Annular Pressure-Volume Interaction Analysis for HPHT Well Based on Multi-scale

Lihu Cao¹, Yihua Dou²*, Kelin Wang¹, Shuai Xue³, Hailong Geng¹

¹Tarim Oilfield Company, PetroChina, Korla, 841000, China
²Xi’an Shiyou University, Shaanxi, Xi’an, 710065, China
³Institute of Technology, Shaanxi, Xi’an, 710065, China

*Corresponding author e-mail: yhdou@vip.sina.com

Abstract. Annulus pressure build-up is a potentially serious issue with high-pressure and high-temperature wells created by annuli which maybe heated up during production. Considering the mass conservation, energy conservation, and heat stability of fluid, the pressure-volume interaction models of multi-scale annulus are established based on PVT and the matrix of micro-annular temperature fields. Results indicate that the pressure-volume interaction moves the balance point of adjacent annulus early, which is a potentially serious issue for well integrity. The relationship between annulus temperature and pressure is linear. Moreover, at the same production, annulus pressure rapidly rises as the temperature increases, and the change rate of temperature increases at a negative exponential function. After the same production time, the relationship among temperature, pressure, and production is a quadratic function.

1. Introduction

The structure of the high pressure and high temperature (HPHT) well with more than one annulus is complex. The pressures of annulus between tubing and production casing or production casing and intermediate casing increase as the wellbore temperature increases in the production process [1]. The pressures of annulus were difficult to accurately control, resulting in negative effects on the safety of casings.

J. Yang, et al. [2] analyzed the casing annulus temperature change during production and predicted the annulus pressure on the basis of the relationship between the casing annulus pressure and volume. D.Gao, et al. [3] considered the influence of temperature on the thermodynamic parameters of annulus liquids, and the trend of annulus pressure with temperature was obtained. B. Zhang, et al. [4] established a wellbore heat transfer model and predicted the trend of annulus pressure in accordance with the principle of volume compatibility, and R. Williamson, et al. [5] ignored the radial deformation of the casing under pressure and analyzed the relationship between a one casing annulus pressure and temperature. U.B. Sathuvalli, et al. [6] considered the influence of the proportion of components in the annulus fluid on the thermodynamic parameters, analyzed the relationship between the annulus pressure and volume, and obtained the numerical calculation method to predict the annulus pressure. P. Oudemam, et al. [7] analyzed the test data and considered that the variation in the annulus pressure is proportional to the amount of temperature changed. S.P. Wang, et al. [8] established a calculation method for the annulus injection volume based on the principle of volume compatibility. A.R. Hasan, et al. [9]
established a wellbore heat transfer model and proposed an evaluation method for annulus pressure and volume under temperature. X.L. Huang, et al. [10] considered the casing strain caused by annulus pressure, analyzed the influence of the fluid flow rate and other factors on annulus pressure, and preferred the annulus pressure prevention countermeasures. L.Ding, et al. [11] aimed to solve the problem of changes in the annulus pressure in the lower part under packer during the horizontal well fracturing process by considering the pressure-volume change of the annulus and the ballooning effect of the tubing; thus, the prediction model of the lower annulus pressure of the tail casing hanger is established, and the tubing strength safety factor is obtained. B.L. Zhang et al. [12] compared the existing two annulus pressure prediction models and concluded that the pressure prediction model based on state equation and temperature-pressure coupled iterative calculation is more suitable for deep sea wells.

The multi-scale annulus pressure-volume two-way interaction numerical calculation program compiled by MATLAB is used in this paper to analyze the influence of production and production time factors on annulus pressure. The variation trend of each annulus pressure and volume under different production and time conditions is obtained.

2. Discrete annulus and analysis of micro-scale annulus temperature field

As shown in Figure 1, Combined with the structural characteristics of HTHP wells, a semi-transient heat transfer model of the wellbore is established, and the distribution law of micro-scale annulus temperature field is analyzed [13].

The micro-scale annulus is numbered, and the volume of the discrete micro-scale annulus is defined as \( V(i, j) \). \( i \) is the radial number of the micro-scale annulus, and \( j \) is the axial number of the micro-scale annulus. A small-scale annulus position can be determined by \( i \) and \( j \).

The heat transfer \( q \) of the fluid micro-component \( dz \) per unit length of the tubing can be expressed as follows:

\[
-q\Delta z = Wc(T_{z+\Delta z} - T_z)
\]

(1)

where \( q \) is the heat transferred by the unit length of fluid to the formation, \( J/(m) \); \( W \) is the mass flow rate of the fluid, \( kg/s \); and \( c \) is the specific heat capacity of the fluid, \( J/(kg\cdot^\circ C) \).

When \( \Delta z \) moves toward 0, the differential equation of the axial temperature distribution of the wellbore can be expressed as

\[
\frac{dT}{dz} + \frac{T}{A} - \frac{T_w - T_f}{A} = 0
\]

(2)
where the coefficient \( A = \frac{W_c \left[ f(t) + 2 \pi \lambda_d \sum_{n=0} \frac{R_n}{n} \right]}{2 \pi \lambda_d} \); and \( T_o \) is the bottom temperature of the well, °C.

