Sensitivity Analysis of Thermal Phenomena in Annular Pressure Buildup in Oil Wells

Luiz E. da Silva Filho[1], Thiago B. da Silva[1], Catarina N. A. Fernandes[1], William W. M. Lira[1], João P. L. Santos[1], Charlton O. de Souza[2], Emilio C. C. M. da Silva[3]

[1]*Laboratory of Scientific Computing and Visualization, Technology Center, Federal University of Alagoas*
Av. Lourival Melo Mota s/n, Cidade Universitária, 57072-900, Maceió, Alagoas, Brazil
luiz.elias@lccv.ufal.br, thiago.barbosa@lccv.ufal.br, catarina@lccv.ufal.br, william@lccv.ufal.br, jpls@lccv.ufal.br
[2]*Petróleo Brasileiro - CENPES/PDIDP/EPOCOS/PERF*
Av. Horácio de Macedo, 950, Cidade Universitária, 21941-915, Rio de Janeiro, Brazil
charlton@petrobras.com.br
[3]*Petróleo Brasileiro*
Rua do Senado, 115, 16º andar 20231-003, Rio de Janeiro, Brazil
emiliosilva@petrobras.com.br

Abstract. This paper presents a sensitivity analysis to understand how certain parameters of the thermal problem affect the increase in Annular Pressure Buildup (APB) in oil wells. The structure of an oil well experiences high-temperature gradients throughout its lifespan, directly affecting its components such as casings, annuli, and cement sheath. Among the undesirable effects caused by temperature variation, APB stands out, related to the expansion of fluids confined between casings, a severe phenomenon that can lead to well failure. This justifies studies aimed at better understanding temperature distributions and, consequently, the increase in pressure in the annular spaces of oil wells. Changes in fluid and component temperatures during well operation depend on many factors, such as operating flow rate, inlet pressure and temperature, operating time, formation type, and properties of the produced/injected fluid. Some of these parameters are chosen for inclusion in the parametric analysis proposed in this work. To achieve the proposed objective, the methodology adopted in this work is based on four steps: a) selection of a reference well used for the analyses; b) definition of the variables to be studied and their assumed values; c) generation and simulation of scenarios formed by the combination of chosen variables; and d) selection and description of the sensitivity analysis method to be employed. The main contribution of this work is to present a sensitivity analysis of certain well parameters in annular pressure buildup, allowing inferences about the importance of some properties in the thermomechanical response.

Keywords: Heat transfer, Pressure increase, Parametric analysis

1 Introduction

In recent decades, technologies have been developed to optimize the oil and gas production process, especially in challenging exploration fields. For example, oil wells in offshore basins, according to Xue et al. [1], face rigorous operational conditions, including high pressures and temperatures. Therefore, strategies aimed at predicting undesirable structural behaviors caused by high temperatures are useful in the operation and maintenance of producing and injection wells.

Among these behaviors, according to Barcelos [2], is the Annular Pressure Buildup (APB), a phenomenon caused by the expansion of fluids within the confined annuli. This expansion results from the temperature variation to which the well is subjected during operations, where high-temperature hydrocarbons flow through the production tubing, heating the casings, annuli, and adjacent formation. It is a severe phenomenon that can even lead to the structural failure of the well, highlighting the importance of adequately considering this pressure increase and justifying studies that contribute to its understanding.

In this context, this work presents a sensitivity analysis of some parameters that affect the APB in an oil-producing well scenario, in order to provide a better understanding of how certain operational parameters influence the pressure increase in the annuli.

2 Methodology

The methodology for developing this work is divided into four main stages, as presented in Fig. 1.

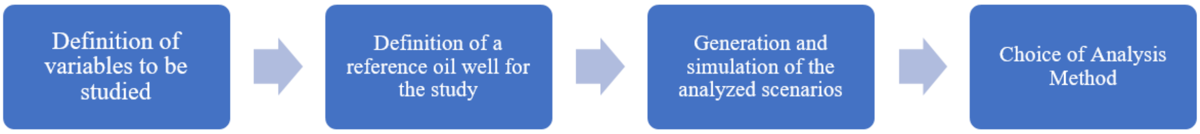

Figure 1. Methodology adopted.

