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Analyzing Packer's Deformation of Tubular for Unsetting Process in HTHP Wells under Variable (T, P) Fields

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Abstract: In this paper, the axial stress and deformation of high temperature high pressure super-deep deviated gas wells are studied. A new model presents multiple nonlinear equation systems, which comprehensively consider the axial load of the tubular string, internal and external fluid pressure, normal pressure between the tube and well wall, friction and the viscous friction of fluid flowing under variable temperature and pressure fields, instead of the traditional methods. The initial axial load, the pressure effect, the friction, temperature effect and sucker-rod pumping effect are derived using a dimensionless iterative interpolation algorithm. Basic data from the X Well (high temperature-high pressure gas well), 6115 meters deep, are used for case history calculations. The results and some useful conclusions could provide technical reliability in oil and gas well testing design.

Keywords: Axial deformation, HTHP well, helical buckling, variable (T, P) fields.

1. INTRODUCTION

Because of the peak-modulating or maintenance demand in the production process of gas wells, the well needs to be frequently turned off and on. In deep well testing applied basic theory research, tubular string mechanical analysis is very complex, and fluid temperature and tubing pressure affect the force of the tubular string heavily. Some conditions, such as packer failure, abnormal pressure formation and pipe leakage, have a great impact on test production and are key technical problems affecting test success. The packer is an important well tool, which, in complicated and volatile working conditions, can be more easily damaged than other tools. Because the temperature and pressure of gas wells change during production and closing, for HTHP wells, the excessive pressure can cause a large pressure difference on the packer, which not only damages the packer's rubber but also makes it slip upward. As a result, the packer fails. Further, the fluid flow, temperature change, tubular deformation and the increase in the axial force can cause a reduction in the packer's bearing capacity. At the same time because of the pressure differences, the sealing arrangement is crushed and the packer also fails. The intensity of the rubber tube is decreased if the bottom-hole temperature exceeds its rated working temperature. The rubber tube is easily damaged and causes the packer to lose effect. With the variable temperatures and pressure, the deformation and load exerted on the tubing strings, as well as the change in the pressure and gas reservoir, there are serious safety concerns. If the tubing fails, the whole borehole would be unable to maintainits integrity and safety [1]. Therefore, it is veryimportant for HTHP wells to be able to predict the axial forces.

Significant contributions on tubular mechanics were made by [2]. He proposed four effects between the packer forces and the tubing length change: the temperature effect, the ballooning effect, the axial load effect and the helical buckling effect. Much research has been done on the effect of buckling behaviour, and it is considered that an inflexion is caused on the axial force under certain conditions, causing collisions on parts of the drill string with the well bore. When the tube buckles beyond the well-hole's control, the buckling configuration is transformed from a state of stabilization into sinusoidal buckling and helical buckling with an increase in the load. The buckling tube problem was first studied and theory put into practice by [3]. He emulated an experiment which looked at the buckling behaviour of tubes in deviated wells and found the computation formula for the critical buckling load of the tube in deviated wells. That the number of sinusoids in the buckling mode increases with the length of the tube was found by [4]. The buckling behavior of the inner and outer fluid pressure of the tubing was analysed and the mathematical relationship between pitch and axial pressure was deduced based on the principle of minimum potential energy [2]. The asymptotic solution for the sinusoidal buckling of an extremely long tube was analyszed by [5] based on a sinusoidal buckling mode of constant amplitude. Numerical solutions were also sought by [6] using the basic mechanics equations. His solutions confirmed the thought that, under a general loading, the deformed shape of the tube is a combination of helices and sinusoids while helical deformation occurs only under special values of the applied load. The tubing forces formula proposed, however, applied only to shallow wells and does not accommodate the complicated states of deep wells. Up to now, much research has centred on water injection tubes but

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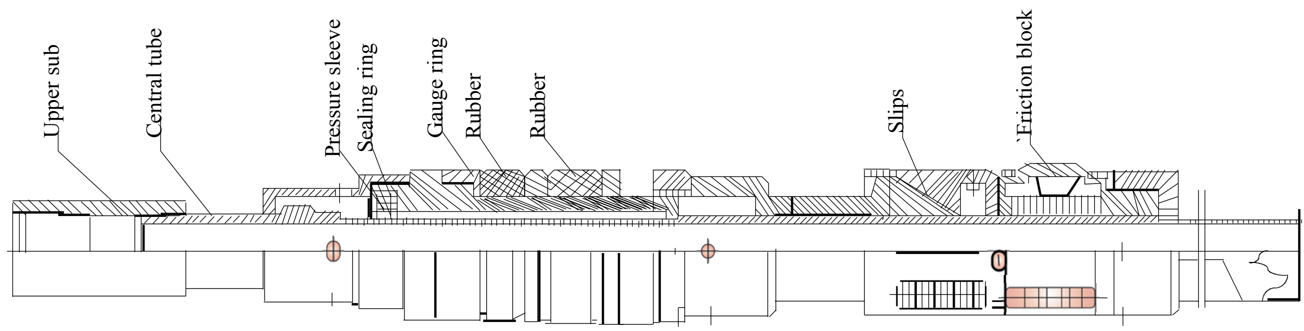

Fig. (1). The structure schematic of packer.

not well shut-in. Among them, the values of the temperature and pressure are considered as constant or lineal functions which could cause large errors in tubular deformation computing [7].

