Modeling strategies on the geological formation for APB calculus in oil wells

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Abstract. The thermal gradient imposed on oil wells along its life cycle can cause pressure variations in the annular spaces, a phenomenon called Annular Pressure Build-up (APB). This subject is relevant, given the frequency of occurrences in offshore fields located in deep and ultra-deep areas, such as the Brazilian Pre-salt, whose exploratory interest has grown, given its potential for oil and gas production. The accurate modeling of the APB phenomenon can prevent damage to the casing and the cement sheath, which may even lead to loss of well integrity. Among the several variables involved in the problem, considering the geological formation as rigid or deformable directly influences the APB estimate. Thus, this work aims to evaluate the effect of the flexibility of the geological formation in the APB calculation. Numerical simulations of the pressure increase are performed using a multilayer one-dimensional axisymmetric thermomechanical model. The methodology adopted is based on four macro steps: reproduction of the reference scenario to verify the implementation of the APB calculation; considering formation with null stiffness, result analysis considering rigid formation; evaluation of results adopting a linear constitutive equation for the rocks. For the reference scenario, it was observed that the value of the formation modulus of elasticity modifies the APB level by up to 35%.

Keywords: Annular Pressure Build-up, Offshore Oil Wells, Finite Element Method

1 Introduction

This paper evaluates the effect of the bending of the geological formation in the Annular Pressure Build-up (APB), investigating it in three situations: i) rigid; ii) elastic-linear and iii) formation with null stiffness. APB is the consequence of the difference between the unconstrained volume change of a fluid and the volume change allowed by its container [1]. Pressure buildup can also to provoked by fluid thermal expansion in sealed annuli of high-pressure and high-temperature wells [2]. Before well production begins, the fluids between the rocks are in thermal equilibrium with the formation. During production periods, the high temperatures developed in the well aggravate the phenomenon of pressure buildup in the annuli because the thermal expansion of liquids tends to increase at higher temperatures [2]. It is essential to take into consideration the correct choice of the APB analysis method, as this can strongly affect the final results [3].

In their study, Vasconcelos [4] developed and implemented a multilayer one-dimensional axisymmetric thermomechanical model, aiming at numerically model and analyse the APB phenomenon, considering the prescribed thermal increment and/or the creep mechanism presented by salt rocks. Two constitutive models been used to represent the salt rock formation, the linear elastic and the double deformation mechanism [4]. A finite element model was developed and it associates heat transfer phenomenon, through the weak thermomechanical coupling for the analysis of the displacement of the saline rock [4]. On the other hand, Sathuvalli et al. [1] present the differences caused by neglect of formation elasticity for water based and synthetic muds.

In this context, this work uses the implementation developed by Vasconcelos [4] to simulate the APB in a case study and its variations, to evaluate the variability of the APB levels according to the elasticity of the rock formation used for water-based muds.

2 Methodology

The methodology adopted starts with the reproduction of the reference case study to verify the implementation of the APB calculation, in order to certify the correct use of the tools and the parameters considered in the model. Then, one outer diameter (OD) value is selected for the production casing and its variations for the wall thickness, according to ISO-TR 1400 [5]. This generates a list of models variations for the case study. These models are simulated in each of the three situations proposed in this paper, with a total of thirty models, as shown in Fig. 1.