The first stage describes the variables chosen for the study and their respective values, including defining the variation intervals of the parameters under study. These values must be coherent and within a feasible operational range; otherwise, the study will incorrectly infer the influence of the respective parameter. Therefore, according to Gianniou et al. [3], determining the operational range of each parameter is an important phase of the analysis. In the second stage, the oil well used as a reference for the analysis is described, serving as the basis for generating the evaluated scenarios. In the third stage, the scenarios comprising the analysis are generated and simulated. These scenarios are formed by the combination of the values assumed by the studied parameters. The simulation involves evaluating the pressure variation for each scenario. The APB calculation is performed using the simulator developed by Vasconcelos [4]. One of the necessary information for the APB calculation is the annular thermal profiles, which are obtained using the tool developed by Silva Filho [5]. The fourth stage corresponds to the description of the method employed to quantitatively infer the influence of each studied parameter. Finally, the analysis of the pressure increase data in the annuli is conducted.

2.1 Studied Variables and Assumed Values

The variables used in the sensitivity analysis are production flow rate, operation time, and the thermal conductivity of the fluid confined in the annuli. The justification for choosing the flow rate and operation time is that these parameters have a significant influence on thermal phenomena in oil wells, as shown by Silva Filho et al. [6]. The choice of the thermal conductivity of the fluid in the annuli is due to the fact that there are various drilling fluids with different properties (mainly depending on the water percentage in their composition). Thus, understanding the influence of the fluid's conductivity on heat transfer in the well can assist in deciding which fluid to use in wells subjected to high temperature gradients.

To determine the assumed values for the production flow rate, an interval with the maximum and minimum allowable flow rate values for the well is first determined. This range is then divided into a predetermined number of sub-intervals. The flow rate can be expressed as the product of the average cross-sectional velocity v and the pipe area A. Since A is constant, using the maximum and minimum allowable velocities, it is possible to establish a range for the flow rate. Standard [7] states that the velocity limitations aim to prevent issues such as erosion, water hammer, and vibration. Thus, considering a carbon steel production pipe, the maximum velocity for liquids is 6 m/s, and the minimum velocity is 0.8 m/s.

The operation time t of wells varies greatly from one well to another, this study adopts values ranging from 1 month to 16 months, following a geometric progression with a ratio of 2.

For the selection of the possible interval for conductivity, typical values of different drilling fluids presented in DrillCool [8] are used as a basis, where the thermal conductivities of the fluids range from 0.5 to 4.5 times the conductivity of water. Therefore, the conductivity of the fluid in the annulus is a function of the water conductivity (k_w) which, according to Sui et al. [9], can be described by Eq. 1.

$$k_w = -0.92247 + 2.8395 \cdot t_{ad} - 1.8007 \cdot t_{ad}^2 + 0.52577 \cdot t_{ad}^3 - 0.07344 \cdot t_{ad}^4, \tag{1}$$

where t_ad is defined by Eq. 2.

$$t_{ad} = \frac{T + 273.15}{273.15}. \tag{2}$$

Considering the defined intervals for each of the variables under study, Table 1 summarizes the discrete values adopted for each parameter.

Table 1. Values assumed by the variables.

Variable	Unit	Values				
Production flow rate	m³/s	0.0150	0.0395	0.0640	0.0885	0.1129
Operation time	month	1	2	4	8	16
Thermal conductivity	k_w	0.5	1.5	2.5	3.5	4.5

The reference well used in this work is simulated by varying the parameters presented above.

2.2 Reference Well

The well used in this study is based on the one presented by Silva Filho et al. [6]. It is a synthetic scenario of a vertical offshore well with a water depth of 1500 m, which has 2 annuli and 4 casings in production operation. The necessary data for the geometric characterization of the well, are presented in Table 2.

Table 2. Geometric data of the reference well phases.

Phase	D_{out} [”]	w [mm]	B [”]	Pf_{Hanger} [m]	Pf_{Shoe} [m]	TOC [m]
1	36	38.1	40	1500	1600	1500
2	30	38.1	34	1500	2500	1500
3	20	16.0	25	1500	3000	2300
4	9.625	12.0	12	1500	5000	2800

In Table 2, D_{out} is the outer diameter of the phase in inches, w is the tube thickness in millimeters, B is the drill bit diameter in inches, Pf_{Hanger} is the depth of the hanger in meters, Pf_{Shoe} is the shoe depth in meters, and TOC is the top of cement depth in meters.

