INTRODUCTION

Marine petroleum is important fossil energy that accounts for about 34% of the total global petroleum resource. With the improvement of the exploitation technology, the production of the marine fossil resource become one of the main sources of world oil and gas production growth. Studying the engineering problems in the production of marine petroleum is of great economic significance. In the development of marine oil and gas, annular pressure buildup (APB) is an important problem that has received extensive attention. In the production of the offshore oil field, the wellbore structure is constructed with casings and cement. Annuli between the casings are isolated and sealed in most wells, as shown in Figure 1. The fluid remaining in annuli is heated when the oil and steam...
with high temperature flow in the tubing, especially in high temperature and high pressure (HPHT) wells or thermal recovery wells. Hence, the expansion of the fluid is restricted and causes pressure buildup in annuli. APB will bring additional pressure on casings. It will cause casing failure and even threaten the wellbore integrity.\textsuperscript{2,3} Furthermore, the production environment of subsea wells is limited and the cost is much higher than that of the wells on land. The accidents caused by APB usually mean great economic losses.\textsuperscript{4} Some mitigation methods were proposed to help to solve the problem but still have limits.\textsuperscript{1,5,6} Therefore, the study of the APB problem has important engineering significance. Accurate prediction of APB could provide valuable reference and guidance for the production and selection of APB control measures.

Adams et al studied annular fluid heat-up behavior by analyzing the expansion and compression of the fluid.\textsuperscript{7} Oudeman proposed a simplified model derived from the PVT equation to calculate APB in unconfined sealed annuli. It is valuable work and provides a good direction for APB studies.\textsuperscript{8,9} Yang et al derived a wellbore temperature prediction method and established an APB prediction model for deepwater wells according to the volume change of annular fluid.\textsuperscript{10} Pai et al provided valuable field test data of the temperature and pressure during flow tests in their work. The predicted results of APB and temperature were compared with the test data to make the verification.\textsuperscript{11} Zhou et al studied the mechanism and applicability of the mitigation effect of nitrogen injection in wells with APB. A model was established to calculate the APB based on the ideal gas PVT equation and volume relationship when nitrogen exists. It is concluded that APB could be controlled by injecting 5%-15% gas into annuli.\textsuperscript{12,13} Zhang et al analyzed the effect of APB on the cement sheath integrity and established a model to evaluate the safety factor of cement sheath.\textsuperscript{14} Ai et al established a critical production model to determine the critical production rate based on analysis of APB and casing safety.\textsuperscript{15} Liu et al studied APB with a semi-steady state temperature model. The influence of production rate, well depth and annulus length were also analyzed.\textsuperscript{16} Ma et al evaluated the mitigation effect of a novel recovery relief method through the laboratory test. They proposed a method to achieve the pressure relief threshold of a mitigation tool.\textsuperscript{17} Jandhyala et al used finite element modeling to analyze the effect of APB on cement sheath. The resilient cement was considered able to withstand a bigger APB load than conventional cement.\textsuperscript{18} Williamson et al presented valuable laboratory tests about APB. Eight fluid combinations were used in the test including the foamed fluid. Their work indicated that at least 5% nitrogen is needed to mitigate APB.\textsuperscript{19} Wang et al considered the change of the fluid properties with temperature and pressure in the proposed APB prediction model. The effect of the foamed spacer was also studied and a model was proposed to make the prediction when nitrogen exists. Pressure experiments were conducted in a cylindrical container without cement to verify the model.\textsuperscript{20,21} Hasan et al proposed a semi-steady state and a transient temperature prediction model and further analyzed APB phenomena.\textsuperscript{22} Pattillo et al presented a 16in casing failure instance caused by APB on the Pompano A-31 well and gave the detailed analysis.\textsuperscript{23} Zhang et al reviewed the prediction models of APB phenomena and introduced different mitigation measures.\textsuperscript{24} Adams et al considered the APB and wellhead growth problem in casing design and presented a novel method for multistring design.\textsuperscript{25} Zhang et al developed a new casing with relief space and relief value to control the APB problem and conducted theoretical analysis.\textsuperscript{26} Xi et al analyzed the accumulated plastic deformation of the cement during multistage fracturing with laboratory experiments and 3-D numerical simulation. A new cement slurry was developed to eliminate sustained casing pressure.\textsuperscript{27} The present researches on APB are mostly theoretical or about field investigation. Most scholars studied APB without considering the effect of the cement and treated the annulus as a sealed zone without mass change of annular fluid.\textsuperscript{10,12,13,15,16} However, the presence of cement has a nonignorable effect on casing deformation and affects APB indirectly, including the influence on annular temperature and casing pressure. Moreover, some wells with APB adopt a wellbore structure that makes the TOC below the previous casing shoe,\textsuperscript{8,19,28} which is called “cement shortfall.” An open-hole section of the formation is exposed in this structure to reduce fluid mass for relieving APB. There is a lack of analysis about APB under this structure. Besides, only a few researches provide basic experiments in sealed containers and the experimental
studies simulating actual annuli are insufficient. In this paper, the effect of cement on APB is considered and a prediction model is proposed to analyze the APB phenomena. Laboratory experiments were also conducted with a radial full-size tri-annuli setup. Two experimental results were compared to analyze the effect of cement on APB. Finally, a case study was carried out and the evaluation of the open shoe and gas or foam injection mitigation methods was conducted to make the further analysis. Although this study may have shortcomings and limits, it is hoped that this work could provide reference and guidance for the engineering study of APB phenomena.

