



Original Paper

# Study on prediction of annular trap pressure in ultra-high temperature and high pressure gas wells

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ABSTRACT

Accurate calculation of annular trap pressure in ultra-high-temperature and high-pressure (UHTHP) wells is crucial for ensuring the safety and integrity of tubular systems. Existing annular pressure prediction models often fall short due to inadequate consideration of key factors, resulting in reduced accuracy and, consequently, unreliable predictions for tubular safety assessments. This paper examines the underlying mechanisms of annular trap pressure in UHTHP wells and proposes a multi-annular pressure prediction model grounded in the compatibility principle. A gas-liquid two-phase multi-annular pressure coupling model is also developed, incorporating nitrogen injection into the A annulus and utilizing the BWSR equation of state to enhance the model's accuracy. Additionally, a pressure prediction model for the annular space between dual packers is introduced, building upon the multi-annular pressure prediction framework. The results demonstrate that the proposed multi-annular pressure model significantly improves the accuracy of APB predictions for UHTHP gas wells. The findings provide valuable theoretical insights and practical guidance, facilitating more precise prediction of annular trap pressure in extreme downhole conditions and offering essential support for safe operations in these challenging environments.

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1. Introduction

As the global demand for oil and gas resources continues to rise, an increasing number of ultra-high-temperature and high-pressure (UHTHP) gas wells are being brought into production. These wells operate under more complex conditions, making the prediction of annular trap pressure critical for ensuring wellbore stability, optimizing extraction efficiency, and minimizing operational risks. Annular pressure variation is influenced not only by environmental factors such as temperature and pressure but also by the interactions between liquids and gases within the wellbore, the mechanical behavior of the tubular system, and the thermo-physical properties of the liquids. Therefore, accurately predicting

annular trap pressure is essential for the effective design and safe operation of HP/HT gas wells.

Traditional models for predicting annular trap pressure have several limitations. Single-annulus models often overlook the dynamic interactions between multiple annuli, resulting in inaccurate pressure predictions under complex well conditions. Non-coupled models fail to account for the thermo-hydraulic-mechanical (THM) coupling effects, which are particularly significant in ultra-high-temperature and high-pressure (HPHT) wells, where thermal expansion, liquid compressibility, and phase changes play a crucial role in annular pressure evolution. In contrast, our proposed model introduces a fully coupled multi-annulus pressure prediction framework that incorporates detailed thermodynamic properties of gas-liquid mixtures, accounts for liquid compressibility, and simulates THM interactions across concentric annuli. This approach improves predictive accuracy and expands the model's applicability to deep HPHT wells.

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In previous studies, researchers have extensively investigated the prediction of annular trap pressure. Early research primarily focused on annular pressure models under conventional temperature and pressure conditions, where simplified models were developed by analyzing the single-phase behavior of liquids and gases in response to temperature and pressure variations. To address the increase in annular pressure and its impact on casing thermal stress, [Adams and Maceachran \(1994\)](#) established an estimation method, while [Halal and Mitchell \(1994\)](#) developed a numerical model for analyzing liquid density and volume changes using the P-V-T equation, and [Gao \(2002\)](#) employed a matrix algorithm to account for casing deformation in both the sealed and free sections of the tubing, establishing a model for predicting annulus closure pressure. [Oudeman and Kerem \(2006\)](#) developed an annular trap pressure prediction model, highlighting the impact of liquid temperature, annular volume, and liquid quality, while [Deng et al. \(2006\)](#) enhanced the accuracy of the model by applying an iterative method for more systematic and precise calculations. [Yang et al. \(2013\)](#) established a prediction model for casing annulus pressure increase in deepwater environments. [Zhang et al. \(2015a, 2015b, 2016, 2018\)](#) calculated annular trap pressure based on the volume compatibility principle and analyzed the effects of fluid thermal conductivity, thermal expansion coefficient, compressibility coefficient, temperature, and production time on annular pressure. [Dou et al. \(2016\)](#) developed a multi-annular trap pressure prediction model that incorporates the effects of annular liquid temperature, pressure, and casing elastic deformation on the annular liquid volume. [Zhang \(2017\)](#) improved the annulus closure pressure prediction model by calculating closure pressures for multiple annuli and double packers using well sectioning. [Zhang and Wang \(2017\)](#) investigated the interaction between annular trap pressure and cement sheath and demonstrated that higher annular pressure increases the risk of cement sheath damage. [Wu et al. \(2018\)](#) solved annular pressure using the Newton downhill method based on deepwater wellbore structure and heat-transfer processes. [Xu \(2019\)](#) refitted the isothermal compression and isobaric expansion coefficients to re-establish the annular trap pressure prediction model. [Zhang et al. \(2021\)](#) examined the influence of oil-pipe deformation under temperature and pressure on the closed annulus and predicted annulus closure pressure between double packers. [Sun et al. \(2020, 2024a, 2024b\)](#) and [Zhang et al. \(2024a, 2024b, 2024c\)](#) advanced the understanding of drilling operations by revealing the rock-breaking mechanisms of PDC cutters, liquid-flow dynamics through vibrating screens, gas invasion behavior in fractured reservoirs, and multiphase-flow temperature prediction models. [Jing et al. \(2025\)](#) conducted a safety-risk analysis of well control in wells