The production string of the well has an outer diameter of 7 inches, a thickness of 16 mm, starting from the wellhead, and a length of 3500 m. It is noteworthy that at the lower end of the string, there is a packer isolating first annulus. The properties of the materials constituting the components of the well are presented in Table 3.

Table 3. Properties of the reference well materials.

Material	Conductivity [W/m.K]	Specific heat [J/kg.K]	Density [kg/m³]
Steel	45.34	460.90	7849.00
Cement	0.983	837.90	1890.17

The rock formation surrounding the well consists of three layers: sandstone, marl, and shale. The thermal properties are considered homogeneous within each layer. To define the geothermal profile, it is assumed that at the wellhead, the temperature is 4 °C and the geothermal gradient is 16 °C/km. The thickness, arrangement, and thermomechanical properties of the rocks (extracted from the work of Barcelos [2]) are presented in Table 4, where “Top” refers to the upper boundary of the layer and “Base” refers to the lower boundary.

Table 4. Description of the reference well’s rock formation.

Rock	Top [m]	Base [m]	Conductivity [W/m.K]	Specific heat [J/kg.K]	Density [kg/m³]
Sandstone	1500	2200	2.50	737	2198
Marl	2200	3800	1.38	1734	1970
Shale	3800	5000	1.60	2151	2057

The produced fluid is water, chosen for the ease of obtaining Pressure-Volume-Temperature (PVT) data. These data are obtained from NIST [10], allowing the replication of this study. Additionally, it is considered that the annuli are filled with seawater. The lifting system is by natural flow. The fluid is extracted at a depth of 5000 m, subjected to a pressure of 103.42 MPa (15000 psi), and at a temperature of 70°C. A schematic summarizing the main information of the well, the rock formation, and the geothermal profile is shown in Fig. 2.

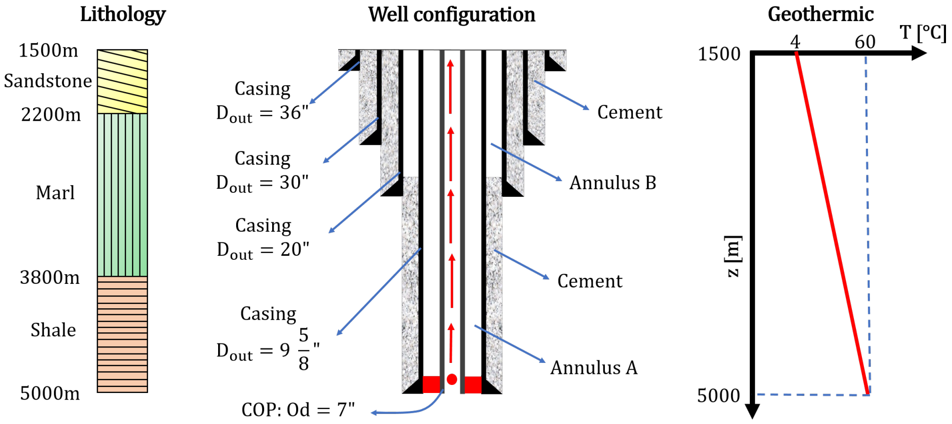

Figure 2. Oil well diagram.

2.3 Data Generation and Scenario Simulation

The generation of scenarios is carried out by creating multiple wells through the variation of production time, flow rate, and annular conductivity. Considering the combination of values presented in Table 1, a set of 125 wells is formed to compose the study. Finally, the temperature profiles in annuli A and B are calculated. These profiles feed the simulator developed by Vasconcelos [4], which calculates and returns the APB for each annulus. This pressure buildup is the data used in the analysis.

2.4 Sensitivity Analysis Method

According to Saltelli et al. [11], sensitivity analysis is a tool that allows evaluating how model responses behave as a function of input data. The analysis method used in this work is more detailed by Silva Filho et al. [12] and is based on measuring the rate of variation generated by each variable.