In fact, tubular string deformation includes transverse deformation and longitudinal deformation. Because the transverse length (with an order of magnitude of 10^{-3} *m*) is significantly smaller than the longitudinal length (with an order of magnitude of $10^{3}m$), the axial deformation (longitudinal) is mainly considered for the tubular string deformation analysis in this paper. Here, the force states of tube in the process of well shut-in are analysed. The variable (T, P) fields are considered to compute the values of several deformations. The axial load and four deformation lengths of tubular string are obtained using a dimensionless iterative interpolation algorithm. Basic data for the X Well (HTHP well), 6115 meters deep in China, are used for case history calculations. Some useful suggestions are drawn.

This paper is organized as follows. Section 2 outlines the features of HTHP Wells and the Principle of Packers. A tubular mechanics and deformation system model is presented in Section 3. Section 4 gives the parameters, initial condition and algorithm for solving the model. In section 5, an example is given from an HTHP well, 6115 meters deep in China, and an analysis conducted. Section 6 gives our conclusions.

2. FEATURES OF HTHP WELLS AND PRINCIPLE OF PACKER

2.1. Characteristics of HTHP Wells

Generally, the working condition and technological features of HTHP wells can be reduced to two simple points. The bottom hole temperature is high at around 160°C. Tubing measurements are multiple. The tools ' combination, such as the bottom hole test valve, the safety valve and the packer, are complex. The particularity of the tube's mechanics is as follows.

1. The distribution of temperature and pressure on the tubing has significant differences under variable outputs (flow velocity) but this is not a simple linear relationship and the density of fluid is not constant.
2. The sensitivity of force and deformation in tubes, for temperature, pressure, density of fluid, viscous friction loss and coulomb friction between tubing and well, increases with the depth of well.
3. The stretching forces and the creeping displacement of down hole strings impacts the sealed state of the packer or even causes the packer to dislodge.

The first postulation implies that this model will consider the variable temperature and pressure. In fact, this often provides a more realistic picture. The rest of two postulations are valid and acceptable and the details can be found in [8-10].

2.2. Packer's Principle

As shown from Fig. **(1)**, the packer includes five parts: anchor, sealing, setting, locking and unsetting. The unsetting part, whose role is controlling the unsetting force, is mainly composed of shear ring, fixing sleeve and central tube. Then, the principles of packer will be discussed below.

2.2.1. Setting

After pressurizing the hydraulic pressure from the tubing, the hydrostatic pressure impacts the fluid cylinder of the packer through the centre bore and pushes up the control piston. As the pressure reaches a certain degree, the shear stud connectors shear to control the piston going up. The connecting block is released, and the packer setting process is started. Because of the sufficient hydrostatic pressure, while the connecting block is set free, the setting organization supports it down hole. Then, the outer central tube moves down to hold the anchor open and compress the packer. The setting of packer is completed.

2.2.2. Unsetting

Lifting the tubing string while the outer central tube and the anchor organization hold their positions relative to the casing, the inner central tube moves up to release the shear ring. The tube continues going up, and the packer is released. So, the snap spring of the inner tube drives the outer tube up and makes the anchor ineffective. The packer is unset.

3. THEORETICAL MODEL

The main cause of packer failure in wells is the tubing deformation caused by pressure and temperature change, which causes the shear ring to release. However, if a larger sized shear ring is selected, the unset forces increase, leading to increased inventory costs. Therefore, it is necessary to research the stress distribution of the packer before the unset process. The structural diagram of the hydraulic packer is shown Fig. **(2)**.

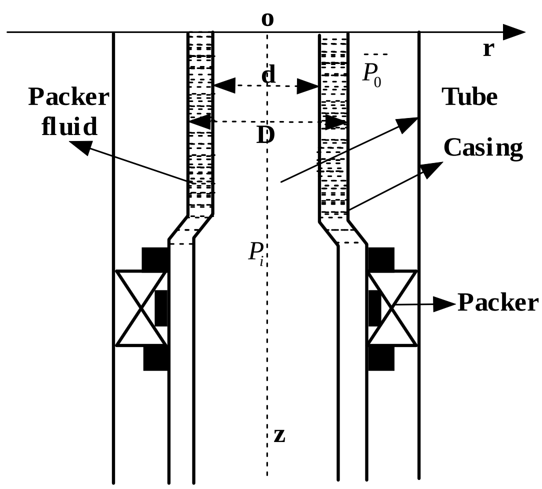

Fig. (2). The physical figure of forces analysis on tube.