2 | ESTABLISHMENT OF APB PREDICTION MODEL

2.1 | APB prediction model

Equation 1 is often used by many scholars to calculate APB. It is deduced from the PVT equation. This equation considers the isobaric thermal expansion coefficient and isothermal compression coefficient of fluid as constants and is only suitable for small temperature and pressure change. Hence the errors can’t be avoided when applying this equation under big temperature or pressure change.

\[
\Delta P = \frac{a_{\text{isob}}}{k_{\text{isot}}} \Delta T - \frac{1}{k_{\text{isot}}} \Delta V_{\text{ann}} + \frac{1}{k_{\text{isot}}} \Delta V_{\text{flow}}
\]  

(1)

In this work, a novel integral model considering the dynamic change of isobaric thermal expansion and isothermal compression coefficient is proposed to predict APB. When annuli are trapped, the total mass of the annular fluid is constant. The volume change of the fluid is mainly caused by isobaric thermal expansion and isothermal compression. When annuli are open, the outflow or inflow of the fluid could cause the mass change and compression or expansion of the remaining fluid accordingly. The total volume change of the liquid in annuli can be achieved as follows:

\[
\begin{align*}
\Delta V_l &= \Delta V_{\text{isob}} + \Delta V_{\text{isot}} + \Delta V_{\text{flow}} \\
\Delta V_{\text{isob}} &= \int_{P_{\text{fin}}}^{P_{\text{ini}}} a_{\text{isob}} v_{\text{isob}} dT \\
\Delta V_{\text{isot}} &= -\int_{P_{\text{fin}}}^{P_{\text{ini}}} k_{\text{isot}} V_{\text{isot}} dP \\
\Delta V_{\text{flow}} &= \frac{\Delta m_{\text{flow}}}{\rho_{\text{flow}}}
\end{align*}
\]

(2)

The deduced balance equation is shown as Equation 3.

\[
\int_{P_{\text{ini}}}^{P_{\text{fin}}} a_{\text{isob}} v_{\text{isob}} dT - \int_{P_{\text{ini}}}^{P_{\text{fin}}} k_{\text{isot}} V_{\text{isot}} dP = \ln \left( \frac{V_{\text{fin}}}{V_{\text{ini}} + \Delta V_{\text{flow}}} \right)
\]

(3)

The isobaric thermal expansion coefficient and isothermal compression coefficient are functions of temperature and pressure, expressed in Equation 4. The functions can be obtained by experimental data fitting or theoretical deduction.

\[
a_{\text{isob}} = f(P, T) \ldots k_{\text{isot}} = g(P, T)
\]

(4)