Initially, a functional operator is adjusted to describe the behavior of the APB as a function of the variables under study for each of the annuli. In this work, polynomial functions are used. Thus, there is a function that describes the pressure increase in each of the annuli. The analysis is performed separately for each of these functions. Thus, given the adjusted function $f(\vec{X})$, the importance (or sensitivities) can be evaluated by calculating the gradient vector of the function ($\vec{\alpha}$) at a point $\vec{X}_0$, as shown in Eq. 3.

$$\vec{\alpha} = \frac{\nabla f(\vec{X}_0)}{|\nabla f(\vec{X}_0)|}. \tag{3}$$

The sensitivity of variable i at point $\vec{X}_0$ is defined as the square of the i-th coordinate of the vector $\vec{\alpha}$, as shown in Eq. 4.

$$I_i = \alpha_i^2 \cdot 100\%. \tag{4}$$

The sensitivities I_i are the squares of the entries of a unit vector, and, therefore, having this vector with w coordinates, at each point, the importance is divided among the w variables, so that the sum of these terms corresponds to 100%, that is, the total sensitivity. The most influential variables are those in which small perturbations lead to large variations in the response of the function, that is, the variables with the highest rates of variation.

However, the sensitivity calculated at a point $\vec{X}_0$ only reflects the influence of the variables locally. To overcome this, the importance is calculated at points used in the fitting of each function. Thus, for each variable, there is a set of $\bar{n} = 125$ sensitivities. From this set, the global importance of each parameter is inferred.

The interpretation of this set of sensitivities is based on the theory of elementary effects developed by Morris [13], where the global importance $(\bar{\mu}_i)$ is obtained by averaging the $\bar{n}$ sensitivities of variable i, as shown in Eq. 5.

$$\bar{\mu}_i = \frac{1}{\bar{n}} \cdot \sum_{j=1}^{\bar{n}} I_{i,j} \tag{5}$$

According to Morris [13], comparing the means of sensitivities allows identifying which factors have the greatest influence on the model's response, with those with higher means being the most influential.

3 Results

The method described in the previous section quantitatively measures the influence of each of the parameters studied on the increase in pressure in the annuli. Before applying it, a qualitative analysis of the APB varying with the parameters under study is presented in isolation. This analysis allows for a preliminary visual assessment of the intensity of the influence of each variable.

3.1 Qualitative analysis

To preliminarily evaluate the behavior of the APB, Fig. 3 presents the pressure increase in annuli A and B according to the variation in production flow rate.

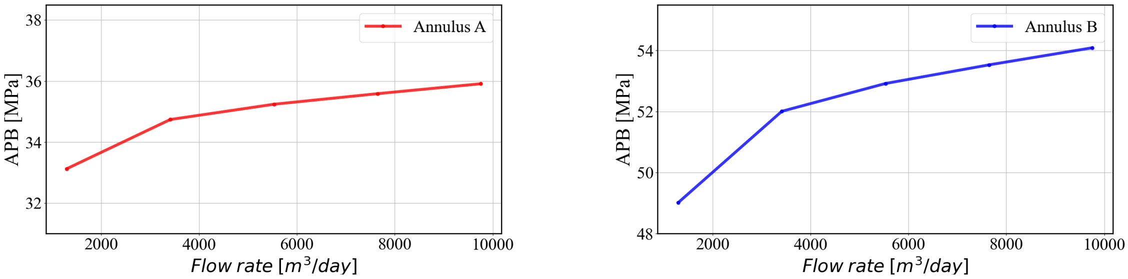

Figure 3. APB as a function of production flow rate.

It can be observed that in both annuli, the increase in flow rate causes a rise in APB. This result is natural since higher flow rates represent higher temperatures. The main reason for this behavior is that with more fluid flowing through the tube in the same time interval, more energy is provided to the system, which increases the radial heat flow and consequently elevates the temperature distributions.

Fig. 4 presents the pressure increase in annuli A and B according to the variation in production time.