3.1. Basic Assumption

The material properties of the tube such as the elastic modulus and the linear expansion coefficient all change with the temperature and pressure, so the stress of the tubing is very difficult to calculate. Thus, the following assumptions are included in the paper.

(1) The hole curvature of the considered modular section is constant.

(2) On the upper side or underside of the section, which is the point of contact of the pipe and the tube wall, the curvature is the same as the hole curvature.

(3) The radius of the string, in contrast to the curvature of the borehole, is insignificant.

(4) The string is at a linear elastic relationship state.

3.2. Factors Affecting the Unset Force

Generally, the factors affecting the unset force of the hydraulic packer can be summarized as follows: (1). A ballooning effect and a piston effect from the pressure variation. (2). A temperature effect from the tubing temperature variation. (3). A sucker-rod pumping effect. (4). A piston force effect on the supporting packer's pressure.

3.3. Basic Equations

As shown in Fig. **(2)**, a constant cross-sectional flow area A, inner diameter d, outer diameter D, material density ρ_1, packer fluid density ρ_2 and a total length Z. Through this tubing gas flows from the bottom to the top with a mass flow rate W. The distance co-ordinate in the flow direction along the tubing is denoted by z. The cylindrical coordinate system $r\theta z$, the origin of which is in the wellhead and the Z axis is down as the borehole axis, is used.

3.3.1 Initial Axial Load

In this section, the distance from the wellhead z (m) is considered. The axial static load by the dead weight of the tube.

$$N_{qz} = \int_z^L q\cos\alpha dz = \frac{\pi}{4}\rho_1 g(D^2 - d^2)\int_z^L \cos\alpha dz \qquad (1)$$

where, N_{qz} is the tube deadweight of tubular, L is the tube length of tubular, ρ_1 is the tube density of tubular, and α is the inclination angle.

The axial static load by the buoyant weight.

$$N_{bz} = -\rho_2 gzA_2 = -\rho_2 gz(\frac{D}{2})^2 \qquad (2)$$

where, N_{bz} is the tube buoyant weight of tubular, ρ_2 is the density of packer fluid density.

Therefore, summing the Eq.1 and 2, the axial forces in the section are obtained as follows:

$$F_i = N_{qz} + N_{bz} \qquad (3)$$

3.3.2. Pressure Effect on Packer Setting

While the packer is setting, the tubes internal pressure is higher than its external pressure, which produces a piston axial load effect which is derived from the following equation.

$$F_z = \frac{\pi}{4}d^2\Delta P_{start} \qquad (4)$$

where, F_z represents the axial tensile strength, ΔP_{start} is the differential pressure at startup. After the packer is anchored by the slips, the tubes internal pressure can continue to increase, but the length of tube will not change. Therefore, the differential pressure in Eq. 4 should be at startup, which is the differential pressure shove off anchor.

At the same time, the differential pressure between the casing and the tube produces a ballooning effect, which causes the length of the tube to decrease as shown in Fig. **(3)**.

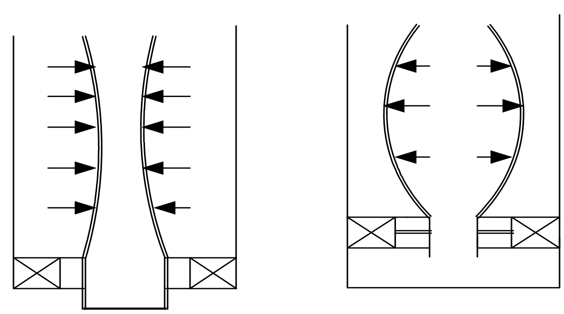

Fig. (3). The figure of ballooning effect.

In reference to the thick-wall cylinder, generalized Hooke's law, so the length change is calculated using the following formula. (The equation was also obtained by Lubinski *et al*.[3])

$$\Delta L_{bi} = -\frac{\mu\Delta Z_i^2}{E}\frac{d^2\Delta\rho_{ii}g - D^2\Delta\rho_{oi}g - \delta(1+2\mu)/(2\mu)}{D^2 - d^2} - \frac{2\mu\Delta Z_i}{E}\frac{d^2\Delta P_{ii} - D^2\Delta P_{oi}}{D^2 - d^2} \qquad (5)$$

where, ΔP_{ii} represents the change in tubing pressure at i length, ΔP_{oi} represents the change in annulus pressure at the i length, E is the steel elastic modulus of the tube, δ is the drop of in pressure in the tubing due to the flow per unit length, $\Delta\rho_{ii}$ is the change in the density of liquid in the tubing at the i length, μ is the Poisson's ratio of the material, $\Delta\rho_{oi}$ is the change in density of the liquid in the casing at i length. From the assumption ($\Delta\rho_{oi} = 0$, $\Delta\rho_i = 0$, $\Delta\rho_o = 0$, $\delta = 0$), the equation can be reduced as follows.