If the annulus is not sealed or the cement shortfall method is adopted, the mass change of the fluid is also an important factor that affects APB. Considering that the inflow or outflow volume of fluid is quite small compared to the remaining fluid in annuli, the density change of the annular fluid is ignored to simplify the calculation. The volume change caused by inflow or outflow is obtained by Darcy equation as follows:

\[
\Delta V_{\text{flow}} = \frac{k_A \Delta P \Delta t}{\eta \mu}
\]

(5)

Due to the filtration of the filter cake, the permeability and the thickness of the filter cake change with time and finally tend to be constant. For different kinds of filters, they can be obtained by laboratory test directly. Once the inflow or outflow volume is calculated, the total volume change of the annular fluid and the APB could be achieved by Equations 2 and 3.

From experiments and field study, it is observed that some gas always exists in each annulus. It could be dissolved gas or gas introduced by operations. The volume change of the gas can be obtained by PR-equation of state as follows.

\[
P = \frac{RT}{v - b} - \frac{a}{v^2 + 2bv - b^2}
\]

(6)

Where,

\[
a = (1 + m(1 - T^{0.5}))^2 \quad a_c = 0.457235R^2T^2_c / P_c \\
m = 0.374640 + 1.54226α - 0.26992α^2 \quad b = 0.077796RT_c / P_c
\]

According to the volume relationship, the volume change of the annulus is equal to that of the fluid, which is caused by expansion and compression, and mass change. The relationship equation is shown as follows.

\[
\Delta V_{\text{ann}} = \Delta V_l + \Delta V_g
\]

(7)
2.2 Volume change of annuli

In Equation 7, the annular volume change is mainly caused by casing deformation. It can be obtained as follows:31

\[ u_i = (1 + 2\mu_c)\alpha_c r \Delta T_r \]  

(8)

\[ u_p = \frac{1 + \mu_c}{E_c (r_{so}^2 - r_{ci}^2)} \left[ -\frac{r_{ci}^2}{r_{so}^2} (P_a - P_i) + (1 - 2\mu_c) (P_{r2}^2 - P_{r1}^2) r \right] \]  

(9)

When casings are cemented, the APB leads to the deformation of the cement sheath. But conversely, the cement deformation affects the pressure on the casing and consequently affects the annular volume change and APB. It is a coupling effect that cannot be ignored. Hence, the pressure on each contact interface needs to be determined to obtain the deformation of cemented casings. The conventional casing-cement structure is shown in Figure 2.

If the cementing quality is eligible, the cement deformation could be given as follows31:

\[ u_i' = (1 + 2\mu_c)\alpha_c r \Delta T_r \]  

(10)

\[ u_p' = \frac{1 + \mu_c}{E_c (r_{so}^2 - r_{ci}^2)} \left[ -\frac{r_{ci}^2}{r_{so}^2} (P_a' - P_i') + (1 - 2\mu_c) (P_{r2}^2 - P_{r1}^2) r \right] \]  

(11)

For different interfaces, the inside and outside material is different. The material inside and outside the interface is represented as m and n, respectively. Then the displacement relationship on each interface could be given as follows by the principle of continuity.

The pressure on each contact interface can be obtained by Equation 13. The deformation of each cemented casing and cement could be obtained by Equations 8-11. Finally, the APB can be recalculated by an iterative method.

\[
\begin{align*}
A_i &= \frac{2 (1 - \mu_m^2) r_{mo}^2 r_{ni}}{\xi E_m (r_{mo}^2 - r_{mi}^2)} \\
B_i &= \frac{2 (1 - \mu_n^2) r_{mo}^2 r_{ni}}{\xi E_n (r_{mo}^2 - r_{ni}^2)} \\
C_i &= -\frac{[(1 + 2\mu_m)\alpha_m r_{mo} - (1 + 2\mu_n)\alpha_n r_{ni}] \Delta T_r}{\xi} \\
\xi &= \frac{(1 + \mu_m) [r_{mo}^2 r_{ni} + (1 - 2\mu_n) r_{ni}^2]}{E_m (r_{mo}^2 - r_{ni}^2)} + \frac{(1 + \mu_n) [r_{ni}^2 r_{ni} + (1 - 2\mu_n) r_{ni}^2]}{E_n (r_{mo}^2 - r_{ni}^2)}
\end{align*}
\]

(13)

In some cases, some companies may adopt the practice of making the TOC below the bottom of the previous casing shoe. Thus annuli directly contact the surrounding formation. As it is shown in Figure 3.

