Top of cement influence on APB mitigation in high pressure and high temperature oil wells

Antonio P. O. Teodoro[1], Catarina N. A. Fernandes[1], Gilberto L. L. Santos[1], Thiago B. Silva[1], William W. M. Lira[1]

[1]*Universidade Federal de Alagoas*
Av. Lourival Melo Mota, S/N, Tabuleiro do Martins, 57072-970, Maceió-AL, Brazil
antonio.teodoro@ctec.ufal.br, catarina@lccv.ufal.br, gilberto.santos@lccv.ufal.br, thiago.barbosa@lccv.ufal.br, william@lccv.ufal.br

Abstract. This work presents a study on the influence of top of cement (TOC) in mitigating annular pressure build-Up (APB) in wells subjected to high pressure and high temperature (HPHT) conditions. Oil and gas exploration in HPHT wells poses significant engineering challenges, including an increased occurrence of APB, which can compromise structural integrity and jeopardize operational safety. The objective of this study is to analyze how TOC height influences APB behavior. Additionally, the study examines how fluid leak-off affects APB response. The methodology adopted consists of four stages: i) study on the characterization and modeling of APB; ii) implementation of a numerical model proposed in the literature to calculate APB considering leak-off to formation; iii) modeling scenarios with varying TOC heights; and iv) analyzing results to observe the relationship between APB, TOC heights and well structural integrity. The results obtained with the implemented model demonstrate that positioning the TOC below the previous casing shoe effectively reduces APB. However, caution is warranted when reducing TOC height, as it is crucial for wellbore stability. Thus, this study aims to contribute to developing a methodology for evaluating the impact of TOC height and leak-off on APB, guiding practical applications in the industry.

Keywords: APB mitigation, well structural integrity, HPHT wells, leak-off.

1 Introduction

The exploration of oil and gas in ultra-deep wells, which exhibit high pressures and high temperatures (HPHT), poses numerous challenges to the petroleum industry. One of these challenges is the phenomenon of annular pressure build-Up (APB), which occurs due to the temperature increase of the trapped fluids in the annular spaces between casings or between casings and the well formation. In extreme cases, APB can compromise the well structure, as evidenced by the Marlin A-2 well accident in the Gulf of Mexico, investigated in the works of Bradford et al. [1] and Ellis et al. [2].

Reducing the height of the top of cement (TOC) in an annulus is a potential solution for mitigating APB, as lowering the TOC below the shoe of the previous casing (open shoe) facilitates the drainage of fluids into the formation, a process known as leak-off. However, according to Thomas et al. [3], cementing also prevents the infiltration of unwanted fluids into the structure and provides mechanical support to the casings.

In this way, this work consists of studying the behavior of APB as a function of the TOC height in the annuli of a fictitious well, modeled according to the procedures described by Wang et al. [4]. The study is limited to evaluating the permissible APB for the annular casings, obtained with the help of the software *StrinGnosis®*.

The methodology adopted in this work is based on four stages: i) study on the characterization and modeling of APB; ii) implementation of a numerical model proposed in the literature to calculate APB considering leak-off to formation; iii) modeling scenarios with varying TOC heights; and iv) analyzing results to observe the relationship between APB, TOC heights and well structural integrity. Stage i is described in Section 2 (Numerical model to calculate APB), while Stages ii, iii, and iv are described in Section 3 (Case study).

Finally, this work aims to contribute to enhancing the understanding of the relationship between APB, TOC height, and the structural integrity of oil wells.

2 Numerical model to calculate APB

The works of Oudeman and Bacarreza [5] and Oudeman and Kerem [6] present the APB based on the premise that the volume variation of the annulus, ΔV_a, is given by the relation between the volume variation of the fluid due to expansion and compression processes, ΔV_f, and the fluid flows entering and exiting the annulus, ΔV_l, as shown in eq. (1):

$$\Delta V_a = \Delta V_f + \Delta V_l. \tag{1}$$

Thus, when the system reaches equilibrium, after the start of well production and the consequent temperature rise of the structure, it is possible to calculate the APB by knowing the equations governing the volume variations presented in eq. (1).

To quantify the annular volume variation, Wang et al. [4] provide a formulation for calculating the deformations of the annular casings, as per eq. (2) given by:

$$\Delta V_a = \int_0^h \pi[2r_{ao}\Delta r_{ao} + \Delta r_{ao}^2 - (2r_{ai}\Delta r_{ai} + \Delta r_{ai}^2)]dh, \tag{2}$$

where r_{ao} is the outer radius of the annulus, r_{ai} is the inner radius of the annulus, Δr_{ao} and Δr_{ai} are the variations of the inner and outer radii of the annulus. These variations are the results of casing deformations caused by thermal variations and the pressures they are subjected to.