$$\Delta L_{bi} = -\frac{2\mu\Delta Z_i}{E}\frac{d^2\Delta P_{ii}}{D^2 - d^2} \quad (6)$$

The total axial deformation of the variable pressure fields can be derived by accumulating each element.

$$\Delta L_b = \sum_{i=1}^{N} \Delta L_{bi} \quad (7)$$

The force leading to the temperature effect is calculated using the follow formula according to Hooke's law.

$$F_b = \frac{\Delta L_b}{L} EA \quad (8)$$

3.3.3. The Contact Force and Friction Between the Casing and the Tubing

Researchers, in general, call the buckling a bending effect. The tube is freely suspended in the absence of fluid inside as shown in Fig. **(4a).** A force F is applied at the lower end of the tube and if the force is large enough the tube will buckle as shown in Fig. **(4b).**

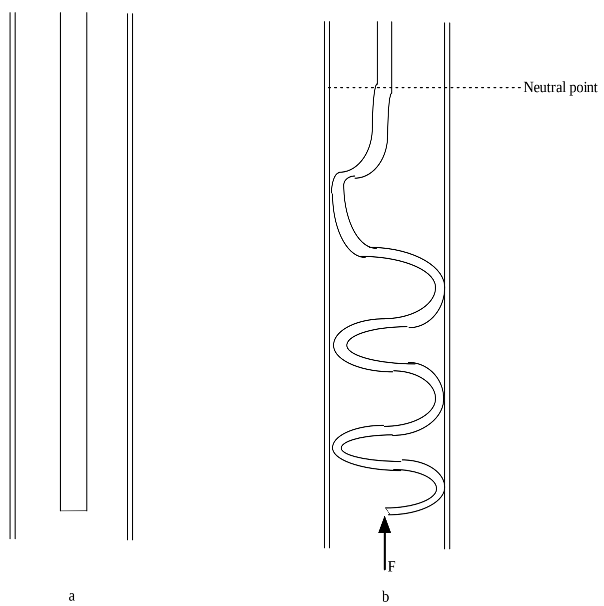

Fig. (4). Buckling of tubular.

Lubinski *et al.* [3] has done much research on this phenomenon. From his work, the buckling effect is determined. Define the virtual axial force of the tubing as follows:

$$F_f = A_P(P_1 - P_0) \quad (9)$$

where, P_1 is the pressure inside the tube at the packer length, P_0 is the pressure outside the tube at the packer length and A_P is the area corresponding to the packer bore.

To determine whether the tube is buckling or not use Eq.13. The string will buckle if F_f is positive or remain straight if F_f is negative or zero. The tubular string buckling axial deformation is

$$\Delta L_3 = -\frac{r^2 A_P{}^2 (\Delta P_1 - \Delta P_0)^2}{8EIW} \quad (10)$$

The contact force between the helically buckled tubing and the casing within an axial unit length is expressed as follows [6]:

$$N = -\frac{r^2 F_f{}^2}{8EI} \quad (11)$$

According to the Coulomb's friction principle [9], the friction force is derived by through multiplying the contact force with the friction factor.

$$F_f = \mu N \quad (12)$$

3.3.4. Temperature Effect

The tubing temperature changes as the steam injection, oil production and well shut-in after packer setting, cause changes in the tubular length. The temperature on injection or shut-in process changes significantly compared with other operating duties. In this paper, the temperature change on well shut-in is chosen as the temperature effect of the unset force.

For the tubular dz micro-element, the temperature change unit deformation is as follows: [8- 10]:

$$\Delta L_{ti} = \int_{Z_{i-1}}^{Z_i} \frac{\sigma_{zt}}{E} dz = \beta \Delta T_i \Delta L_i \quad (13)$$

where, σ_{zt} represents the axial thermal stress, E is the steel elastic modulus of the tube, β is the warm balloon coefficient of the tubular string, ΔT is the temperature change with before and after well shut-in. The same principle is that the total axial deformation caused by the variable temperature fields can be determined by accumulating each element.

$$\Delta L_t = \sum_{i=1}^{N} \Delta L_{ti} \quad (14)$$

The force, which is lead by the temperature effect, is calculated using the following formula according to Hooke's law.