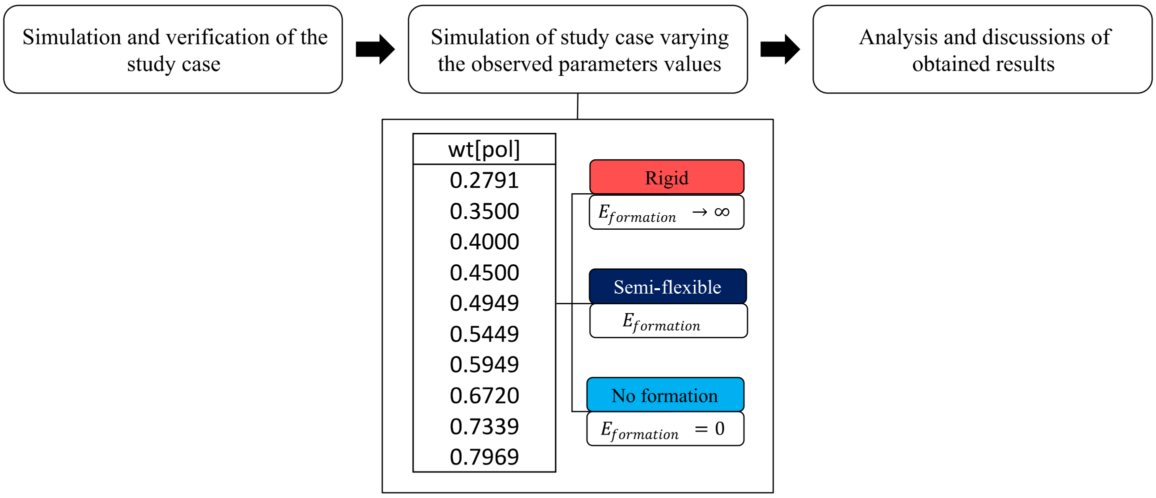

Figure 1. Methodology

With the simulation results, comparative graphs are generated for better visualization and to make inferences about the obtained results. The graph of the semi-flexible formation and no formation (zero stiffness) behavior in relation to the rigid formation behavior is generated in order to compare with the curves presented by Sathuvalli et al. [1]. Also, the graph of absolute values of APB in the three formation modeling situations is generated, according to the increase in the wall thickness of the casing production. This graph aims to measure the APB value variation according to the formation stiffness.

3 Theoretical formulation of APB

The adopted method for estimating the APB is based on the variation of the temperature and volume of the fluid through its coefficient and its compressibility, as shown in the expression 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. Equation (1) can re-cast in terms of the definition of the net fluid volumetric strain:

$$\frac{\Delta P}{B_{fl}} = \frac{\alpha_{fl}\Delta T V_{fl} - \Delta V_{fl}}{V_{fl}} \tag{2}$$

The change in volume of the fluid is equal to the change in volume of the annulus (ΔV_a) it is contained in, as shown in the Equation (2).

$$\Delta V_{fl} = \Delta V_a \tag{3}$$

The changes in the volume of the casing strings due to pressure and temperature changes are calculated by using Lamé's equations for a thick walled cylinder. Equation (2) can be used to calculate the APB in a single annular (single string analysis). For analyses with multiple annuli (multistring analysis), the pressure change in a given annulus affects the pressure changes in adjacent annuli. Thus, applying the Equation (2) to each annulus of the well results in the Equation (4), whose solution yields the APB magnitudes.

$$[\Delta V_{fl}] = [\Lambda][\Delta P] + [\eta][\Delta T] \tag{4}$$

where $[\Lambda]$ is the flexibility matrix for the wellbore annuli and $[\eta]$ is a matrix whose terms provide the volume change of each annulus due to thermal expansion of the strings that bound the annulus. More details about the theoretical formulation and modeling of the APB are available in [1] and in [4], where aspects related to the numerical modeling of the fluid contained in the annulus are also presented.

4 Case study

The reference model adopted in the evaluations of this paper is the well presented by Santos [6], as shown in the scheme of Fig. 2. Its represents the case of a single annular, eliminating the effect of adjacent annulars; filled with pure water [7]. The well is closed in with a head pressure of 1500 psi. Numerical values associated with geometric parameters and materials properties (formation and casing) are presented in Table 1. The temperature profile to which the well is subjected is shown in Fig. 3.

