XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Evaluation of Annular Pressure Buildup in Oil Wells

Pedro R. Magalhães, Thiago B. Silva

Laboratory of Scientific Computing and Visualization, Technology Center, Federal University of Alagoas
Campus A. C. Simões, 57072-900, Maceió, Alagoas, Brazil
pedro.magalhaes@ctec.ufal.br, thiago.barbosa@lccv.ufal.br

Abstract. In the search for new sources, the oil wells become increasingly deep and, consequently, new challenges arise in their construction and operation. Annular Pressure Build-up (APB) is a phenomenon caused by the resistance imposed by the casing strings, that limit the annulus, against the free thermal expansion of the trapped fluid. This balance between the pressure increase and the volume changes due to deformations in the well structure, which cannot be treated as a totally rigid system, is fundamental to the correct scaling of the problem according to the multistring casing design philosophy. APB usually occurs in the production phase, when the hot fluid from the reservoir flows through the tubing, radially transferring heat to the outermost layers. In this paper, a computational APB model was developed, considering the effect of the interaction between casing strings (multistring), and it is applied in a case study in order to validate the formulation and illustrate its efficacy. This model can be broken down into selecting a thermal simulator, a Pressure-Volume-Temperature (PVT) model suitable for annular fluids, a casing displacement model, and a numerical method to solve the APB equations.

Keywords: Annular pressure build-up, Well Casing integrity, PVT model

1 Introduction

The Annular Pressure Build-up (APB) is a well-known problem in the oil industry, however, the importance of its evaluation has grown in the past years as deep-water wells are much more common [1]. This is due to the reservoir increasing temperatures as the well gains depth, causing heating of the well components during the production of the fluid. On top of that, in offshore installations, accessing the wellhead is limited, restricting the bleed-off of all annuli [2].

It is essential to take into consideration the correct choice of the APB analysis method, as this can strongly affect the final results. Halal and Mitchell [2] showed that single-string analysis, which designs each column individually, can yield results that are both too high or too low, depending on how the cement is treated. The multistring analysis method, on the other hand, considers the interdependence of the casing strings and annuli of the well, that is, the changes that occur in a certain annular have a direct influence on the adjacent annuli, due to the elastic casing tubulars between them. Therefore, this second methodology is more complete and makes a more accurate representation of the analyzed scenarios.

This phenomenon, if not considered, can lead to serious structural damage, as in the Marlin A-2 well, which collapsed the 16-inch casing after a few hours of operation. In this case, later studies showed that the most plausible causes were APB or hydrate formation [3]. Therefore, the APB needs to be evaluated in the design phase so that the casing tubulars are chosen properly and/or a mitigation strategy is implemented.

This paper deals with the implementation of a computational model for calculating the APB based on the formulations present in Sathuvalli et al. [4] and its application in a case study. Such formulations follow the multistring casing design philosophy, i.e., it is considered that interaction occurs between all casing strings and annuli in the APB calculation process.

2 Theoretical Formulation

The fluid is trapped in the annular at an initial temperature, which is usually assumed to be the geothermal gradient. When production begins, this fluid and the rest of the well elements are subjected to a temperature considerably higher than the initial one due to the hot hydrocarbons flowing through the tubing. This temperature differential causes the volume of the annular and the trapped fluid to vary, but the second one tends to be much larger [1].

The annular fluid will try to expand freely, but it will be limited by the resistance imposed by the casing stiffness, causing the annular pressure to build-up [3]. However, as the casings and cement/formation behave as an elastic system, the increase in pressure in the annular will cause their deformation and, consequently, the expansion of the annular volume. Lamé's equations and PVT equations are used to estimate, respectively, the volume changes of the annular and the volume changes of the fluids as a function of pressure and temperature [4].

One of the main ways to account for the variation of fluid volume due to temperature and pressure changes is to use the coefficient of (isobaric) thermal expansion and the (isothermal) bulk modulus as shown below:

$$\Delta V_{fl} = V_{fl}\left[\alpha_{fl}\Delta T - \frac{1}{B_{fl}}\Delta P\right], \tag{1}$$

where V_{fl} is the initial volume of the fluid, T is temperature, P is pressure, and α_{fl} and B_{fl} are the coefficient of (isobaric) thermal expansion and (isothermal) bulk modulus. However, this approach assumes constant fluid properties, which are not usually true in those kinds of scenarios.