compresses the liquid, reducing its volume and thereby decreasing the annular trap pressure. Similarly, an increase in casing temperature causes casing expansion, which reduces the annular volume, leading to an increase in annular trap pressure. Although the expansion of the annular volume cannot fully balance the volume expansion of the liquid, it results in an overall increase in annular trap pressure.

Based on the analysis of the mechanism behind the increase in annular trap pressure, the partial differential form of the annular trap pressure increase calculation model (Oudeman and Bacarreza, 1995; Liu et al., 2015) is as follows:

$$\Delta = \left(\frac{\partial}{\partial T}\right)\Delta + \left(\frac{\partial}{\partial p_{an}}\right)\Delta_{an} + \left(\frac{\partial}{\partial V_l}\right)\Delta \quad (1)$$

The temperature effect on liquid volume:

$$\alpha_l = \frac{\Delta}{\cdot \Delta} \quad (2)$$

The pressure effect on liquid volume:

$$= \frac{\Delta}{\cdot \Delta} \quad (3)$$

Annular trap pressure increase formula:

$$\Delta = \alpha_l \Delta - \frac{1}{\alpha_n} \Delta_{an} + \frac{1}{\alpha_l} \Delta_l \quad (4)$$

In the formula:

- $\alpha_l$ —the liquid's thermal expansion coefficient, 1/°C;
- $\alpha_n$ —the liquid's isothermal compressibility coefficient, 1/MPa;
- $\Delta$ —the temperature change of the liquid, °C;
- $\Delta_{an}$ —the increase in annular trap pressure, MPa;
- $\Delta_{an}$ —the total change in annular volume, m<sup>3</sup>;
- $\Delta_l$ —the change in the volume of the annular liquid, m<sup>3</sup>.

Assuming that the annular space is sealed, with no inflow or outflow of annular liquid, the entire process of increasing annular trap pressure can be regarded as a combination of two processes: a constant-pressure thermal expansion process due to temperature rise and an isothermal compression process due to pressure change. Therefore, the integral formula for the annular trap pressure increase is given by:

$$\int \alpha_l dT - \int \frac{1}{\alpha_n} dp_{an} = \int \frac{1}{\alpha_l} dV_l \quad (5)$$

In the formula:

- $V_l$ —the volume of the liquid under constant-pressure thermal expansion, m<sup>3</sup>;
- $V_l$ —the volume of the liquid under isothermal compression, m<sup>3</sup>.

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The annular liquid volume refers to the volume of liquid in the annulus that changes due to variations in temperature and pressure. According to Eq. (5), it is evident that both  $\alpha$  and  $V_l$  are key factors influencing the annular liquid volume. The partial differential calculation formula is given by:

$$\alpha = \frac{1}{V_l} \left( \frac{\partial V_l}{\partial T} \right) = \frac{1}{V_m} \left( \frac{\partial V_m}{\partial T} \right) \quad (6)$$

$$= -\frac{1}{V_m} \left( \frac{\partial V_m}{\partial p_m} \right) = -\frac{1}{V_m} \left( \frac{\partial V_m}{\partial p_m} \right) \quad (7)$$

In the formula:

- $\alpha$ —the isobaric expansion coefficient, 1/MPa;
- $V_m$ —the molar volume of the annular liquid, m<sup>3</sup>/mol.

In order to more accurately obtain the volume change of the annular liquid due to thermal expansion, the best fitting isothermal compression coefficient and isobaric expansion coefficient (Yin and Gao, 2014) are used, and the calculation formula is:

$$\alpha = \frac{Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8}{1 + Z_7 + Z_8} \quad (8)$$

$$= \frac{1 + c_2 + c_3 + c_4}{1 + c_5 + c_6 + c_7} \quad (9)$$

Due to the significant variation in axial temperature distribution in high-temperature, high-pressure gas wells, previous methods that averaged the temperature changes across the entire annulus to calculate liquid volume changes introduced substantial errors. These methods did not accurately calculate the annular liquid volume and failed to account for the changes in thermo-physical properties caused by temperature and pressure fluctuations. To obtain a more precise estimation of the annular liquid volume, the annulus is discretized into small segments, and the liquid volume change within each segment is calculated. The sum of these individual segment changes gives the total annular liquid volume change. By substituting the fitted Eqs. (8) and (9) into Eq. (5), the final volume change of the annular liquid for each segment can be expressed as:

$$V_l = e^{(\alpha_l \Delta T - \frac{1}{\alpha_n} \Delta p_{an})} V_{l,ini} \quad (10)$$

$$\Delta V_l = e^{(\alpha_l \Delta T - \frac{1}{\alpha_n} \Delta p_{an})} V_{l,ini} - V_{l,ini} \quad (11)$$