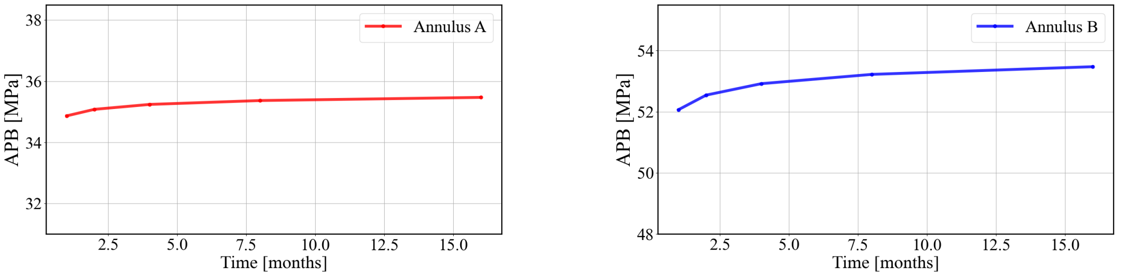

Figure 4. APB as a function of production time.

For the production time, it can be observed that over the months, the APB increases, similar to the behavior with flow rate, but with substantially less intensity.

Fig. 5 presents the pressure increase in annuli A and B according to the variation in the conductivity of the fluid confined in the annuli of the well.

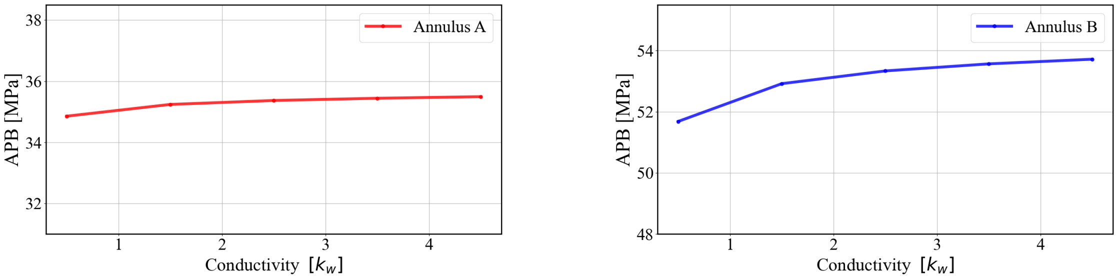

Figure 5. APB as a function of conductivity.

In all cases, it can be observed that the APB in annulus A is substantially lower than the APB in annulus B. This result is similar to that observed by Barcelos [2], where the outer annuli exhibited greater pressure increases than the inner ones. Additionally, the absolute pressure variation caused by the parameters in annulus B is more distributed, meaning that all variables significantly affect the pressure increase. For this reason, it is expected that in the quantitative analysis, the importance of the variables will be more balanced in annulus B. In contrast, for annulus A, the variable that showed significant importance in the APB is the flow rate, and it is expected that in the quantitative analysis, the importance of this variable will be superior to the others.

3.2 Quantitative analysis

Using the simulator developed by Vasconcelos [4], the APB is calculated for the 125 well scenarios of the study. Then, the method described in section 3.4 is applied, and the global importances $(\bar{\mu})$ of each variable in the pressure increase in annuli A and B are obtained. These values are presented in Fig. 6.

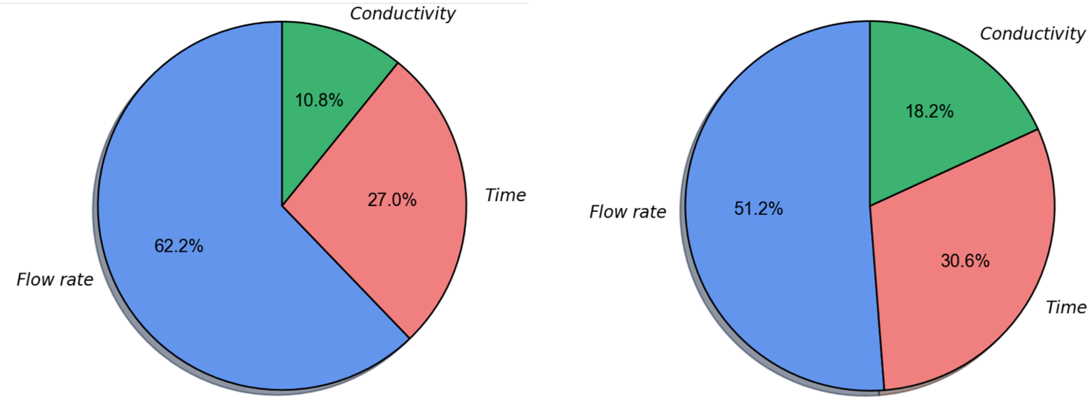

Figure 6. Global importances $(\bar{\mu})$ in the Annular Pressure Buildup.