3.3.5. Sucker-rod Pumping Effect

In the course of the sucker-rod pumping, the up stroke of pump decreases the load of the tube with an increase in the load on the down stroke of the pump, which will causes a change in the force at the top of the tube located at the packer. The expansion forces or contraction forces may lead to packer unset.

As shown in Fig. **(5)**, the pump force is determined using the following equation.

$$F_s = \frac{\pi}{4t} d^2 h \rho_i v_s \quad (15)$$

where, F_s represents the pumping force, h is the depth of the top tube tubular located at the packer, ρ_i is the density of the fluid in the tubing, g is the acceleration of gravity, v_s is the down stroke velocity, t is the down stroke time. Because of the small change in fluid density, ρ_i here is regarded as constant.

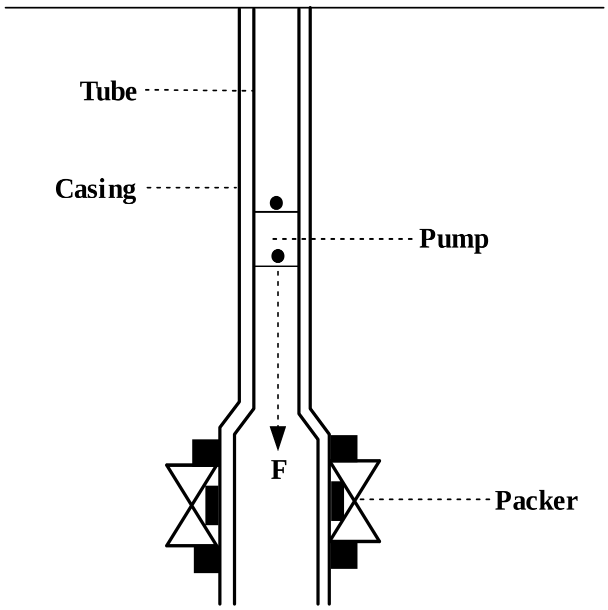

Fig. (5). The physical figure of forces analysis on pumping effect.

3.3.6. Piston Effect in Supporting the Packer's Pressure

From the work principium mentioned in section 2.2, to support the deferential pressure from top to bottom, the structure of the hydrostatic packer adopts the inner central tube connecting with the down joint. The hydrostatic pressure is transmitted to the casing through the slips. While supporting the deferential pressure from the bottom to the top, the packer pushes up the outer central tube and the hydrostatic pressure is transmitted to the casing through the hydraulic anchor, the measure of which is obtained from the following equation.

$$F_c = \Delta P_c A_c \tag{16}$$

where, F_c represents the piston to support the packer's pressure, ΔP_c is the differential pressure from top to bottom, A_c is the effective area.

3.3.7. Analysis of Pressure and Temperature Fields

In the course of modelling, the factors affecting the packer unset force are temperature and pressure. In fact, these two parameters vary according to depth and time. The variation in pressure and temperature has a significant effect on the unset force. Thus, variable (T, P) fields need to be researched. The variation maximums are founds in steam injection or well shut-in processes. In this paper, the variable (T, P) fields on well shut-in are chosen as the study objectives.

From previous studies, the variable (T, P) fields were deduced strictly based on the mass, momentum and energy balances in the HTHP well shut-in procedures [11]. The model focused on the heat transmission in the stratum, and then calculate the temperature through differential equation based on Cullender-Smith method.

$$\begin{cases}
\dfrac{\partial v}{\partial z} = -\dfrac{1}{\rho}\left(\dfrac{\partial \rho}{\partial t} + v\dfrac{\partial \rho}{\partial z}\right) \\
\dfrac{\partial P}{\partial z} = -\rho\dfrac{\partial v}{\partial t} + v\dfrac{\partial \rho}{\partial t} + v^2\dfrac{\partial \rho}{\partial z} - \rho g\cos\theta - \dfrac{f\rho v^2}{2d} \\
\dfrac{\partial T}{\partial z} = -\dfrac{1}{C_P}\left[\dfrac{\partial}{\partial t}(\rho C_P T)A + -C_J C_P\dfrac{\partial P}{\partial z} + \dfrac{\partial}{\partial z}\left(\tfrac{1}{2}\rho v^3 A + \rho g v A z\cos\theta\right) + a(T - T_e) + \dfrac{f\rho v^3 A}{2d}\right] \\
\dfrac{\partial T_e}{\partial t_D} = \dfrac{\lambda_e}{C_{P_e}\rho_e}\left(\dfrac{\partial^2 T_e}{\partial r_D^2} + \dfrac{1}{r_D}\dfrac{\partial T_e}{\partial r_D}\right) \\
\rho = MP_i/(RZ_g T) \\
\left.\dfrac{\partial T_e}{\partial r_D}\right|_{r_D=1} = -\dfrac{dQ}{dz}(2\pi\lambda_e)^{-1},\ \left.\dfrac{\partial T_e}{\partial r_D}\right|_{r_D\to\infty} = 0 \\
P(z,0) = P_0(z), T(z,0) = T_0(z), v(z,0) = v_0(z), T_e(r_D,0) = T_e^0(r_D) \\
P(0,t) = \overline{P}_0(t),\ T(0,t) = \overline{T}_0(t),\ v(0,t) = \overline{v}_0(t),\ T_e(0,t) = T_e^0(t)
\end{cases}$$