In the formula:

- $V_{l,ini}$ —the annular liquid volume under certain temperature and

$$2 = \frac{1}{6Z_7^4} * \left( \begin{aligned} &6Z_2 \ 2Z_7^3 + 3Z_3 \ 2Z_7^3 + 2Z_4 \ 2Z_7^3 - 6Z_3 \ 2Z_7^2(1 + Z_8 \ 2) - 3Z_4 * \\ &2Z_7^2(1 + Z_8 \ 2) + 6Z_4 \ 2Z_7(1 + Z_8 \ 2)^2 - 6 \ln(1 + Z_7 \ 2 + Z_8 \ 2) * \\ &[Z_4(1 + Z_8 \ 2)^3 + Z_2Z_7^2(1 + Z_8 \ 2) - Z_3Z_7(1 + Z_8 \ 2)^2] \end{aligned} \right) \tag{13}$$

In the formula:

- 1—the annulus temperature before production, °C;
- 2—the annulus temperature during production, °C;
- 1—the annulus pressure before production, MPa;
- 2—the annulus pressure during production, MPa.

• 1 and • 2 are the integrals of the isothermal compressibility fitting formula:

$$\bullet_1 = \frac{c}{2} \frac{4}{7} \ln \left( \frac{2}{c} \frac{c}{7} \frac{6}{1} + \frac{1+c}{c} \frac{5}{7} \frac{2}{2} \right) + \frac{2}{c} \frac{7}{c} \left( \frac{1+c}{c} \frac{2}{2} \frac{2+c}{c} \frac{3}{2} \frac{2}{2} \right) \frac{c}{c} \frac{4}{c} \frac{6}{c} * \frac{2}{\sqrt{4(1+c/5)2/c} \ 7} * \arctan \left( \frac{2}{\sqrt{4(1+c/5)2/c} \ 7} \right) \tag{14}$$

$$\bullet_2 = \frac{c}{2} \frac{4}{7} \ln \left( \frac{2}{c} \frac{c}{7} \frac{6}{2} + \frac{1+c}{c} \frac{5}{7} \frac{2}{2} \right) + \frac{2}{c} \frac{7}{c} \left( \frac{1+c}{c} \frac{2}{2} \frac{2+c}{c} \frac{3}{2} \frac{2}{2} \right) \frac{c}{c} \frac{4}{c} \frac{6}{c} * \frac{2}{\sqrt{4(1+c/5)2/c} \ 7} * \arctan \left( \frac{2}{\sqrt{4(1+c/5)2/c} \ 7} \right) \tag{15}$$

The above formula can be used to calculate the annular liquid volume  $V_{1A}$ ,  $V_{1B}$ ,  $V_{1C}$  of A, B, and C under different conditions for A, B, and C. To account for non-Newtonian liquid behavior, we propose modifying the liquid volume calculation models to include rheological properties. The liquid volume change equations (Eqs. (6-14)) will be expanded to incorporate viscosity functions that are dependent on shear rate and other rheological parameters. Additionally, constitutive equations for non-Newtonian fluids, such as the Power-Law model or the Herschel-Bulkley model, will be considered to enhance the model's accuracy in describing viscous or contaminated fluids.

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The annular volume refers to the volume of the enclosed space formed by the inner and outer tubing. The variation in annular volume is primarily caused by thermal expansion due to temperature changes, the bulging effect induced by radial compression of the tubing, axial forces causing radial displacement, and radial displacements at the cemented section.

(1) Radial displacement due to temperature variations in the free section of the tubing:

$$1 = (1 + 2\mu) \alpha \ \Delta \tag{16}$$

In the formula:

- $\alpha$  —the thermal expansion coefficient of the pipe string, 1/°C;
- $\mu$  —the Poisson's ratio of the pipe string, dimensionless;
- $r$  —the radius of the calculation point of the pipe string, m;

$\Delta$  —the temperature change of the pipe string, °C.

(2) Radial displacement due to annular pressure

When the annular pressure increases, the liquid in the annulus exerts pressure on the outer and inner casings, causing the annular volume to expand. This results in the compression of the outer casing and the bulging of the inner casing, as shown in Fig. 2.