The stress on the borehole wall can be calculated as follows12:

\[
\begin{align*}
\sigma_r &= p_t - p_p \\
\sigma_\theta &= (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h) \cos 2\theta - p_t - p_p
\end{align*}
\]

(14)

The borehole wall deformation can be obtained by Equation 15.

\[ u_f = \frac{(1 + \mu_f)r_f^2 p_t}{E_f} \]  

(15)

Finally, the annular volume change is:

\[ \Delta V_{ann} = \int_0^H \pi [(2r_{ao}\Delta r_{ao} + \Delta r_{ao}^2) - (2r_{ai}\Delta r_{ai} + \Delta r_{ai}^2)] dH \]  

(16)

The iteration method is necessary for the APB prediction model proposed in this work. The prediction process is shown in Figure 4.
3 | EXPERIMENTS AND MODEL VERIFICATION

3.1 | Experimental results

Two experiments were conducted to verify the model and study the APB phenomenon. The first was under the condition that the annuli were filled with freshwater without cement, and the second was under the condition that the annulus C was cemented. The water-cement ratio of the cement slurry used is 0.44. The setup structure and its picture are shown in Figures 5 and 6.

The grade of the casing used in this work is P110. Three annuli were sealed and isolated. A circulating filling method was adopted to eliminate the residual gas in annuli. The setup was preheated to designed initial temperature to simulate the wellbore actual temperature distribution. Temperature and pressure were recorded during the experiment with sensors. The experimental results are shown in Figure 7.

The results indicate that the annular pressure increases with the increasing annular temperature in each annulus in both two experiments. When the annulus C is cemented, the final annular temperature and pressure are both higher. It is because the cement replaced the water and reduced the heat transferring to the outside due to its poorer heat transfer capability. The change of pressure increasing rate is also caused by cement. Since the annulus C is cemented, the external pressure on the 9-5/8” casing was changed and affected the pressure in annulus A and B accordingly. It is necessary to note that the increase of pressure increasing rate in annulus C is caused by setup structure. The casing is axially unconstrained in this setup. Thus, the cement could expand and compress the water in annulus C. To conclude, the APB prediction error will be introduced if the effect of the cement is ignored.

There is an obvious bend at the beginning of the scatter plots of each annulus. It is caused by dissolved gas in freshwater since the residual gas had been eliminated. The dissolved gas is invisible and could affect the compressibility and expansibility of annular fluid. With the increasing annular pressure, the dissolved gas is compressed and has a smaller effect on the compressibility and expansibility of annular fluid. Hence, the scatter plots become approximately linear gradually after the bend.

3.2 | Model verification and experiment analysis

The prediction model proposed in this paper was used to calculate the theoretical APB based on the experimental temperature. The comparison between the predicted and experimental results and error analysis were conducted to evaluate the accuracy of the prediction model. According to the experimental environment and related researches, the initial volume of the dissolved gas contained in each annulus is calculated by Equations 17 and 18.

\[
\ln C = A_0 + A_1 T_s + A_2 T_s^2 + A_3 T_s^3 \quad (17)
\]

Where,

\[
T_s = \ln \left( \frac{571.3 - T}{T} \right) \quad (18)
\]

The calculated dissolved gas volume fractions (DGVF) are shown in Table 1.
The predicted results are shown in Figure 8. Predicted results-1 is the APB predicted under the condition of the first experiment (without cement). Predicted results-2 is the APB predicted under the condition of the second experiment (annulus C cemented). Predicted results-3 is the APB predicted under the condition of the second experiment but ignoring the cement deformation for comparison.