where, P_i is the pressure in the tubing, T_i is the temperature in the tubing, v_i is the fluid velocity in the tubing, ρ_i is the fluid density in the tubing, C_J is the Joule-Thompson coefficient, C_P is fluid heat capacity, T_e is the initial formation temperature and t_D is dimensionless time.

4. SOLUTION METHODOLOGY

To simplify the calculation, the wells are divided into several short segments of the same length. The length of a segment varies depending on the variations in wall thickness, hole diameter, fluid density inside and outside the pipe and well geometry. The model begins with a calculation at one particular position in the well: the top of the pipe.

Set the depth step length . In addition, the relative tolerance error is denoted by ε . The smaller h , ε are, the more accurate the results are. However, this leads to a rapid increase in calculating time. In our paper, we set h = 1(m), and ε = 5%.

With reference to Fig. (**6**), the proposed methodology involves the following steps:

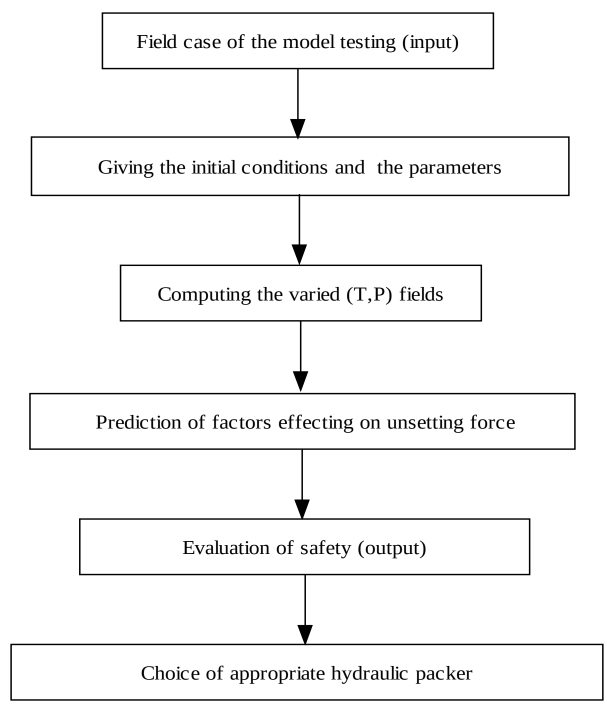

Fig. (6). Architecture of the proposed methodology.

Table 1. Parameters of Pipes

Diameter (mm)	Thickness (mm)	Weight (Kg)	Expansion	Elastic (Gpa)	Possion's Rations	Using length (m)
88.9	12.95	23.791	0.0000115	215	0.3	700
88.9	9.53	18.28	0.0000115	215	0.3	2850
88.9	7.34	15.034	0.0000115	215	0.3	1430
88.9	6.45	13.582	0.0000115	215	0.3	950
73	5.51	9.493	0.0000115	215	0.3	185

Table 2. Well Parameters

Measured (m)	Internal (mm)	External (mm)
3301.7	154.78	193.7
5936.83	152.5	177.8
6115	108.62	127

Table 3. Parameters of Azimuth, Inclination and Vertical Depth

Number	Measured (m)	Inclination (degree)	Azimuth (d)	Vertical depth (m)	Number	Measured (m)	Inclination (degree)	Azimuth (d)	Vertical depth (m)
1	1000	2.82	240.84	999.88	17	4800	3.04	229.14	4798.38
2	1200	2.28	237.69	1199.53	18	4900	3.59	243.86	4898.23
3	1300	1.13	213.69	1299.49	19	5000	5.79	366.45	4997.87
4	2800	1.19	26.21	2799.41	20	5100	8.14	258.61	5097.01
5	3000	1.74	44.39	2999.25	21	5200	7.01	236.71	5196.12
6	3400	1.92	190.95	3399.21	22	5300	5.78	239.1	5295.51
7	3900	1.98	268.9	3899.14	23	5400	5.05	244.42	5395.04
8	4000	2.00	297.38	3999.11	24	5500	3.92	228.03	5494.72
9	4100	4.68	324.34	4098.96	25	5600	4.44	233.71	5594.49
10	4200	1.97	302.88	4198.74	26	5700	5.03	234.87	5694.17
11	4300	1.03	204.57	4298.72	27	5800	5.13	233.21	5793.77
12	4400	1.54	164.16	4398.68	28	5900	4.53	234.82	5893.44
14	4500	2.37	195.11	4498.61	29	6000	3.67	232.4	5993.21
15	4600	2.12	214.67	4598.54	30	6115	4.94	233.11	6107.88
16	4700	1.96	216.31	4698.47					

Step 1. Generate a sample of the model testing. This sampling data can be either experimental or field measured.