Another way to calculate the volume variation is to relate it to the specific mass of the fluid as a function of pressure and temperature, following the principle of conservation of mass. This approach, in contrast to the previous one, considers the variation of the fluid properties through the change in density [4]. The equation that makes this relationship is given by:

$$\Delta V_{fl}(P,T) = -\int_{V_a} \frac{\Delta\rho(P,T)}{\rho_i(P_i,T_i) + \Delta\rho(P,T)} dV_a, \tag{2}$$

where $\rho(P,T)$ is the density of the fluid at pressure P and temperature T, and the integration is over the annular volume V_a.

2.1 Fluid PVT Model

The PVT fluid models are integrated with the APB model to calculate the density of the fluid under different conditions of temperature and pressure, being of great importance in the casing designing of the HPHT (high-pressure, high-temperature) and deep-water wells. Drilling fluids are mixtures composed of a base, such as oil (natural or synthetic) or water, and additions of solids, in order to give the desired properties to the fluid. Second-order polynomial equations are used to estimate the density of each constituent:

$$\rho_{base} = (a_1 + b_1 P + c_1 P^2) + (a_2 + b_2 P + c_2 P^2)T, \tag{3}$$

where ρ is the density of the base in lbm/gal, T is temperature in ^{o}F, P is pressure in psi, and a_1, b_1, c_1, a_2, b_2, c_2 are correlation coefficients, calculated from experimental results, as shown by Zamora et al. [5]. Then, the density of each component is multiplied by the corresponding volumetric fraction and added to calculate the density of the compositional fluid.

2.2 Stiffness Matrix and Volume Coupling

As previously shown, both the volume variation of the trapped fluid and the annular itself depends on the acting pressure.Therefore, the configuration that leads to this pressure balance should be sought, which is done in an iterative procedure. In the end, the equality of the following equation must be true:

$$\Delta V_{fl} = \Delta V_a. \tag{4}$$

In the case of a single string analysis, the principle of eq. (4) should be applied for each annular individually. In the multistring analysis, which considers that the pressure variation of a certain annular also affects adjacent annuli, it is necessary to find, iteratively, the APB value that satisfy the following system of equations:

$$[\Delta V_{fl}] = [\Lambda][\Delta P] + [\eta][\Delta T], \tag{5}$$

where $[\Delta V_{fl}]$ is a vector that denotes the fluid volume changes in the wellbore annuli, $[\Delta P]$ is the vector of unknown APB in the annuli, $[\Lambda]$ denotes the flexibility matrix for the wellbore annuli, $[\eta]$ is a matrix whose terms provide the volume change of each annulus due to thermal expansion of the strings that bound the annulus, and $[\Delta T]$ is a vector of temperature changes in the casing strings. Sathuvalli et al. [4] show in their work more details of the components of those matrices.

3 Case Study

The APB model that was developed in this work is based on the formulations presented by Sathuvalli et al. [4] and Perez [6], together with the PVT model shown by Zamora et al. [5]. To verify its application, a case study is presented and the results will be compared with those obtained by Perez [6]. The information on the well geometry and its casing tubulars is shown in Table 1, in addition to the fluid used in each annular. Figure 1 illustrates the well scheme, which presents three annuli with different boundary conditions.

Table 1. Well casing configuration

Section	Name	Type	OD (in)	MD (m)			Hole Size (in)	Annulus Fluid (ppg)
				Hanger	TOC	Base		
1	Conductor	Casing	30	1800	1800	1872	36	-
2	Surface	Casing	20	1800	1800	2800	26	-
3	Intermediate	Casing	13.625	1800	2800	4150	17.5	12
4	Production	Casing	10.75	1800	5000	5400	14.75	12
5	Production	Liner	7.0	5300	5300	5965	8.5	12
6	Production	Tubing	6.625	1800	-	5400	-	diesel oil

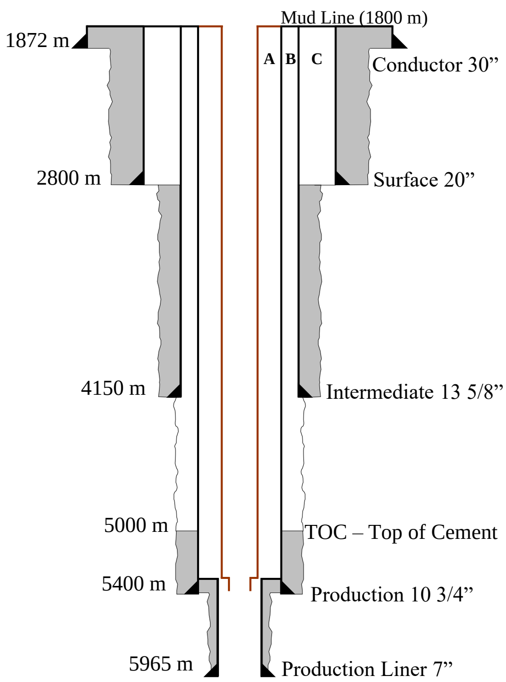

Figure 1. Hypothetical well scheme for APB analysis

In the present APB model, thermal data is used as an input variable, i.e., it needs to be generated separately. Figure 2 shows the thermal profiles used in this simulation, which were taken from Perez [6]. According to the author, a commercial thermal simulator was used to generate them for a production of 5000 bpd.