The calculation formula for this effect is given by:

$$2 = \frac{1 + \mu}{2} \left[ \frac{2}{i} \frac{2}{o} + \frac{(1 - 2\mu)}{i} \frac{2}{i} \frac{2}{i} \right] i - \frac{2}{i} \frac{2}{o} + \frac{(1 - 2\mu)}{i} \frac{2}{o} \frac{2}{o} \tag{17}$$

In the formula:

- $E$  —the elastic modulus of the tubing, MPA;
- $i$  —the internal pressure of the tubing, MPA;
- $o$  —the external pressure of the tubing, MPA;
- $i$  —the inner diameter of the tubing, m;
- $o$  —the outer diameter of the tubing, m.

(3) Radial displacement caused by axial force:

$$3 = \mu \alpha \Delta \frac{2\mu^2 \left( \frac{2}{i} \Delta \ i - \frac{2}{o} \Delta \ o \right)}{\left( \frac{2}{o} - \frac{2}{i} \right)} \tag{18}$$

(4) Radial displacement of sealing section:

$$4 = - \frac{i(1 + \mu)}{2} \left[ (1 - \mu) + \mu \frac{+1 -}{-1 +} \right] \Delta \ + (1 + \mu) \ i \alpha \Delta \tag{19}$$

In the formula:

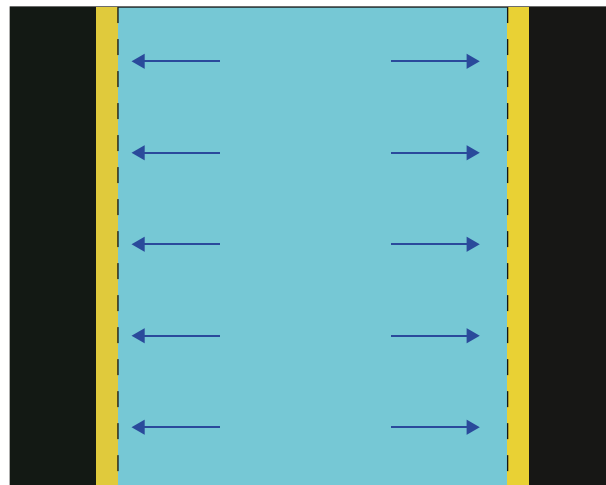


Fig. 2. Diagram of column radial displacement caused by annulus pressure.



$$B_6 = -\frac{ci_2(1+\mu)}{(1-\mu)+\mu\frac{+1-}{-1+}} \Delta B + (1+\mu) ci_2 \alpha \Delta_2 \quad \Delta B = \Delta_{B-f} + \Delta_{B-s} \quad (38)$$

(35)

In the formula:

$\Delta_2$ —the temperature change of the casing, °C.  
Then the volume change of annulus B is:

$$\Delta_{B-f} = \pi_3 \left( (ci_2 + B_3 + B_5)^2 - (co_1 + B_1 + B_2 + B_4)^2 - (ci_2^2 - co^2) \right) \quad (36)$$

$$\Delta_{B-s} = \pi_3 \left( (ci_2 + B_6)^2 - (co_1 + B_1 + B_2 + B_4)^2 - (ci_2^2 - co^2) \right) \quad (37)$$

When the temperature is , the volume of annulus B is:

$$B = B_{-f} + B_{-s} \quad (39)$$

In the formula:

- $l_3$ —the length of B annulus, m.
  - $\Delta_{B-f}$ —the change in volume of the free segment of the B-shaped annulus;
  - $\Delta_{B-s}$ —the change in annular volume of B-annular sealed section;
  - $B_{-f}$ —the volume of the free segment of the B-annulus at temperature ;
  - $B_{-s}$ —the volume of the annulus in the sealed section B at temperature ;
  - $B$ —the volume of B-annulus at temperature .
- C annulus volume calculation model:  
The radial displacement of the technical casing affected by temperature is:

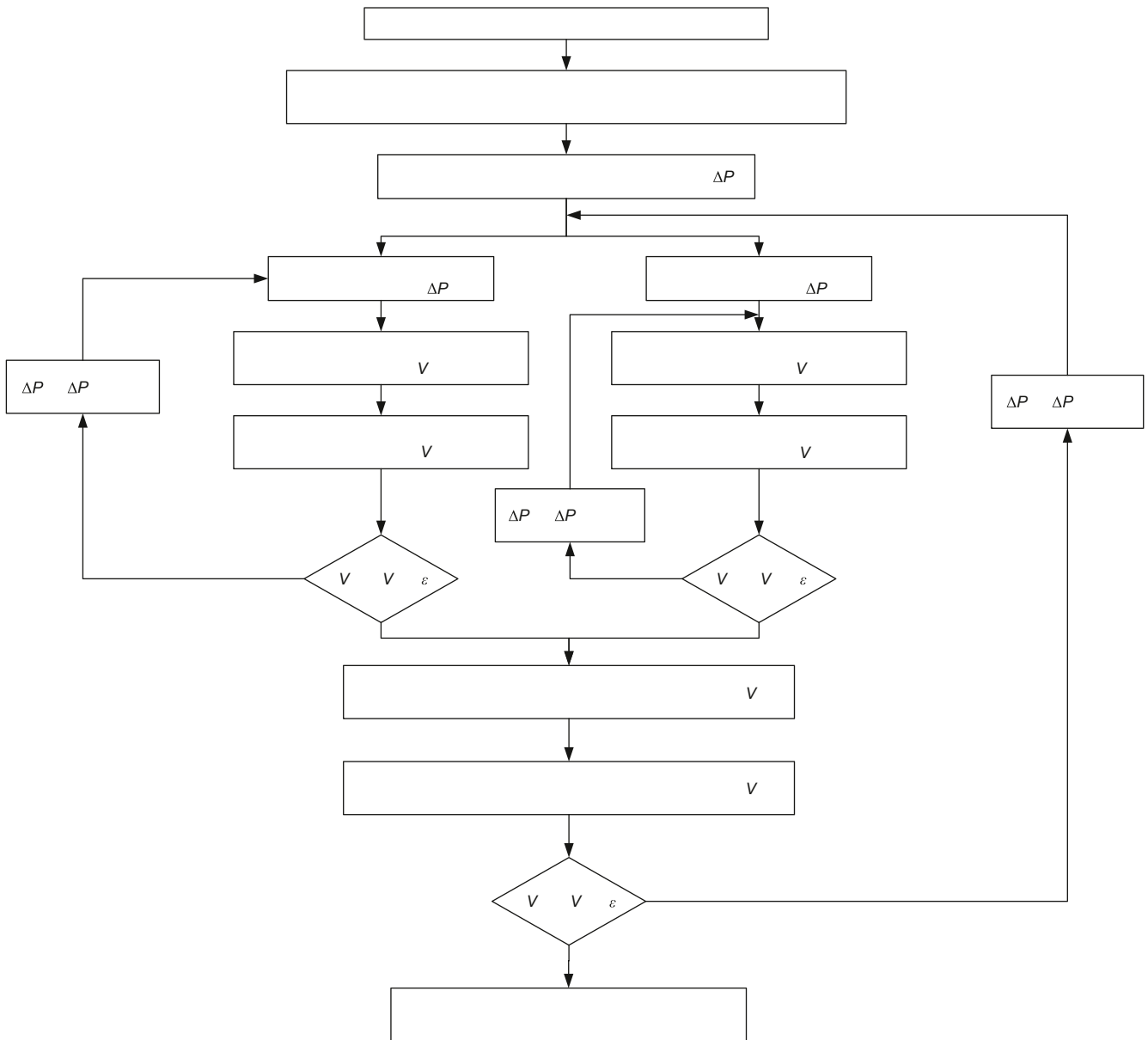


Fig. 3. Multi-annulus pressure calculation flow chart.  
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$$c_1 = (1 + 2\mu) \alpha_{co2} \Delta_2 \quad (40)$$

Radial displacement of technical casing caused by pressure:

$$c_2 = \frac{1 + \mu}{\left( \frac{2}{co2} - \frac{2}{ci2} \right)} \left[ \frac{ci2^2}{co2^2} + (1 - 2\mu) \frac{ci2^3}{ci2} \Delta_B - \frac{ci2^2}{co2^2} + (1 - 2\mu) \frac{ci2^2}{co2} \Delta_C \right] \quad (41)$$

The radial displacement of the outer wall of the technical casing caused by the axial force:

$$c_3 = \mu \alpha_{co2} \Delta_2 - \frac{2\mu^2 \left( \frac{2}{ci2} \Delta_B - \frac{2}{co2} \Delta_C \right)}{\left( \frac{2}{co2} - \frac{2}{ci2} \right)} \quad (42)$$

Radial displacement of sealing section:

$$c_4 = - \frac{ci3(1 + \mu)}{\left[ (1 - \mu) + \mu \frac{+1 -}{-1 +} \right]} \Delta_C + (1 + \mu) ci3 \alpha_{ci3} \Delta_3 \quad (43)$$

In the formula:

$\Delta_3$ —the temperature change of the surface casing, °C.

Then the volume change of annulus C is:

$$\Delta_{C,f} = \pi \left[ (ci3 + c3 + c5)^2 - (co2 + c1 + c2 + c4)^2 - (ci3^2 - \right.$$

$\Delta_g$ —the change in annulus gas volume,  $m^3$ .

The liquid volume in the annulus can be calculated by Eq. (10) and the annulus volume can be calculated by Eq. (27), so it is necessary to calculate the change in the annulus gas volume.

Compared to the ideal gas law and the Peng-Robinson (PR) equation of state, the Benedict-Webb-Rubin-Starling (BWSR) equation provides significantly improved accuracy in describing the thermodynamic behavior of real gases under high-pressure and high-temperature (HPHT) conditions. The ideal gas law assumes negligible molecular interactions and is only applicable under low-pressure, moderate-temperature regimes, which is inadequate for deep gas wells. The PR equation, although widely used in petroleum engineering for phase equilibrium calculations, tends to underestimate compressibility and density near the critical point or under extreme thermal environments.