The error analysis results are shown in Table 2. As it is shown in Figure 8 and Table 2, the predicted results-1 and predicted results-2 calculated by the proposed model coincides well with experimental data. The final prediction error and the RMSE of each annulus are all less than 1MPa (except for annulus A, which has bigger final pressure). Thus, the accuracy and availability of the prediction model proposed are verified. The predicted results-3 indicate that if the effect of the cement deformation is ignored, the predicted APB is much bigger in annulus B and consequently affects the APB in annulus A and C. Thus, the cement deformation and its effect on heat transfer can both affect APB. Taking the effect of cement into consideration is necessary for the prediction of APB.
4 | APPLICATION AND DISCUSSION

4.1 | Case study

A deepwater well is used to make the case study in this work. The depth of this well is 3570 m and the packer was set at the depth of 3500 m. The mudline depth is 1300 m and a subsea wellhead is adopted. The local geothermal gradient is 4.3°C/100 m. Its detailed wellbore structure and strings size are shown in Table 3.

The semi-steady state temperature calculation model is widely used in wellbore temperature calculation.\textsuperscript{20,22} The method proposed by Hasan et al\textsuperscript{22} is adopted to obtain the temperature distribution of this well. The temperature distribution of this well is shown in Figure 9.

As it is shown in Figure 9, the temperature distribution is shaped like a cone. In the axial direction, the formation temperature increases with the increasing depth, and the temperature of the formation is 98°C at the bottom of the wellbore. In the radial direction, the temperature gradually decreases with the increase of the distance from the wellbore. The temperature in the wellbore is much higher than the temperature of the formation. It is because of the heat insulation effect of the tubing, casing and cement in oil production.

Considering the temperature changes with the well depth, a discrete element method was used to calculate the volume change of the annular liquid. It is shown in
The volume change of each annulus can be obtained with Equation 19.

$$\Delta V_f = \sum_{i=1}^{n} \Delta V_{f(i)} = \sum_{i=1}^{n} \left[ \int_{T_{\text{ini}}(i)}^{T_{\text{fin}}(i)} a_{\text{iso}}(\theta) dT - \int_{P_{\text{ini}}(i)}^{P_{\text{fin}}(i)} k_{\text{iso}}(\theta) dP \right]$$  

(19)

In this well, the seawater depth is 1300 m, the initial pressure at the wellhead is higher than on-land wells and reaches 13MPa. Hence the annuli were considered filled with seawater and no extra gas is introduced including dissolved gas. The APB calculated by the model proposed is shown in Table 4.

The analysis indicates that the temperature increases of the three annuli are similar but APB is different. It is due to the different fluid properties and confining pressure at different depths. The liquid is harder to be compressed when the pressure is bigger and easier to expand when the temperature is higher. Annulus C of short length is at a shallow depth, thus it has smaller confining pressure and lower initial temperature and pressure, which makes the APB in annulus C is only 9.139MPa. Meanwhile, the APB in annulus A is 20.764MPa when cement deformation is considered and 24.120MPa when ignored. The relative error of the prediction result reaches 16% in annulus A and it is bigger in annulus B and C, which reaches 48% and 101%. Therefore, the depth of TOC and cement deformation both have a significant effect on APB, ignoring the effect of the cement may result in prediction error of APB.
Predicted results of annular pressure

| Group               | Annulus | Final prediction error (MPa) | RMSE*(MPa) |
|---------------------|---------|------------------------------|------------|
| Predicted results-1| A       | -0.187                       | 0.473      |
|                     | B       | -0.308                       | 0.277      |
|                     | C       | 0.005                        | 0.037      |
| Predicted results-2| A       | 1.063                        | 0.747      |
|                     | B       | 0.861                        | 0.597      |
|                     | C       | 0.179                        | 0.187      |
| Predicted results-3| A       | 1.342                        | 2.059      |
|                     | B       | 2.477                        | 6.095      |
|                     | C       | 0.214                        | 0.677      |

*(RMSE is the root mean square error of the predicted results.)*

| Strings                  | Outer diameter (mm) | inner diameter (mm) | Setting depth (m) | Depth of TOC (m) |
|--------------------------|---------------------|---------------------|-------------------|-----------------|
| Conductor                | 914.40              | 863.60              | 1370              | -               |
| Surface casing           | 508.00              | 482.60              | 2050              | 1300            |
| Intermediate casing      | 339.73              | 315.35              | 2600              | 1950            |
| Production casing        | 244.48              | 220.50              | 3570              | 2500            |
| Production tubing        | 88.90               | 76.00               | 3570              | -               |
4.2 Evaluation of two mitigation methods

4.2.1 Open shoe

At present, many companies have adopted the practice that makes the TOC below the bottom of the previous casing shoe to control APB in subsea wells. It could mitigate APB at a low cost but may reduce the wellbore integrity. In this work, the APB under this wellbore structure is analyzed to further study this practice. In order to make the evaluation, the basic structure of the well in the case study is used and the TOC of the intermediate casing is modified lower accordingly, as is shown in Figure 11.