Subsequently, Wang et al. [4] present an equation for the volume variation ΔV_f of the fluid contained in the annulus, considering isobaric expansion and isothermal compression processes of the fluid, according to eq. (3) given by:

$$\Delta V_f = \int_{t_i}^{t_f} V_a \alpha_{isob}(p,t)dt - \int_{p_i}^{p_f} V_a k_{isot}(p,t)dp, \tag{3}$$

for which the isobaric expansibility coefficient of the fluid, α_{isob} is integrated as a function of the initial t_i and final t_f temperatures of the system, the isothermal compressibility coefficient, k_{isot} is integrated as a function of the initial p_i and final p_f pressures of the system, and V_a is the initial volume of the annulus. Wang et al. [7] describe equations obtained by polynomial regressions for the calculation of the isobaric expansibility and isothermal compressibility coefficients as a function of temperature and pressure for water.

Oudeman and Bacarreza [5] and Oudeman and Kerem [6] propose a simplified model for calculating the volume drained into the formation, as shown in eq. (4) given by:

$$\Delta V_l = I\sqrt{\Delta P_l \cdot t}, \tag{4}$$

where t is the time elapsed since the start of well production, I is the injectivity, presented in eq. (5):

$$I = \frac{kA}{\mu h}. \tag{5}$$

In this equation, k is the permeability of the formation, A is the drainage area, μ is the viscosity of the fluid contained in the annulus, h is the drainage length and ΔP_l is the leak-off pressure differential, given by eq. (6):

$$\Delta P_l = p_f - p_p, \tag{6}$$

where p_f is the pressure acting on the formation and p_p is the pore pressure of the formation.

The Fig. 1 presents the algorithm used for the numerical calculation of APB in a well with two annuli. It employs the processes described in Wang et al. [4].

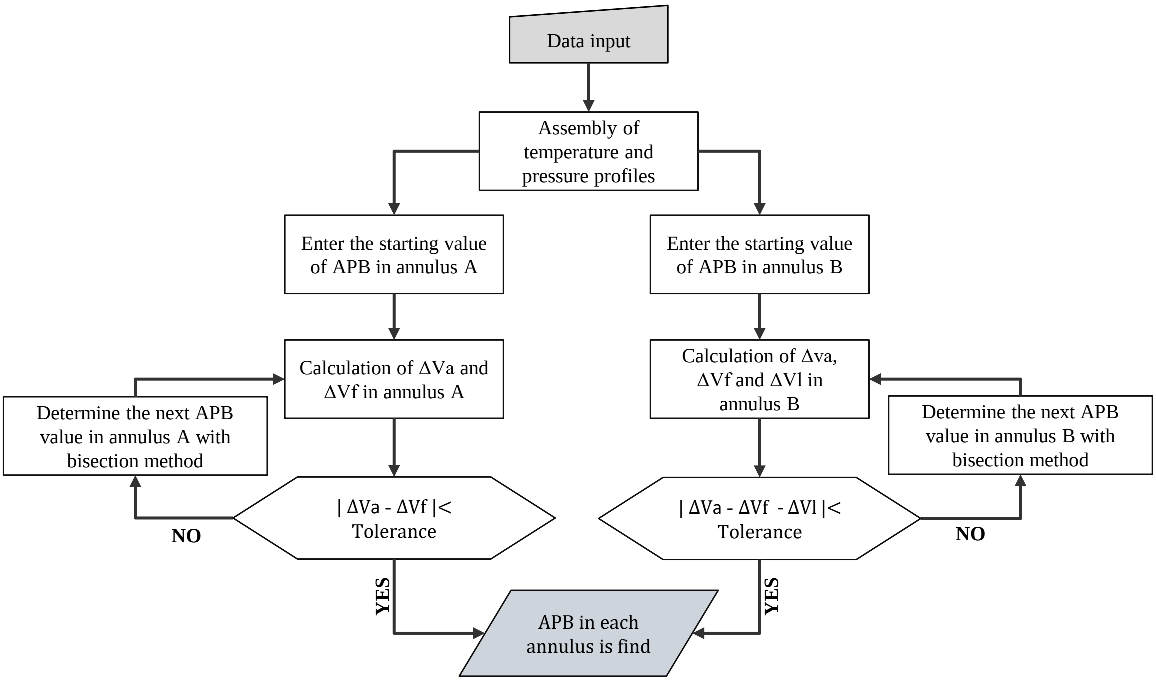

Figure 1. Flowchart for APB calculation (adapted from Wang et al. [4])

3 Case study

To evaluate the influence of the TOC on mitigating APB, a scenario is modeled with varying TOC heights of a annulus, using the methodology described in Wang et al. [4] and implemented computationally in *Python*. The scenario is also modeled in the *StrinGnosis*® software, which is used to obtain accurate thermal profiles of the well production phase, ensuring that the model reflects real-world thermal conditions. Figure 2 illustrates a reference well scenario used for the study in question.