In contrast, the BWSR equation incorporates higher-order terms to account for intermolecular forces and volume exclusions, enabling it to more accurately characterize non-ideal behavior of gas-phase mixtures at elevated temperatures and pressures. As a result, the use of the BWSR equation enhances the reliability of pressure and temperature predictions in HPHT

annular systems, particularly when liquid compressibility and real-gas effects are non-negligible.

According to the BWSR state equation, it is changed into a functional form:

$$(\rho) = \rho + \left( A_0 - 0 - \frac{0}{2} + \frac{0}{3} + \frac{0}{4} \right) \rho^2 + \left( c - Z - - \right) \rho^3 + \alpha \left( Z + - \right) \rho^6 + \frac{\rho^3}{2} \left( 1 + \gamma \rho^2 \right) e^{(-\gamma \rho^2)} - = 0 \tag{49}$$

The choice of the BWSR state equation for modeling the gas phase is justified by its ability to more accurately characterize non-ideal behavior of gas-phase mixtures at elevated temperatures and pressures compared to the ideal gas law and the PR equation. The ideal gas law assumes negligible molecular interactions and is only applicable under low-pressure, moderate-temperature regimes, which is inadequate for deep gas wells. The PR equation, although widely used in petroleum engineering for phase equilibrium calculations, tends to underestimate compressibility and density near the critical point or under extreme thermal environments. In

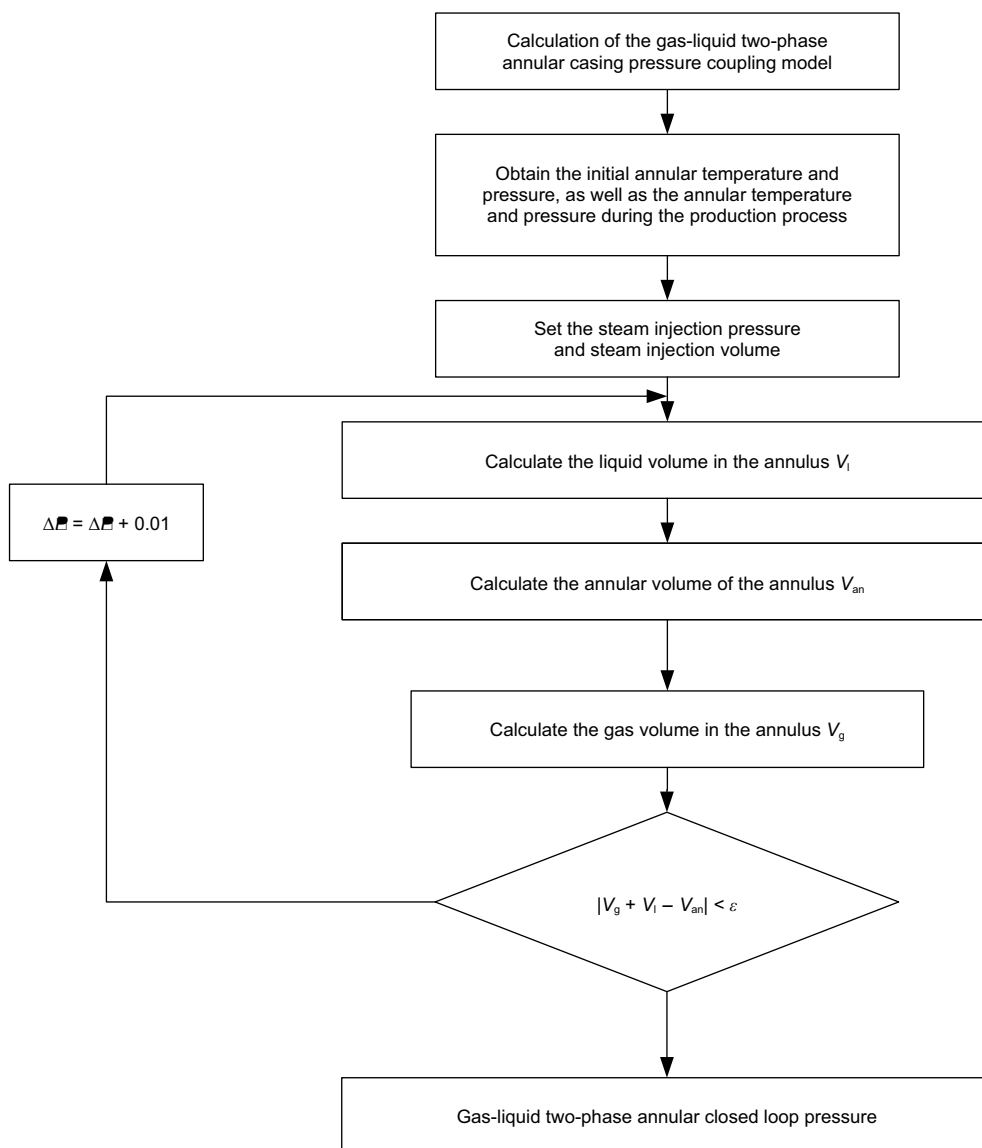


Fig. 6. Flow chart of gas-liquid two-phase annulus pressure calculation.