By solving Eq. 2, the wellbore temperature with well depth distribution function is:

\[
T_i = T_o - g_d(z - A) + Be^{-\frac{z}{A}}
\]  

where the coefficient \( B \) is determined by the axial temperature boundary condition of the wellbore; and \( g_d \) is the geothermal gradient, °C/m.

3. Micro-scale annulus pressure and volume calculation

By considering the expansion and compressibility of the annulus fluid, the variation laws of the micro-scale annulus pressure and volume of the temperature field well are analyzed.

3.1. Micro-scale annulus pressure calculation

Considering the influence of the non-uniform distribution of the annulus temperature on annulus pressure, the matrix expression of the micro-scale annulus pressure field under the action of the temperature field is

\[
\begin{pmatrix}
\Delta p(1,1) & \Delta p(i,1) \\
M_{ij} & M_{ij} & M_{ij} & M_{ij} \\
\Delta p(1,j) & \Delta p(i,j)
\end{pmatrix}
= \frac{\alpha}{\kappa} \left[ \begin{pmatrix}
\Delta T(1,1) & \Delta T(i,1) \\
M_{ij} & M_{ij} & M_{ij} & M_{ij} \\
\Delta T(1,j) & \Delta T(i,j)
\end{pmatrix} \right] - \frac{1}{\kappa V_f} \Delta V_f
\]

As shown in Eq. 6, under the action of radial temperature gradient, the micro-scale annulus pressure changes at the same depth vary, which destroys the steady state of the annulus pressure and causes the fluid density in the annulus to change [15]. With the increase in time, the annulus pressure demonstrates a new steady state again. To reasonably evaluate the temperature change of the annulus fluid in accordance with the conservation of fluid energy and mass before and after the steady state, the equivalent temperature \( \Delta T_a \) of the annulus is introduced as

\[
\Delta T_a = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} Q(i,j)}{c_w \sum_{i=1}^{n} \sum_{j=1}^{m} m(i,j)}
\]

where \( \Delta T_a \) is the equivalent temperature of the annulus, °C; \( Q(i,j) \) is the heat of the micro element, J; \( c_w \) is the specific heat capacity of the annulus liquid, J/(kg⋅°C); and \( m(i,j) \) is the mass of the unit, kg.

By replacing the temperature field matrix with the annulus equivalent temperature \( \Delta T_a \), we can simplify the calculation formula of the micro-scale annulus pressure under temperature as follows:

\[
\Delta p = \frac{\alpha}{\kappa} \Delta T_a - \frac{1}{\kappa V_f} \Delta V_f
\]

3.2. Micro-scale annulus volume calculation

With the dispersion of the annulus volume, the volume field of the micro-scale annulus is

\[
V_{vol} = \begin{pmatrix}
V_f(1,1) & \cdots & V_f(i,1) \\
\vdots & \ddots & \vdots \\
V_f(1,j) & \cdots & V_f(i,j)
\end{pmatrix}
\]
Through the principle of conservation of volume, the discrete micro-scale annulus volume satisfies the following expression:

$$V_f = \sum_{i=1}^{n} \sum_{j=1}^{m} V_f(i, j)$$

where $V_f$ is the total volume of the annulus, m$^3$; and $V_f(i, j)$ is the micro-scale annulus volume, m$^3$.

4. Macroscopic annulus pressure-volume two-way interaction analysis

The HPHT well exhibits a multi-layered cylindrical nested structure, and a plurality of annulus forms a stable pressure-volume system. When the pressure volume of a single annulus changes, the steady state of the entire annulus system is disturbed and causes changes in other annulus pressure volumes.

At the macroscopic scale, a single annulus simultaneously withstands internal and external pressure. The sleeve is an elastic material that is radially deformed by internal and external pressure, causing a change in the annulus volume. Considering the effect of temperature on the axial deformation of the casing, the annulus volume increment under the action of internal and external pressure can be expressed via elastic mechanics [16]:

$$\Delta V = \frac{(1 + \mu) \pi L}{2E} \left[ d_1^2 \frac{(1-2\mu)d_2^2 D_1 + d_1^2 D_2}{2(D_1^2 - d_1^2)} \Delta p_{1o} - \frac{(1-2\mu)d_2^2 D_1 + d_1^2 D_2}{2(D_1^2 - d_1^2)} \Delta p_{2o} \right] + \frac{\pi}{4} (d_2^2 - d_1^2) \Delta L$$

where $\mu$ is Poisson’s ratio of the casing material, dimensionless; $E$ is the elastic modulus of the casing material, Pa; $d_1$ is the inner diameter of the inner casing of the annulus, m; $d_2$ is the inner diameter of the outer casing of the annulus, m; $D_1$ is the outer diameter of the annulus inner casing, m; $D_2$ is the outer diameter of the annulus inner casing, m; $p_{1o}$ is the outer casing outer pressure of the annulus, Pa; $p_{1i}$ is the annulus inner casing In -pipe pressure, Pa; $p_{2o}$ is the outer pressure of the outer sleeve of the annulus, Pa; and $p_{2i}$ is the inner pressure of the inner casing of the annulus, Pa.