The “L” shown in Figure 11 is the distance from the bottom of the intermediate casing to TOC in annulus B. It was set from −200 to 700 m to make the analysis. The properties of the filter cake in relevant research were used to calculate the outflow volume of the annular fluid and APB with the proposed model. The analysis results are shown in Figure 12.

Figure 12A presents the change of APB and fluid outflow volume with time. The outflow volume increases rapidly in the first 20 hours because the filter cake has good permeability at the beginning. Then the permeability becomes poorer with time due to solid deposition. Therefore, the APB in annulus B decreases rapidly at first and tends to be steady (about 9.3MPa when it reaches 100 hours). As it is shown in Figure 12B, when TOC is below the bottom of the intermediate casing, the APB in annulus B has an obvious decrease because of the outflow of the annular fluid and the decreasing rate of the curve decreases with the longer “L.” The mitigation effect decreases with the increasing open-hole length but more damage is brought to the wellbore integrity. Thus, the length of the open-hole section should be designed carefully to achieve the balance between the wellbore integrity and APB control. The minimum length could be determined through the proposed method according to field conditions.

4.2.2 Gas or foam injection

Gas (mostly Nitrogen) or foam is sometimes used to fill the annuli to control APB due to the good compressibility of the gas. However, the situation is different in deepwater wells due to the high hydrostatic pressure near the mudline. The well in the case study is used to analyze the effect of this mitigation method. The initial pressure of nitrogen is 13MPa in this analysis because the wellhead depth is 1300 m underwater.

Figure 13 shows that the APB decreases with the increasing gas volume fraction. The pressure decreases most in the first section (0%-10%) and then decreasing

| Annulus | Average temperature increase (°C) | APB considering cement deformation (MPa) | APB ignoring cement deformation (MPa) |
|---------|---------------------------------|---------------------------------|---------------------------------|
| A       | 22.514                          | 20.764                          | 24.120                          |
| B       | 25.278                          | 14.361                          | 21.239                          |
| C       | 24.367                          | 9.139                           | 18.400                          |
rate decreases. The necessary gas volume fraction to keep APB in three annuli less than 5MPa is 3.6%. The final APB in each annulus tends to be the same around 1.3MPa.

In some researches, a small gas volume fraction (about 5%) is thought to be sufficient to prevent APB since the initial gas pressure was assumed to be 1 atm. It is a valuable suggestion but dealing with the APB problem in deepwater wells is more difficult due to the special production environment. More gas may be needed in deepwater wells because of the high hydrostatic pressure at the subsea wellhead. The compressibility of the gas is greatly weakened and its effect on APB control is also reduced. Hence, it is necessary to determine the reasonable gas volume or the underestimation may cause potential dangers. The APB and its drop percentage with the increasing gas volume fraction when the initial gas pressure is 3MPa, 10MPa, 20MPa, 30MPa is studied and the results are shown in Figure 14.

In Figure 14A, curves have a nearly right-angled bend and the drop percentage reaches more than 95% when the gas volume fraction is only 5%. In this case, only a little volume of the gas is sufficient to mitigate APB. In Figure 14D, when the gas volume fraction is 5%, it still has APB of 9.01MPa in annulus A and the drop percentage is only 51%. Extra gas is necessary if 5MPa is the maximum allowable pressure. With the increasing initial pressure of the gas, curves become separated and the approaching value of APB in annuli becomes bigger, from 0.2MPa to 3.4MPa. It indicates that the initial pressure of the gas has a significant influence on the mitigation effect. The gas volume should be designed under actual wellhead pressure and engineering needs.

