall theory, and the limited setting force was obtained by the strength theory with the consideration of the slip shape. The changes of the limited setting force of casing with the variable length of packer and the face angle of slip teeth were discussed taking the general packer and casing as example. And, some conclusions can be drawn from the example.

(1) We can estimate the bearing capacity of casing by the equation of limited setting force when the parameters of a certain packer such as number of slips, length of slip, width of slip, wedge angle of slip and shape angle of slip teeth are known.

(2) The limited setting force of casing increased with the length of slip when the packer and casing remained the same. The shorter the slip, the faster the force grows. And, to keep good bearing capacity of casing, it was recommended that the length of slip be between 100mm to 140mm.

(3) The limited setting force of casing increased non-linearly with the face angle of slip teeth. The smaller the angle, the faster the force grows. With the view of safety of the casing and shape optimization of slip, it was recommended that the face angle of slip teeth be around 60° to decrease the contact stress of casing from slip.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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