Considering the thermal expansion of the axial line of the casing under the action of temperature, the amount of linear expansion of the casing material under temperature can be expressed as

$$\Delta L = \int_0^H \alpha_s \Delta T(H) dL$$

where $\alpha_s$ is the coefficient of linear expansion of the casing material, m/$^\circ C$.

The iterative expression of multiple annulus pressure-volume two-way interaction at the macroscopic scale is

$$\Delta p_n = \alpha_n \Delta T_{na} - \frac{1}{\kappa V_{ns}} \Delta V_{ns}$$

where $\Delta p_n$ is the nth annulus pressure change, Pa; $\Delta T_{na}$ is the nth annulus equivalent temperature, $^\circ C$; $\Delta V_{ns}$ is the nth annulus pressure change, m$^3$; and $V_{ns}$ is the nth annulus volume, m$^3$.

The multi-scale annulus pressure-volume interaction numerical calculation program compiled by MATLAB is used to analyze the variation trend of multiple annulus pressure-volume interaction under the action of temperature field.

5. Case analysis of annulus pressure-volume interaction under multi-scale action

The parameters of the literature [4] are selected based on the multi-scale annulus pressure-volume interaction model. The multi-scale annulus pressure-volume interaction calculation program compiled by MATLAB is used to analyze the micro-scale annulus temperature field and annulus pressure under
multi-scale action. The temperature field, annulus pressure, and volume change of the wellbore and annulus are calculated when the well production is 120t/d.

![Wellbore average temperature distribution curve](image1)

![A annulus field temperature](image2)

![B annulus field temperature](image3)

![C annulus field temperature](image4)

**Figure 2.** Wellbore temperature and A, B, C annulus field temperatures

The temperature field of the wellbore and annulus is shown in Figure 2. Figure 2(a) shows the variation trend of the effective temperature of the wellbore and annulus with the depth of the well. As the fluid flows from the bottom to the inlet, the temperature of the fluid decreases. The larger the volume, the higher the heat flux density in the upper part of the annulus. Figure 2(b), 2(c), and 2(d) are the temperature fields of the A, B, and C annulus at production 120t/d, respectively.

6. Correlation analysis of influencing factors of annulus pressure under multi-scale action

On the basis of the established multi-scale annulus pressure-volume interaction model and the multi-scale annulus pressure-volume interaction algorithm, the correlation between production and time influencing factors, annulus temperature, and pressure is analyzed. To establish a reasonable production system, the annulus temperature and pressure must be controlled to ensure the integrity of the wellbore throughout the life cycle and provide a reference basis [17,18].

For the annulus pressure, when the production time is less than 26 days, the annulus pressure rises rapidly with the increase in temperature due to the effect of the annulus liquid temperature. The A annulus pressure is the largest, followed by the B annulus pressure; the C annulus pressure is the lowest of the three. From 28 days to 110 days, the A annulus pressure is less than the B annulus, and the rise in the A annulus pressure is lower than that of the B and C annulus. The pressure-volume interaction effect occurs between the annulus, which slows down the A annulus pressure rise rate. After 110 days, the
temperature of the A, B, and C annulus is stable, and the pressure-volume interaction effect between the annulus is also stable. The pressure of the B annulus is the largest at 45.3 MPa, the C annulus pressure is 44.3 MPa, and the minimum pressure of the A annulus is 41.5 MPa.

(a) Relationship between production time and annulus pressure in conventional models

![Graph of annulus pressure versus production time in conventional models.]

(b) Relationship between production time and annulus pressure under multi-scale interaction effect

![Graph of annulus pressure versus production time with multi-scale interaction effect.]

Figure 3. Relationship between production time and annulus pressure at 120t/day

A comparison of the multi-scale interaction effect (a) and the conventional model with (b) the annulus pressure prediction values (Figure 3) demonstrates that the adjacent annulus pressure equilibrium points change from a (27 days) and b (177 days) points to a' (26) Days, b' (110 days) points, and the multi-scale interaction effect significantly reduce the predicted value of the conventional model by about 10%.

7. Conclusion
(1) Predicted annulus pressure of the multi-scale interaction effect is 10%-16% smaller than the conventional model. Risk of wellbore integrity damage increases during the initial stage of production.
(2) The annulus pressure and annulus effective temperature change are basically linear. The annulus temperature determines the trend of the annulus pressure, but multi-scale interaction determines the order of the annulus size.
(3) The single-factor control variable method is adopted, and only the multi-scale annulus pressure volume interaction effect under fixed production and time is studied. When the production and production time change simultaneously, the variation law of the annulus pressure needs further study.

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