Step 2. Conduct numerical simulations using the sample (input) from the previous step and obtain the relative parameters.

Table 4. The Results of the Axial Force and Various Kinds of Deformation Length

Number	Depth (m)	Displacement by temperature changed (m)	Displacement by pressure changed (m)	Axial deformation (m)	Buckling deformation (m)	Total deformation (m)
1	500	0.1139	0.0209	0.033	0	0.168
2	1000	0.9425	0.1709	0.334	0	1.447
3	1500	1.711	0.3209	0.702	-0.005	2.729
4	2000	2.4177	0.4512	1.114	-0.006	3.977
5	2500	3.0559	0.5512	1.565	-0.006	5.167
6	3000	3.634	0.635	2.058	-0.007	6.319
7	3500	4.152	0.685	2.593	-0.016	7.414
8	4000	4.6077	0.7208	3.168	-0.022	8.474
9	4500	4.9955	0.7208	3.782	-0.048	9.450
10	5000	5.3232	0.7075	4.435	-0.057	10.409
11	5500	5.5908	0.6575	5.075	-0.067	11.255
12	6000	5.7957	0.6075	5.704	-0.103	12.003
13	6115	5.8857	0.5775	6.029	-0.109	12.383

Step 3. Use the parameters obtained in the previous steps, compute the variable(T,P) fields on the shut-in process.

Step 4. Calculate the affecting factors of the unset force using the given model with the variable (T,P) fields in step 3.

Step 5. Conduct numerical simulations using the values obtained in the previous step to confirm their performance level.

Step 6. The designer now selects among the best confirmed design values the solution that satisfies the chosen preference structure.

5. FIELD CASE ANALYSIS

5.1. Parameters

To investigate model validity and performance, case field data was studied. Data for this case were taken from X well, which is located in China. The needed parameters are given as follows: Depth of the well is 6115 m, The well bottom pressure is 40 Mpa, Critical pressure is 4.968 Mpa, Gas specific weight is 0.6434; Ground thermal conductivity parameter is 2.06; Ground temperature is 16° C; Ground temperature gradient is 0.0218 (° C /m); Roughness of the inner surface of the well is 0.000015; parameters of pipes, inclined well, inclination, azimuth and vertical depth are given in Tables **1-3**. The variable (T, P) fields are shown in Figs. **(7** and **8)** [12].

5.2. Main Results and Results Analysis

After calculation, the results of this well test are as in Table **4**.

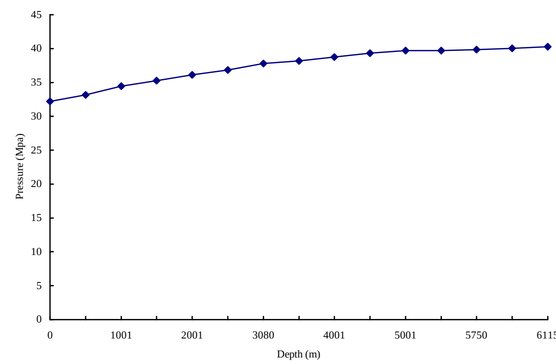

Fig. (7). The pressure fields.

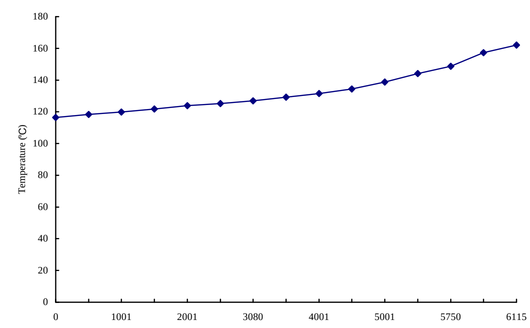

Fig. (8). The temperature fields.

The influence of the outputs on the tubes axial deformation was investigated as shown by Fig. **(9)**.

From the results as shown in Table **4**, some useful conclusions can be drawn.

1. The upward force should be reduced as much as possible on packer design to improve the force-bearing

conditions of the packer and the tube, extending their effective life and increasing total economic efficiency.