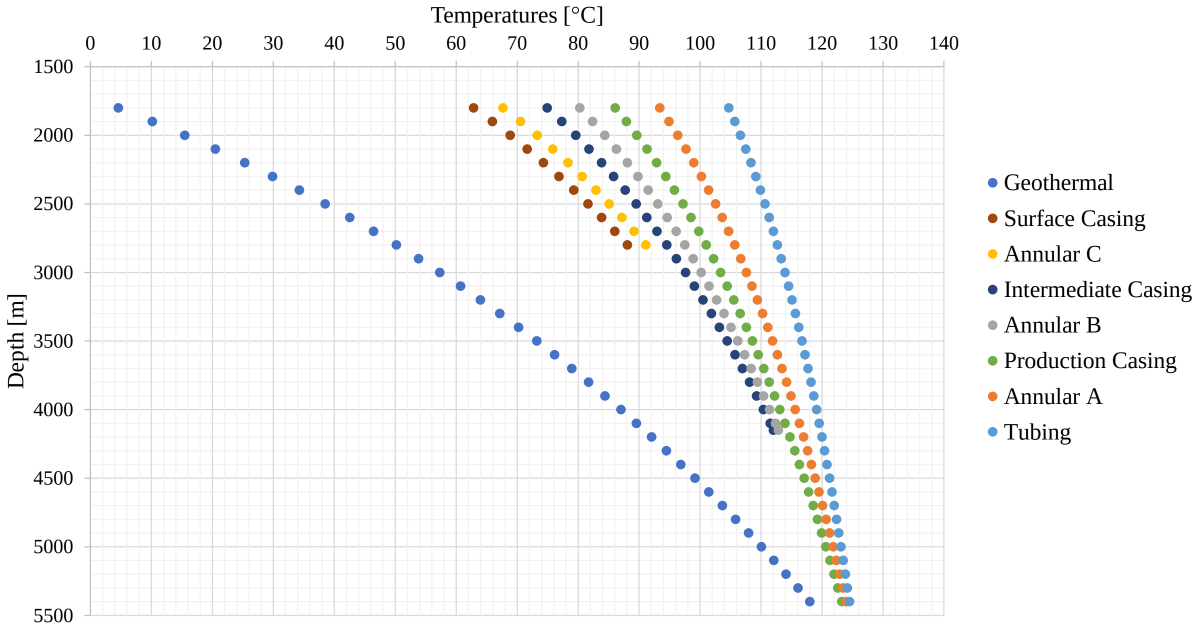

Figure 2. Thermal profiles used in APB simulation (Perez [6])

Table 2 shows the final APB results obtained by using the present model, the model shown by Perez [6], and the commercial software used by the author.

Table 2. APB simulation results

Annular	Comercial Software (psi)	Perez [6] (psi)	Present Model (psi)
A	3939	4027	3979
B	2793	2792	2788
C	4881	4888	4890

The present model generated adequate simulation results, with an average percentage error of 0.35% in relation to the commercial software. In comparison, the average percentage error between Perez [6] and the commercial software was 0.78%.

A second analysis is carried out, based on the scenario already presented, but changing the level of the top of cement (TOC) in annular B, in order to evaluate the influence of this parameter on the final APB results. Figure 3 shows the APB results in each annular for different values of TOC. This variation was from 4000 to 5000 meters with an interval of 50 meters between the simulations.

The increase in the height of cement in annular B caused the growth of APB values in this annular, which, in turn, was the one that suffered the most influence of this variation of TOC, about 69.1% among the extreme values of the interval, 4000 and 5000 m. In the other annuli, this variation was significantly smaller, with 3.2% for annular A and 5.9% for annular C.

The large increase in APB in annular B can be attributed to the decrease in annular volume caused by filling the space with cement. While the changes in the APB values in the other annuli result from the structural response to the pressure increase of the adjacent annular, given the integrated modeling of the system formed by tubular, annuli, formation and cement. It is also possible to notice the change in the tendency of the APB curve of annular B when the TOC approaches 4150 meters. This is because, below that depth, the annular has direct contact with the formation, allowing greater pressure relief.