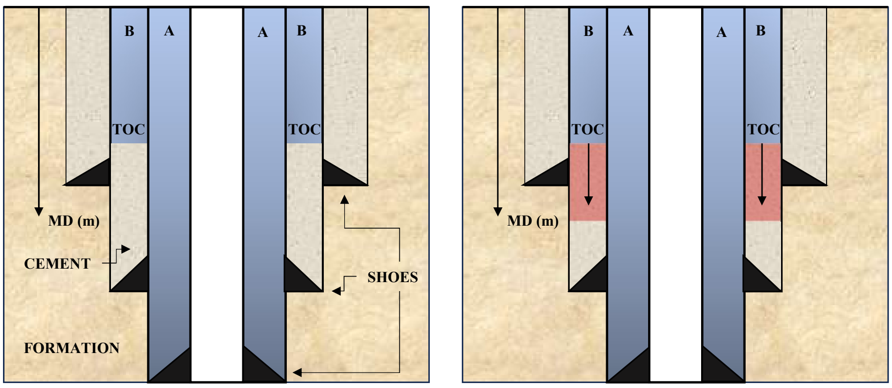

Figure 2. Representation of the reference well scenario with varying TOC heights

The initial well configuration is described in Table 1, where OD stands for Outer Diameter, Wall thk represents Wall Thickness, Grade indicates the steel Grade, Top MD refers to the Top Measured Depth, Bottom MD is the Bottom Measured Depth, and TOC MD denotes the Top of Cement Measured Depth. The structure features two annuli filled with water. TOC of the intermediate casing is reduced from a depth of 400 m, by 50 m increments, until reaching a depth of 800 m. Thus, scenarios with the TOC above and below the shoe of the subsequent casing are obtained.

The input data for the studied model include: well geometry presented in Table 1; temperature and pressure profiles obtained from *StrinGnosis*®, with an initial temperature of 353.15 K, temperature gradient of 0.06 1/K, and

Table 1. Geometry of the well

Strings	OD (m)	Wall thk (m)	Grade	Top MD (m)	Bottom MD (m)	TOC MD (m)
Surface Casing	0.305	0.016	C110	0	600	0
Intermediate Casing	0.244	0.014	C110	0	1200	400 - 800
Production Tubing	0.178	0.013	C110	0	1200	-

wellhead pressure of 69 MPa; elastic modulus, Poisson's ratio and thermal expansion coefficients of the casings and formation, seen in Santos et al. [8] and summarized in Table 2; fluid viscosity is 0.001 Pa·s; formation permeability and mudcake thickness are assumed as constants and valued at 8.59E-18 m² and 0.003 m, respectively; drainage time corresponds to 720 days (62208000 s), a period that *StrinGnosis*® considers for the steady-state of the fluid; and the pore pressure profile generated by a constant profile of 998.15 kg/m³.

Table 2. Materials elastic and thermal parameters

Material	Elastic modulus (MPa)	Poisson's ratio	Linear expansion coefficient (1/K)
Steel	206842.70	0.30	1.24E-5
Cement	10342.10	0.21	1.00E-6
Formation	24000.00	0.36	-

The results obtained from the implemented numerical modeling are presented in Fig.3. Initially, it can be observed that when the top of cement (TOC) height is reduced, the annular pressure build-up (APB) in annulus A increases, while the APB in annulus B decreases. When the TOC falls below the surface casing shoe, the rates of APB reduction in annulus B become more intense, i.e., decreasing the APB at a faster pace, and the rates in annulus A close to zero. This occurs due to a fluid loss (leak-off) caused by TOC that drops below the shoe level and the fluid comes into contact with the formation. This behavior is also observed in the studies by Wang et al. [4] and Santos et al. [8].