It can be observed that the distribution of influence in annulus A is more heterogeneous, with the flow rate being considerably more important than the other variables, confirming the observations from the qualitative analysis. In contrast, the distribution of importance in annulus B is more homogeneous, although the flow rate is still the most influential of the variables, which corroborates the qualitative study.

4 Conclusions

This work presented a sensitivity analysis of how the flow rate, operation time, and thermal conductivity coefficient of the fluid confined in the annulus influence the increase in pressure in the annuli. For the parameters considered, it was found that among the three studied variables, the order of relevance in determining the APB is flow rate, operation time, and annular thermal conductivity. It is also observed that in annulus A, the flow rate has greater importance, while in annulus B, the importance among the variables is more evenly distributed. In future work, it is possible to study the optimization of the operation for the same produced volume to understand whether it is more viable, from the perspective of APB, to produce for a longer time with a lower flow rate or to produce for a shorter time with a higher flow rate. Additionally, the analysis methodology described in this work can be applied to more parameters, understanding the importance of each variable in the calculation of the pressure increase in the annuli.

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References

[1] L. Xue, Y. Hong, Z. Liu, J. Qin, and X. Du. Inclined wellbore stability in high temperature formations of drilling. In *IOP Conference Series: Earth and Environmental Science*, volume 603, pp. 012012. IOP Publishing, 2020.

[2] J. G. A. Barcelos. Modelagem matemática do do aumento da pressão nos anulares (apb) em poços de petróleo. Master's thesis, Universidade Federal de Santa Catarina, Curso de Pós-Graduação em Engenharia Mecânica, Florianópolis, 2017.

[3] P. Gianniou, A. Heller, P. S. Nielsen, and C. Rode. Identification of parameters affecting the variability of energy use in residential buildings. In *Proceedings of CLIMA Conference, Aalborg*, 2016.

[4] T. S. Vasconcelos. Modelagem termomecânica do crescimento de pressão em anulares confinados em poços de petróleo na presença de evaporitos. Master's thesis, Centro de Tecnologia, Programa de Pós Graduação em Engenharia Civil, Universidade Federal de Alagoas, Maceió, 2019.

[5] L. E. Silva Filho. Cálculo de perfis de temperatura para previsão de aumento de pressão em anulares de poços de petróleo. Graduação em engenharia de civil, Centro de Tecnologia, Universidade Federal de Alagoas, Alagoas, 2022.

[6] L. E. Silva Filho, L. P. Gouveia, T. B. Silva, E. T. Lima Júnior, J. P. N. Araújo, W. W. M. Lira, and F. L. Oliveira. Influence of flow rate and operating time on the temperature profiles of oil wells. In *XLII Ibero-Latin-American Congress on Computational Methods in Engineering (CILAMCE-2021)*. ABMEC, 2021a.

[7] N. Standard. Process design. *P-001, Rev*, vol. 1, 1997.

[8] DrillCool. Drilling fluid - trends in thermal conductivity, 2014.

[9] D. Sui, T. Horpestad, and E. Wiktorski. Comprehensive modeling for temperature distributions of production and geothermal wells. *Journal of Petroleum Science and Engineering*, vol. 167, pp. 426–446, 2018.

[10] NIST. National institute of standards and technology, 2011.

[11] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. *Global sensitivity analysis: the primer*. John Wiley & Sons, 2008.

[12] L. E. Silva Filho, C. N. A. FERNANDES, R. A. FERNANDES, W. W. M. Lira, and F. L. Oliveira. Sensitivity analysis of viscous properties of salt rocks during oil well drilling. In *XLII Ibero-Latin-American Congress on Computational Methods in Engineering (CILAMCE-2021)*. ABMEC, 2021b.

[13] M. D. Morris. Factorial sampling plans for preliminary computational experiments. *Technometrics*, vol. 33, n. 2, pp. 161–174, 1991.