5 | CONCLUSIONS AND SUGGESTIONS

Based on the research in this paper, the following conclusions and operation suggestions are obtained as follows:

1. A novel model is proposed in this work to predict APB under cementing condition. The properties and mass change of the fluid and the effect of cement on APB are considered in this model. Two experiments were conducted to verify the accuracy of the model proposed and make the further analysis. This model is appropriate for a wider temperature and pressure variation range with sufficient accuracy.

2. The experimental results show that the cement has a significant effect on APB. First, the cement affects the heat transfer in the wellbore and leads to the change of temperature of the annular fluid and APB. Second, there is a coupling effect between the cement deformation and APB. The cement deformation is caused by APB but it conversely changes the pressure on the cemented casing and further affects APB. Ignoring these
Figure 13: Annular pressure buildup and its drop percentage under different gas volume fraction. A, Initial pressure of the nitrogen: 3MPa. B, Initial pressure of the nitrogen: 10MPa. C, Initial pressure of the nitrogen: 20MPa. D, Initial pressure of the nitrogen: 30MPa.

Figure 14: Annular pressure buildup and its drop percentage with different initial pressure and volume fraction of the gas.
two effects may cause prediction error and even introduce potential danger.

3. Making the TOC below the bottom of the previous casing shoe is an effective method for APB mitigation. The open-hole section provides the leakage channel for the annular fluid and releases the annular pressure. In the case study, the APB in annulus B drops by 34% from 14.1MPa to 9.3MPa with a 200 m cement shortfall. However, since the mitigation effect decreases with the lower TOC, the TOC should be designed carefully to achieve the balance between the wellbore integrity and APB control.

4. The gas or foam injection could reduce APB significantly. However, more gas may be needed in deepwater wells since the compressibility of the gas is weakened by the high initial pressure at the wellhead. In the case study, the drop percentage of the APB in annulus A decreases from 95% to 51% when the gas initial pressure increases from 3MPa to 30MPa. Hence, the necessary volume of the gas needs to be determined according to actual seawater depth and wellbore temperature distribution.

**NOMENCLATURE**

\(\Delta P\), annular pressure buildup (MPa).

\(\Delta V_{\text{ann}}\), volume of the annulus (m³).

\(\Delta V_{\text{annv}}\), volume change of the annulus (m³).

\(\Delta V_{\text{flow}}\), inflow and outflow volume of the annular fluid (m³).

\(\Delta m_{\text{flow}}\), inflow and outflow mass of the annular fluid (kg/m³).

\(\rho_{\text{flow}}\), density of the inflow and outflow of the annular fluid (kg/m³).

\(K\), permeability of the filter cake (m²).

\(A\), filter area (m²).

\(h\), thickness of the filter cake (m).

\(\mu\), fluid viscosity (Pa·s).

\(\Delta t\), filter time (s).

\(\Delta V_{f}\), volume change of the annular fluid (m³).

\(\Delta V_{g}\), volume change of the annular gas (m³).

\(\Delta V_{\text{isob}}\), volume change of the annular fluid caused by thermal expansion (m³).

\(\Delta V_{\text{isot}}\), volume change of the annular fluid caused by isothermal compression (m³).

\(T_{\text{ini}}\), initial annular temperature (K).

\(T_{\text{fin}}\), final annular temperature (K).

\(P_{\text{ini}}\), initial annular pressure (MPa).

\(P_{\text{fin}}\), final annular pressure (MPa).

\(V_{\text{isob}}\), fluid volume in isothermal compression process (m³).

\(V_{\text{isot}}\), fluid volume in isobaric thermal expansion process (m³).

\(V_{\text{fin}}\), final annular volume (m³).

\(P\), annular fluid pressure (MPa).

\(T\), annular fluid temperature (K).

\(R\), Gas constant (J·mol⁻¹·K⁻¹), \(R = 8.314\) J·mol⁻¹·K⁻¹.

\(V\), gas molar volume (m³).

\(\mu_{s}\), Poisson's ratio of the casing.

\(E_{c}\), elastic modulus of the casing (MPa).