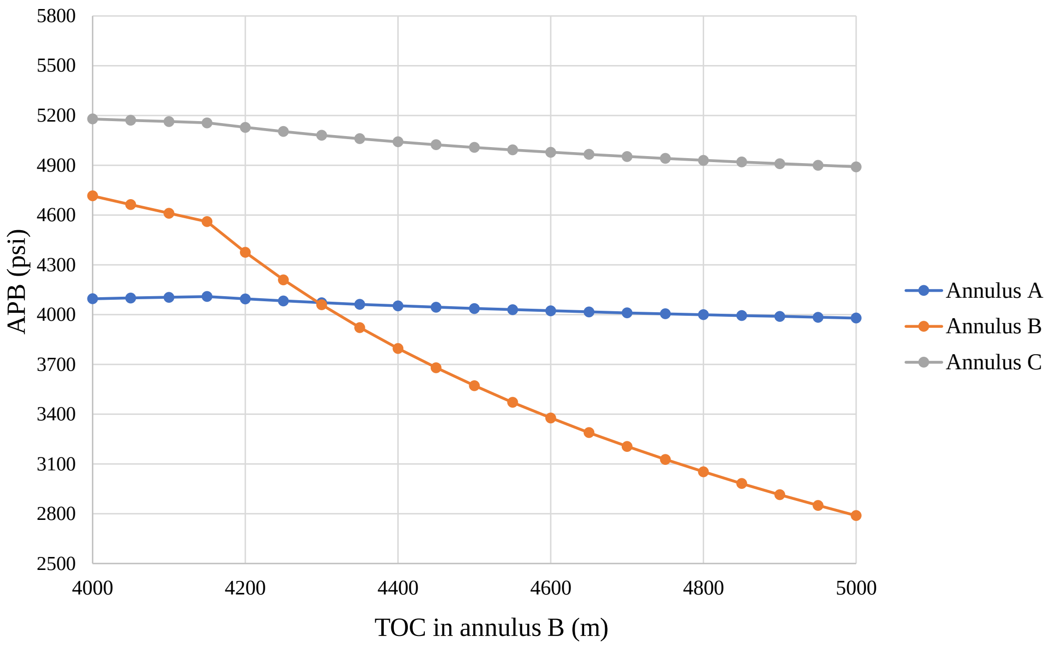

Figure 3. APB results regarding the variation of the top of cement in annular B

4 Conclusions

Given the results of the simulations, it is possible to say that the implementation of the multistring APB model for several annuli based on the formulations shown in Sathuvalli et al. [4] is valid. It is also possible to perceive the high values of pressure increase in the annular that can be reached in an offshore well, and how changes in the geometry of its structure, such as the top of cement, can significantly affect them. This shows how important it is to consider this phenomenon in the casing design process.

Acknowledgements. To PETROBRAS for the technical contributions, and to UFAL for the scholarship granted to the first author.

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] Alcofra, E. L. M., 2014. Aumento de pressão de fluido confinado no anular de poços de petróleo. Master's thesis, Pontifical Catholic University of Rio de Janeiro (PUC-Rio).
[2] Halal, A. S. & Mitchell, R. F., 1994. Casing design for trapped annular pressure buildup. *SPE Drilling & Completion*, vol. 9, n. 02, pp. 107–114.
[3] Ellis, R., Fritchie Jr, D., Gibson, D., Gosch, S., & Pattillo, P., 2002. Marlin failure analysis and redesign; part 2, redesign. In *IADC/SPE Drilling Conference*. Society of Petroleum Engineers.
[4] Sathuvalli, U., Payne, M., Pattillo, P., Rahman, S., Suryanarayana, P., et al., 2005. Development of a screening system to identify deepwater wells at risk for annular pressure build-up. In *SPE/IADC Drilling Conference*. Society of Petroleum Engineers.
[5] Zamora, M., Roy, S., Slater, K. S., Troncoso, J. C., et al., 2013. Study on the volumetric behavior of base oils, brines, and drilling fluids under extreme temperatures and pressures. *SPE Drilling & Completion*, vol. 28, n. 03, pp. 278–288.
[6] Perez, H. E. E., 2015. Efeito da fluência do sal no crescimento de pressão em anular confinado de poços de pré-sal. Master's thesis, Pontifical Catholic University of Rio de Janeiro (PUC-Rio).