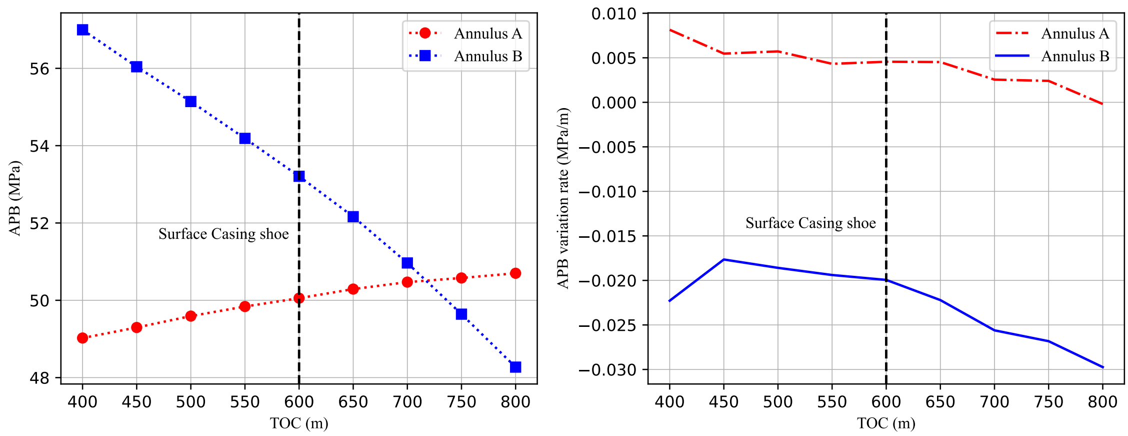

Figure 3. APB results and variation rates

Next, it is assessed whether the APB in the annuli could potentially damage well integrity. In this regard, the *StrinGnosis*® software is used as a reference, as it calculates the maximum allowable APB values for each annulus in the modeled scenarios, considering the values for burst or collapse in the annulus and adopting the lower of these values.

For the modeled scenarios, regardless of the TOC height, the allowable APB values remain constant at 68.32 MPa for burst in annulus A and 54.81 MPa for collapse in annulus B. Table 3 displays the calculated APB for each

TOC height, as well as the allowable APB in the annuli. It is observed that the APB values in annulus A are below the allowable limit in all cases. However, annulus B shows an APB exceeding the allowable limit up to a TOC of 550 m, representing a risk to the structural integrity of the well.

Table 3. Allowed and calculated APB values. In red, the values that exceed the allowed limit

		APB (MPa) with TOC (m)								
Annulus	**Allowed APB (MPa)**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**
A	68.32 (burst)	49.02	49.30	49.59	49.84	50.06	50.29	50.47	50.58	50.70
B	54.81 (collapse)	57.00	56.04	55.14	54.19	53.21	52.16	50.97	49.64	48.27

4 Conclusions

The analysis of the results obtained for the studied scenarios suggests that lowering the TOC in annulus B not only decreases the APB in that annulus but also slows the APB growth rate in the adjacent annulus. A comparison between the modeled APB results and the permissible APB values, obtained using the *StrinGnosis*® software, indicates that as the TOC is reduced, the APB no longer poses a significant threat to wellbore integrity. However, it is crucial to note that this study is confined to analyzing APB limits within the annuli. Consequently, any reduction in TOC height should be approached with caution, given its critical role in maintaining wellbore stability.

In conclusion, the modeled scenarios suggest that lowering the TOC height enhances both safety and efficiency in high pressure and high temperature oil well drilling operations, offering valuable insights for practical applications in the industry.

Acknowledgements. The authors would like to thank PETROBRAS for the financial and technical support related to the development of the research project "Desenvolvimento de produtos digitais para projeto e gestão de integridade de estrutura de poço" (ANP code 23599-4).

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] D. Bradford, D. Fritchie, D. Gibson, S. Gosch, P. Pattillo, J. Sharp, and C. Taylor. Marlin failure analysis and redesign: part 1—description of failure. *SPE Drilling & Completion*, vol. 19, n. 02, pp. 104–111, 2004.

[2] R. Ellis, D. Fritchie, D. Gibson, S. Gosch, and P. Pattillo. Marlin failure analysis and redesign: part 2—redesign. *SPE Drilling & Completion*, vol. 19, n. 02, pp. 112–119, 2004.

[3] J. E. Thomas and others. Fundamentos de engenharia de petróleo. 2ª edição. *Editora Interciência*, 2004.

[4] H. Wang, H. Zhang, J. Li, and T. Sun. Study on annular pressure buildup phenomenon in subsea wells considering the effect of cement. *Energy Science & Engineering*, vol. 10, n. 1, pp. 81–95, 2022.

[5] P. Oudeman and L. Bacarreza. Field trial results of annular pressure behavior in a high-pressure/high-temperature well. *SPE Drilling & Completion*, vol. 10, n. 02, pp. 84–88, 1995.

[6] P. Oudeman and M. Kerem. Transient behavior of annular pressure build-up in hp/ht wells. In *Abu Dhabi International Petroleum Exhibition and Conference*, pp. SPE–88735. SPE, 2004.

[7] H. Wang, H. Zhang, J. Li, A. Chen, J. Liu, T. Sun, and C. Lin. Study on annular pressure buildup in offshore heavy oil thermal recovery wells considering dissolved gas contained in annuli. *Energies*, vol. 14, n. 11, pp. 3213, 2021.

[8] G. L. L. d. Santos and others. Mitigação do aumento de pressão em anulares de poços de petróleo, 2023.