Research on the wellhead growth in deepwater wells by considering the mechanical nonlinear properties of material

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Abstract. Wellhead growth is a severe risk of oil and gas wells. A prediction model is proposed to estimate the potential wellhead growth in deepwater wells. The new model considers the mechanical nonlinear properties of material. Formulas are developed to obtain the fluid expansion coefficient and compressibility, and casing elastic modulus and expansion coefficient. These parameters present a nonlinear relationship with the temperature or pressure. A case study and some key factors are analysed. Results show that the nonlinear properties can’t be ignored to accurately estimate wellhead growth. If the nonlinear properties are ignored, the errors of wellhead growth will larger than 30% when a deepwater well encounters the high temperature condition. Compared with onshore or platform wells, annular pressure in deepwater wells has great influence on the wellhead growth. By mitigating the annular pressure to about 30%, engineers can reduce the risk of wellhead growth considerably. This research has great significance on the safety design of deepwater wells.

1. Introduction

The significant temperature change in oil wells can lead to the thermal expansion of the wellbore architecture that is composed of multiple casings and annulus. Because the casing and annulus are connected to the wellhead, the thermal stress may upward lift the wellhead, which is called wellhead growth. Wellhead growth is a considerable accident that endangers the wellbore integrity. Many accidents have been reported in high-temperature/high-pressure wells, steam injection wells, and offshore platform wells et al. [1, 2]. Deepwater wells are also threatened by the wellhead growth because the temperature variation in the wellbore is considerable [3]. Compared with onshore and offshore platform wells whose wellhead growth is caused by casing’s thermal expansion, the wellhead growth in deepwater wells is a synthetic action of casing and annular fluid thermal expansion. This synthetic action exacerbates the risk of wellhead growth. Thus, the wellhead growth in deepwater wells should be estimated to evaluate the risk and prevent the damage of wellbore integrity.

The theory and prediction model of wellhead growth in deepwater wells have been discussed by many researchers. These published models are similar to the wellhead growth in onshore wells [4, 5]. In the previous models, the wellbore is treated as a parallel spring system. The loadings on wellhead are calculated to obtain the height of wellhead growth [6-8]. However, the previous studies have some limitations that may cause the inaccurate estimation because these researches ignore the mechanical nonlinear properties of material. For the real material properties, the thermal expansion coefficient, compressibility, and elastic modulus vary with temperature or pressure. But the previous models treat these parameters as constant. The ignoring of these nonlinear behavior may lead to inaccurate
prediction [9]. Therefore, to calculate the wellhead growth more accurately, the prediction model should take the mechanical nonlinear properties of material into account.

This paper proposes a mechanical model of wellhead in deepwater wells. This model considers the nonlinear behavior of material’s mechanical properties. By Lagrange interpolation method, the thermal expansion coefficient and compressibility of annular fluid are obtained. Additionally, the expansion coefficient and elastic modulus of casing are also presented. Finally, a case study and some key factors are analyzed to discuss the loadings on the wellhead and compare the new model with published models.

2. The mechanical model of wellhead in deepwater wells

2.1. Force analysis

A deepwater well’s schematic is shown in figure 1. The wellbore consists of three casings: (1) surface casing; (2) technical casing; and (3) production casing. Because of the limitation of engineering technology, the cement outside the technical and production casing are not displaced to the wellhead. Thus, some portions of the technical and production casings that are not cemented are free sections. Commonly, the cement outside the surface casing will be displaced to the wellhead, but the quality of cement is poor in most cases, which leads to the free section occurs in the surface casing [8]. Assuming the wellhead is fixed, the loadings on the wellhead are listed below.

Figure 1. Schematic of deepwater wells.

(1) Pretension force ($F_{pre}$): After the installation of wellhead, the casing and tubing are hung under the wellhead. Thus, there is a pretension force that caused by the gravity of casing and tubing on the wellhead. As shown in figure 1, the pretension force on the wellhead is axially downward.

(2) Axial force caused by the thermal expansion of annular fluid ($F_{APB}$): In deepwater wells, annular fluid is trapped in the sealed annulus. The annular pressure, which is called annular pressure build-up (APB), increases with the increase of fluid temperature. The loading caused by APB is axially upward on the wellhead, as presented in figure 1 [10, 11]. Notably, APB only exits in annulus-B and annulus-C because the pressure in annulus-A can be controlled in most cases.