2. A hydrostatic packer unset force analysis should be conducted understanding the structural principles and considering completely the setting and pressure bearing processes. The factors affecting the unset force of the hydraulic packer are the ballooning and piston effect, the temperature effect, the sucker-rod pumping effect and the supporting packer pressure piston force effect. The simulation results show that the piston force at the packer setting is a fixed value because of the fixed value of the packer's differential pressure at start up.
3. The length of the tubular deformation increases with an increase in outputs, but more slowly.
4. Thermal stress is the main factor influencing tubular deformation.
5. The packer can greatly improve the stress state above the cement surface of the casing in high-pressure conditions. In order to reduce the force or deformation of the tube, a retractable compensation device should be added.

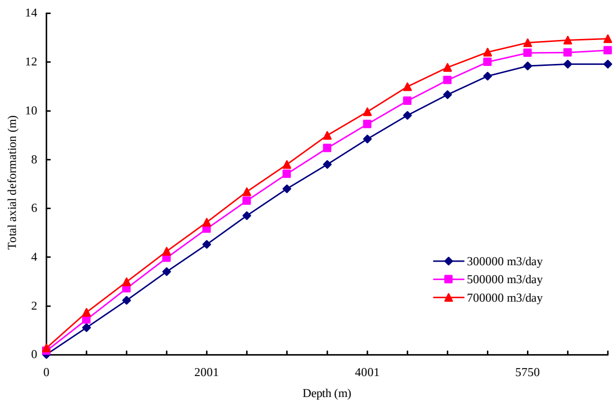

Fig. (9). The total axial deformation under variable outputs.

6. CONCLUSION

The following conclusions can be derived from the results of this work.

1. A coupled system model of differential equations concerning pressure and temperature in HTHP well during shut-in process , which can reduce the error of axial stress and axial deformation, were given instead of average value or simple linear relationship in traditional research.
2. Based on the prediction calculation of pressure and temperature inside the hole of a testing well, together with tubular load, tubular stress and deformation, the downhole testing string model was produced.
3. Based on the simulation result, the effect sequence of different factors is achieved. For unset process, the temperature effect is the most significant.
4. A set of software for mechanical analysis on the testing string for HTHP deep wells can be programmed for providing reference to strength design and verification, and operation parameter calculation.

LIST OF SYMBOLS

d = Inner diameter (m)

d_z = Microelement of the tubular

g = Acceleration of gravity (m/s^2)

h = Depth of top tubular located at the packer (m)

t = Time of down stroke (s)

t_D = Dimensionless time (dimensionless)

$v_{i\ i}$ = Velocity of fluid in tubing (m/s)

v_s = Velocity of down stroke (m/s)

z = Distance co-ordinate in the flow direction along the tubing (m)

A = Constant cross-sectional flow area (m^2)

A_c = Effective area (m^2)

A_p = Area corresponding to packer bore (m^2)

C_J = Joule-Thompson coefficient (dimensionless)

C_P = Heat capacity of fluids (J/Kg·K)

D = Outer diameter (m)

E = Steel elastic modulus of tubular (Mpa)

F_i = Axial forces in the section (N)

F_z = Axial tensile strength (N)

F_f = Friction force (N)

F_c = Piston force for supporting packer's pressure (N)

F_s = Pumping force (N)

L = Length of tubular (m)

N_{bz} = Buoyant weight of tubular (Kg)

N_{qz} = Deadweight of tubular (Kg)

P_o = Pressure outside the tubular (Mpa)

P_0 = Pressure outside the tubular (Mpa)

P_1 = Pressure inside the tubular at the packer length (Mpa)

P_i = Pressure in tubing (Mpa)

T_i = Temperature in tubing (° C)

T_e = Initial temperature of formation (\textcelsius)

W = Mass flow rate (Kg/s)

Z = Total length (m)

ρ_1 = Material density (Kg/m^3)

ρ_2 = Packer fluid density (Kg/m^3)

α = Inclination angle(°)

β = Warm balloon coefficient of hte tubular string (dimensionless)

δ = Drop of any parameter

σ_{zt} = Axial thermal stress (N)

ρ_i = Density of fluid in the tubing (Kg/m^3)

ΔL_3 = Axial deformation of the butular string string buckling (m)

ΔL_t = Total axial deformation by variable temperature fields (m)

ΔL_b = Total axial deformation by the variable pressure fields (m)

ΔP_{start} = Didderential pressure at startup (Mpa)

ΔP_{ii} = Change in tubing pressure at the i length (Mpa)

ΔP_{oi} = Change in annulus pressure at the i length (Mpa)

ΔP_c = Differential pressure from top to bottom (Mpa)

ΔT = Temperature change with before and after well shut-in (°C)

$\Delta\rho_{ii}$ = Change in density of liquid in the tubing at the i length (Kg/m^3)

$\Delta\rho_{oi}$ = Change in density of liquid in the casing at the i length (Kg/m^3)

CONFLICT OF INTEREST

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

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