\(\alpha_{s}\), linear expansion coefficient of the casing (1/K).

\(r\), radius of the calculation position (m).

\(\Delta T_{r}\), temperature change at the calculation position \(r_{si}\), inner radius of the casing (m).

\(r_{so}\), outer radius of the casing (m).

\(P_{i}\), inner pressure of the casing (MPa).

\(P_{o}\), external pressure of the casing (MPa).

\(u_{s}\), cement deformation caused by thermal expansion (m).

\(u_{p}\), casing deformation caused by internal and external pressure (m).

\(\mu_{c}\), Poisson's ratio of the cement.

\(E_{m}\), elastic modulus of the cement (MPa).

\(r_{ci}\), inner radius of the cement (m).

\(r_{co}\), outer radius of the cement (m).

\(P_{i}^{'\prime}\), inner pressure of the cement (MPa).

\(P_{o}^{'\prime}\), external pressure of the cement (MPa)\(P_{r}\), reduced pressure, \(P_{r} = P/P_{c}\).

\(T_{r}\), reduced temperature, \(T_{r} = T/T_{c}\).

\(P_{c}\), critical pressure (MPa), \(P_{c} = 3.394\) MPa for nitrogen.

\(T_{c}\), critical temperature (K), \(T_{c} = 126.15\) K for nitrogen.

\(\omega\), Pitzer’s acentric factor, \(\omega = 0.045\) for nitrogen.

\(P_{i}^{'\prime}\), pressure on interface \(i\) (MPa).

\(P_{\text{ann}}\), annular pressure (MPa).

\(P_{f}\), formation confining pressure (MPa).

\(\mu_{m}\), Poisson’s ratio of the material inside the interface.

\(\mu_{ni}\), Poisson’s ratio of the material outside the interface.

\(E_{m}\), elastic modulus of the material inside the interface (MPa).

\(E_{ni}\), elastic modulus of the material outside the interface (MPa).

\(r_{mi}\), inner radius of the material inside the interface (m).

\(r_{mo}\), outer radius of the material inside the interface (m).
$r_{n1}$ inner radius of the material outside the interface (m).

$r_{o1}$ outer radius of the material outside the interface (m).

$\alpha_m$, linear expansion coefficient of the material inside the interface (1/K).

$\alpha_o$, linear expansion coefficient of the material outside the interface (1/K).

$\Delta T_s$, temperature change at interface (K).

$u_{mo}$, outer radius displacement of the material inside the interface.

$u_{ni}$ inner radius displacement of the material outside the interface.

$\sigma_r$, radial stress (MPa).

$\sigma_\theta$, circumferential stress (MPa).

$\sigma_{Hr}$, maximum horizontal in-situ stress (MPa).

$\sigma_{hr}$, minimum horizontal in-situ stress (MPa).

$\theta$, phase angle ($^\circ$).

$u_f$, borehole wall deformation (m).

$\mu$, Poisson’s ratio of the formation.

$E_f$, elastic modulus of the formation.

$r_f$, radius of the open-hole wall (m).

$p_i$, inner pressure on borehole wall (MPa).

$p_p$, pore pressure of the formation (MPa).

$r_{a0}$, outer radius of the annulus (m).

$\Delta r_{a0}$ outer radius change of the annulus (m).

$r_{ai}$, inner radius of the annulus (m).

$\Delta r_{ai}$, inner radius change of the annulus (m).

$H$, length of the annulus (m).

$C$, nitrogen solubility ($\mu$mol/kg).

$A_0$, solubility coefficient, $A_0 = 6.42931$.

$A_1$, solubility coefficient, $A_1 = 2.92704$.

$A_2$, solubility coefficient, $A_2 = 4.32531$.

$A_3$, solubility coefficient, $A_3 = 4.69149$.

$\Delta V_{f(i)}$, annular fluid volume of unit i ($m^3$).

$T_{ini(i)}$, initial annular temperature of unit i (K).

$T_{fin(i)}$, final annular temperature of unit i (K).

$P_{ini(i)}$, initial annular pressure of unit i (MPa).

$P_{fin(i)}$, final annular pressure of unit i (MPa).

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