(3) Axial force caused by the thermal expansion of casing ($F_{casing}$): Because of the temperature increase, the casing axially expands to cause a loading on the wellhead, as shown in figure 1. $F_{casing}$ on the wellhead is axially upward. The force caused by the tubing is small and can be ignored [3].
(4) Besides, there are some factors that limit the wellhead movement, such as the limitation force caused by the surface casing, the gravity of wellhead, and the wellhead fixed device et al. This paper names these loadings as \( F_{\text{lim}} \).

Equation (1) describes the relationship of the loadings when the wellhead is fixed. This work assumes the upward direction is positive, while the downward direction is negative.

\[
F_{\text{casing}} + F_{\text{APB}} + F_{\text{pre}} + F_{\text{lim}} = 0
\]  

(1)

In the beginning, \( F_{\text{casing}} \) and \( F_{\text{APB}} \) are small. And \( F_{\text{lim}} \) is axially upward to prevent wellhead move downward. With the increase of temperature, \( F_{\text{casing}} \) and \( F_{\text{APB}} \) become larger. Because \( F_{\text{pre}} \) is constant, \( F_{\text{lim}} \) decreases with the increase of \( F_{\text{casing}} \) and \( F_{\text{APB}} \). When \( F_{\text{casing}} \) and \( F_{\text{APB}} \) are large enough, \( F_{\text{lim}} \) becomes axially downward to limit the upward moving of wellhead, as the diagram of force analysis presented in figure 1. But \( F_{\text{lim}} \) has a critical value \( (F_{\text{cri}}) \) it cannot surpass. This critical value is determined by the in-situ conditions. When \( F_{\text{lim}} \) is larger than \( F_{\text{cri}} \), the wellhead will move upward. Equation (2) presents the condition in which the wellhead growth happens.

\[
F_{\text{casing}} + F_{\text{APB}} > \left| F_{\text{pre}} \right| + \left| F_{\text{cri}} \right|
\]  

(2)

Based on the force analysis above, this paper will calculate the loadings on the wellhead and estimate the wellhead growth. The following assumptions are used to simplify the calculation: (1) The wellbore is vertical; and no curved sections exit; (2) The casing program is assumed as a spring system connected in series and parallel; (3) The thermal stress caused by tubing thermal expansion is ignored; (4) The volume change of annulus is ignored.

2.2. The axial force caused by the thermal expansion of annular fluid

APB should be estimated before the calculation of the \( F_{\text{APB}} \). By considering the nonlinear properties of fluid whose expansion coefficient and compressibility vary with temperature and pressure, equation (3) is developed to predict the APB in annulus [12].

\[
\Delta P = \frac{\sum \Delta T \alpha_{t}}{\Sigma k_{t}}
\]  

(3)

In equation (3), \( \Delta P \) denotes the APB in annulus, MPa; the term at the right side denotes that annulus is axially divided into a number of micro-sections; \( \Delta T_{t} \) is the temperature change at section \( t, {}^\circ \text{C} \); \( \alpha_{t} \) is the expansion coefficient at section \( t, 1/\circ \text{C} \); \( k_{t} \) is the compressibility at section \( t, 1/\text{MPa} \).

Firstly, it is necessary obtain the fluid thermal expansion coefficient and compressibility at different temperature and pressure. Equations (4) and (5) describe the thermal expansion coefficient and compressibility.

\[
\alpha = \left(1/V_{f}\right)\left(\partial V_{f}/\partial T\right)_{P} = -\left(1/\rho\right)(\partial \rho/\partial T)_{P}
\]  

(4)

\[
k = \left(1/V_{f}\right)\left(\partial V_{f}/\partial P\right)_{T} = (1/\rho)(\partial \rho/\partial P)_{T}
\]  

(5)

Equations (4) and (5) illustrate that if the fluid density’ function is determined, the expansion coefficient and compressibility can be obtained. Thus, this paper will obtain the fluid density as a function of temperature and pressure. In this work, water is used as the fluid medium because the base fluid of annular fluid is water and their properties are similar [11]. Water’s density at different temperature and pressure is presented in table 1 [13].