contrast, the BWSR equation incorporates higher-order terms to account for intermolecular forces and volume exclusions, enabling it to provide improved accuracy in describing the thermodynamic behavior of real gases under HPHT conditions.

The annular gas density is iteratively calculated using the secant method (Wang, 2023):

$$\rho_{+1} = \frac{\rho_{-1}(\rho) - \rho(\rho_{-1})}{(\rho) - (\rho_{-1})} \quad (50)$$

The initial value of the iteration is  $\rho_1 = 0$ ;  $\rho_2 = \dots$ .

Taking  $\rho_2$  as an example, the comparison between the model calculated value and the measured value is shown in Fig. 5:

The change of gas volume under the influence of annular trap pressure is:

$$\Delta g = g - \frac{\rho_1 g}{\rho_2} \quad (51)$$

In the formula:

$\rho_1$ —the initial density of the gas,  $m^3$ ;

$\rho_2$ —the final density of the gas,  $m^3$ ;

$g$ —the initial volume of the gas,  $m^3$ .

The calculation process is shown in Fig. 6:

#### 4. Calculation of annular trap pressure between double packers

The calculation model of the multi-packer annulus closed pressure is consistent with the pure liquid phase closed pressure model containing only the sealing section under the single annulus, as shown in Fig. 7. The annulus between the double packers is referred to as the annulus between the double packers, the annulus A above the production packer is the upper annulus,

and the distance between the double packers is the spacing between the double packers.

The calculation model is:

$$\Delta A_p = \pi \left( (c_i + A_6)^2 - (t_o + A_1 + A_2 + A_4)^2 - (c_i^2 - t_o^2) \right) \Delta \quad (52)$$

In the formula:

$\Delta$  —the double packer spacing, m.

The calculation process of the double packer annulus closure pressure is shown in Fig. 8:

#### 5. Case calculation

In order to verify the accuracy of the model, the annular trap pressure experimental results in the literature were used to verify the accuracy of the model in this paper. The basic parameters of the experiment are shown in Table 1:

According to the experimental basic data and size relationship, the annular trap pressure data of the three annuli A, B, and C under cementing and non-cementing conditions are compared. The results are shown in Figs. 9–11.

To provide a more comprehensive evaluation of the model's prediction accuracy, specific error indicators such as root mean square error (RMSE) and mean absolute percentage error (MAPE) were calculated and presented in Table 2. The