Taking the data at table 1 as interpolation nodes, equation (6) can be proposed by 2-Dimentional langrage interpolation method [17].

\[
\rho(T, P) = \sum_{i=1}^{7} \sum_{j=1}^{2} \rho(T_{i}, P_{j}) l_{i}(T) l_{j}'(P)
\]  

(6)

In equation (6), \( \rho(T_{i}, P_{j}) \) is the density at \( T_{i} \) and \( P_{j} \); \( l_{i}(T) \) and \( l_{j}'(P) \) are basic functions.

\[
l_{i}(T) = \prod_{r=1}^{T-T_{r}} \frac{T_{r} - T}{T_{r} - T_{i}}
\]  

(7)

\[
l_{j}'(P) = \prod_{s=j}^{P-P_{s}} \frac{P_{s} - P_{j}}{P_{j} - P_{s}}
\]  

(8)

Substituting equation (6) into equations (4) and (5), we can get the thermal expansion coefficient and compressibility at any temperature and pressure. Then, the APB in annulus can be obtained by equation (3), and the axial force caused by APB can be calculated by equation (9).
where $A$ denotes the sectional area of annulus, $m^2$.

\[ F_{APR} = A\Delta P \]  

(9)

### Table 1. Water density.

| Temperature ($^\circ$C) | Density (kg/m$^3$) |
|-------------------------|---------------------|
|                         | At 1 (MPa) ($P_1$) | At 100 (MPa) ($P_2$) |
| 7 ($T_1$)               | 1000.3              | 1043.6               |
| 27 ($T_2$)              | 996.96              | 1037.2               |
| 47 ($T_3$)              | 989.82              | 1028.9               |
| 67 ($T_4$)              | 979.93              | 1019                 |
| 87 ($T_5$)              | 967.81              | 1007.8               |
| 127 ($T_6$)             | 937.87              | 981.82               |
| 177 ($T_7$)             | 890.39              | 943.51               |

2.3. The axial force caused by the thermal expansion of casing

In the real wellbore, the temperature of casing varies with depth and production time, which leads to the variability of elastic modulus and expansion coefficient. So, the mechanical nonlinear properties of casing should be taken into consideration. Generally speaking, the properties of different steel can refer to the manufacturer. In this paper, steel N80 is adopted as an example.

Equation (10) presents the elastic model of steel N80 as a function of temperature [14].

\[ E = -260T + 213180 \]  

(10)

where $E$ is the elastic modulus, MPa; and $T$ denotes the temperature of steel, $^\circ$C.

Equation (11) describes the relationship of temperature and expansion coefficient of steel N80 [14].

\[ \alpha_{N80} = (-0.0004T^2 + 0.2248T - 3.6647) \times 10^{-6} \]  

(11)

where $\alpha_{N80}$ denotes the expansion coefficient of N80, $1/^\circ$C.

To apply the variability of elastic modulus to the prediction model, this paper assumes the casing program as a spring system that is parallel and serial connected.

Equation (12) shows a single casing’s stiffness according to the serial connected spring system.

\[ G = \frac{1}{\sum G_t} \]  

(12)

where $G$ denotes the stiffness of a casing, MPa; the right side denotes that the single casing is axially divided into a number of micro-sections; $G_t$ denotes the stiffness at micro-section $t$, MPa.

$G_t$ can be obtained by equation (13).

\[ G_t = \frac{E_t A_t}{l_o} \]  

(13)

where $l_o$ is the length of the micro-section, m; $E_t$ is the elastic modules of micro-section $t$, MPa; $A_t$ denotes the sectional area of casing, $m^2$.

Then the axial force caused by this single casing can be described as equation (14).

\[ F_{casing} = G \sum \alpha_{N80} \Delta T_t l_o \]  

(14)

where $\Delta T_t$ is the temperature change at micro-section $t$, $^\circ$C;

2.4 Prediction of wellhead growth

When the forces satisfy equation (2), the height of wellhead growth can be calculated by equation (15). $F_{pre}$ can be calculated by the gravity of casing and $F_{cri}$ can be obtained by the in-situ conditions.

\[ \Delta H = \frac{G_{total}}{\Sigma G} \]  

(15)

where the sigma signs in the formula mean the accumulation of the forces caused by each annulus and casing; $G_{total}$ is the total rigidity ($G_{total} = \Sigma G$), MPa.
3. Results and discussion

3.1. Case study

A wellbore architecture of deepwater well is presented in figure 1. The water depth is 700m. The well depth is 3860 m, and the geothermal gradient is 4.1 °C/100m. All these factors indicate that this deepwater well is threatened by high temperature. The critical force that limit the wellhead growth is 800 kN. Because of the poor cement quality, there is a 100 m free section of surface casing. The production rate is 150 t/d. After 100 day production, wellhead temperature increases from 4 °C to about 80 °C. This significant temperature variability means that the wellhead may move upward. The prediction model in section 2 will be adopted to calculate the forces on the wellhead and estimate the wellhead growth.

The temperature estimation is necessary before the prediction of wellbore growth. This paper predicts the temperature by the semi-steady state model, which is comprehensively discussed and used by most researches [12]. Figure 2 shows the temperature distribution of each annulus and casing.