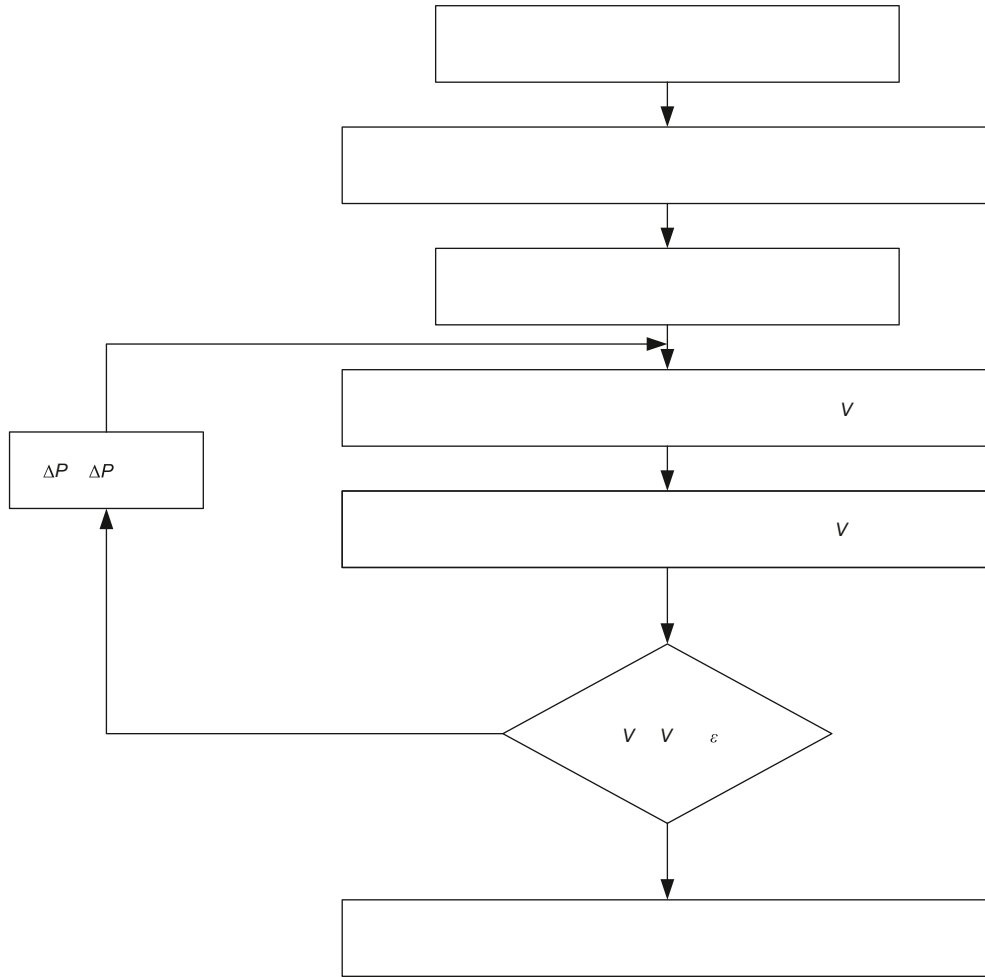


Fig. 8. Flow chart for calculation of annular pressure between packers.

Table 1  
Experimental device and initial parameters.

Device	Size, mm	Initial parameters	A annulus	B annulus	C annulus
Tubing	88.9	Uncemented temperature, °C	62	51	43
Production casing	139.7	Uncemented well pressure, MPa	0.507	0.338	0.201
Technical casing	244.4	Cementing temperature, °C	65	54	42
Surface casing	339.7	Cementing pressure, MPa	0.694	0.275	0.404

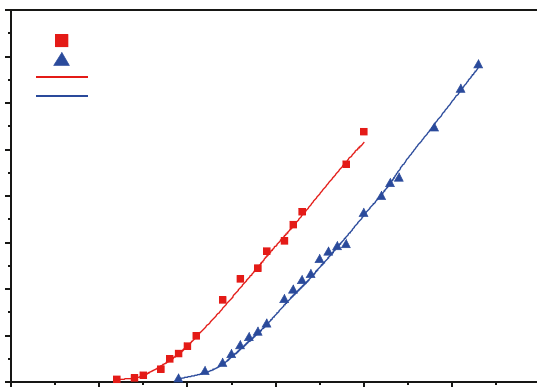


Fig. 9. Comparison of calculation data of APB model and experimental results in A annulus.

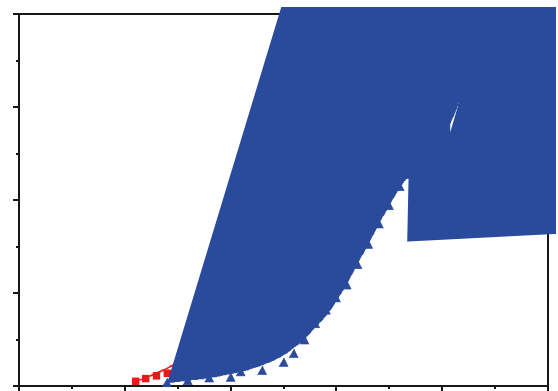


Fig. 10. Comparison of calculation data and experimental results of APB model in B annulus.

influence the objectivity, interpretation, or presentation of the research results in this paper. The research was conducted independently, and all data were collected, analyzed, and reported without any external bias.

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with the experimental data, verifying the accuracy and effectiveness of the prediction model.

## 6. Conclusion

- (1) The mechanism of annular trap pressure increase is analyzed, and a multi-annular trap pressure prediction model was established based on the compatibility principle. It is proved that the model has high accuracy.
- (2) Based on the multi-annulus trap pressure prediction model, the case of nitrogen injection in annulus A was considered, and a gas-liquid two-phase multi-annulus trap pressure coupling model was established based on the BWSR state equation.
- (3) Based on the multi-annulus trap pressure prediction model, the annulus between double packers is considered, and a trap pressure prediction model for the annulus between double packers was established.

## CRedit authorship contribution statement

**Bo-Yuan Yang:** Writing – original draft. **Hui Zhang:** Writing – review & editing. **Bao-Kang Wu:** Data curation. **Kun-Hong Lv:** Data curation. **Rui Yuan:** Methodology. **Yu-Ting Zhou:** Conceptualization. **Xing-Yu Li:** Writing – review & editing. **Ze Yang:** Methodology.

## Conflict of interest

The authors declare that they have no conflicts of interest. None of the authors has any financial or non-financial interests, such as stocks, patents, consultancies, or grants, that could potentially

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