![Figure 2. Temperature distribution.](image)

By the temperature distribution predicted by the semi-steady state model, the temperature variability of each annulus and casing can be obtained. Then, the wellhead growth can be calculated by equation (15). It should be noticed that the temperature variability and wellhead growth should be estimated at every time-step to properly take the nonlinear properties of material into account. Finally, the total wellhead growth is the accumulation of wellhead growth at every time-step.

Table 2 shows the axial force caused by each annulus and casings, and the height of wellhead growth. The negative sign means the downward axial force, while positive the means the upward axial force. The loadings on the wellhead are so considerable that wellhead moves upward 7.46 cm. This could result in the damage of wellbore integrity and considerable economic loss.

| Annulus-B | Annulus-C | Production casing | Technical casing | Surface casing | Tubing | Wellhead growth (cm) |
|-----------|-----------|-------------------|------------------|----------------|--------|----------------------|
| APB (MPa) | F<sub>APB</sub> (kN) | APB (MPa) | F<sub>APB</sub> (kN) | F<sub>pre</sub> (kN) | F<sub>casing</sub> (kN) | F<sub>pre</sub> (kN) | F<sub>casing</sub> (kN) | F<sub>pre</sub> (kN) | F<sub>casing</sub> (kN) |            |
| 50.29     | 1567      | 35.33            | 3261             | -1109          | 594    | -578                 | 481             | -114          | 203            | -220      | 7.46      |

3.2. Analysis of APB

In onshore or platform wells, the wellhead growth is only determined by the thermal expansion of casing because their annulus is not a sealed room. But the wellhead growth in deepwater wells is more complex considering that every casing and annulus do contribution to the wellhead growth. Table 2 shows that, the axial forces caused by the APB are larger than the axial forces caused by casings.
Figure 3 presents the ratio of the axial forces caused by every casing and annulus. The total ratio of the forces caused by the APB reaches about 80% in this deepwater well. Thus, the axial forces caused by the APB are the major factors of wellhead growth. Engineers should mitigate APB to avoid the wellhead growth in deepwater wells. Many methods have been proposed and validated by previous studies to mitigate APB, such as the open shoe, compressible spacer, rupture disk and thermal-insulating casing et al. [15, 16]. A deepwater well should adopt these methods according to its in-situ conditions.

Figure 4 presents the wellhead growth varying with APB. The height of wellhead growth decreases with the decrease of the total APB in annulus. When APB is alleviated to about 30%, the wellhead growth decreases to zero, meaning that the wellhead doesn’t move and the wellbore is safe.

3.3. Analysis of the nonlinear properties

Compared with the published models, the new model in this paper considers the mechanical nonlinear properties of material. As the previous studies did, this work also estimates the wellhead growth by ignoring the nonlinear properties. Results show that wellhead in figure 1 moves upward 5.11 cm if the nonlinear properties are ignored. The result of ignoring the nonlinear properties is smaller than the result of considering the nonlinear properties. And, the relative errors between the two results are larger than 30%. So, in this deepwater well, ignoring the nonlinear properties could lead to unacceptable errors.

Deepwater wells may confront more severe conditions, such as higher geothermal gradient, and deeper well depth. The severe conditions could bring more heat in the wellbore. Figures 5 and 6 present the influence of geothermal gradient and well depth on the wellhead growth. The black lines denote the wellhead growth considering the nonlinear properties of material; the red lines are the wellhead growth ignoring the nonlinear properties.

When the geothermal gradient and well depth are small, the wellhead growth of the new model (considering the nonlinear properties) and published model (ignoring the nonlinear properties) are close. But, with the increase of geothermal gradient and well depth, the discrepancies between the two methods become larger. These phenomena are induced by the heat brought by the geothermal gradient and well depth. When the geothermal gradient is higher and the well depth is deeper, the increase of wellbore temperature leads to the considerable errors between the two models. In the worst case, the relative errors between the two models are larger than 30%, which is unacceptable in engineering. So, it’s necessary to consider the nonlinear properties of material for the purpose of accurate prediction.
4. Conclusions and suggestions
In deepwater wells, the wellhead growth may happen because of the loadings caused by the thermal expansion of annular fluid and casing. The axial force caused by the APB dominates the wellhead growth. So, the APB should be mitigated to alleviate the wellhead growth. In the presented case study, wellhead will not move upward if the annular pressure decreases to 30%. When a deepwater well confronts high temperature conditions, such as higher geothermal gradient and deeper well depth, the mechanical nonlinear properties of material can’t be ignored to accurately estimate the wellhead growth because the errors may up to 30% which is unacceptable in engineering.

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