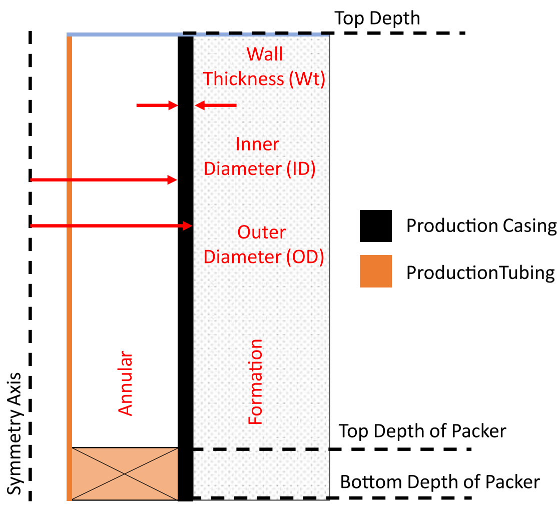

Figure 2. Axisymmetric model scheme

Table 1. Numerical values associated to the case study

Material	Depths (m)		ID [in]	OD [in]	Linear weight [lbf/ft]	Young modulus [psi]	Poisson	Expansion coefficient [°C^{-1}]
	Top	Bottom						
Production Tubing	0	1000	4.408	5.00	15	3.00E+07	0.3	1.24E-05
Production Casing	0	1000	8.681	9.625	47	3.00E+07	0.3	1.24E-05
Formation	0	1000	9.625	-	-	3.00E+06	0,3	-

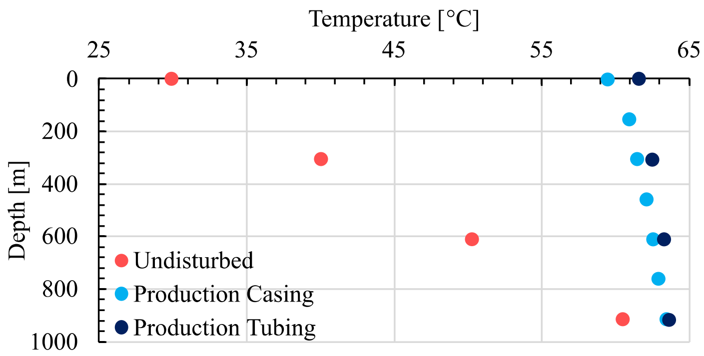

Figure 3. Temperature profile

5 Results

The subsequent sections present the results regarding the reproduction of the reference case study and the effect of evaluating the flexibility of the geological formation in the APB.

5.1 Reproduction of the reference case study

Table 2 presents the values of APB with the case study simulation and those obtained by Santos [6]. The difference between the two results is 1.115%, thus it is verified that the implementation used is correct, since the simulation provided results in accordance with the literature.

Table 2. Comparison of results

ΔP [psi]	ΔP Santos (2007) [psi]	Absolute difference [psi]	Relative difference[%]
1760.413	1741.000	19.413	1.115

5.2 Effect of the flexibility of the geological formation in the APB

As mentioned in the methodology, a value for the outer diameter (OD) of 10.75 inches is adopted. The values for the wall thickness (Wt) of the production casing appear on the x-axis in Fig. 4 (b).

Fig. 4 (a) shows the ratio of APB in an annulus surrounded by a semi-flexible formation and no formation to the APB in completely rigid annulus as a function of OD to wall thickness ratio of the production casing. The model simulated by Sathuvalli et al. [1] was not described in his article, so the graph is not reproduced. In this regard, the aim of this graph is only to compare the overall behavior of the curves. The ratio $\Delta P/\Delta P_{rigid}$, indicates how close the value of the APB approaches the APB for the rigid formation. Once the OD value is fixed, as Wt increases the OD/Wt ratio decreases. Although considering a different model from Sathuvalli et al. [1], the observed behavior is similar.

Fig. 4 (b) shows the absolutes values for APB in this three scenarios. Since the annulus is narrower for thicker casings, the fluid is confined in a smaller volume, thus the APB increases for larger values of Wt. Considering the formation as rigid (undeformable) restricts the volume variation of the annulus, for this case the temperature increase causes elevated values of pressure increase inside the annulus. Considering the formation as elastic-linear (semi-flexible) gives it a deformation capacity, which makes the annulus able to expand, increasing its volume and reducing the level of APB compared to rigid formations. For the case of the formation with null stiffness (no formation), the fluid confined in the annulus has an unconstrained volume change, limited only by the stiffness of the production casing. Therefore, the consideration of zero stiffness formation minimizes the APB values.

For the scenario studied in this paper, modeling the formation as semi-flexible and with null stiffness underestimates the APB by a maximum of 35% and 18%, respectively, in relation to the rigid formation. For design purposes, the most critical and therefore safest case is to treat the formation as rigid, however it leads to a higher cost associated with more resistant casings.

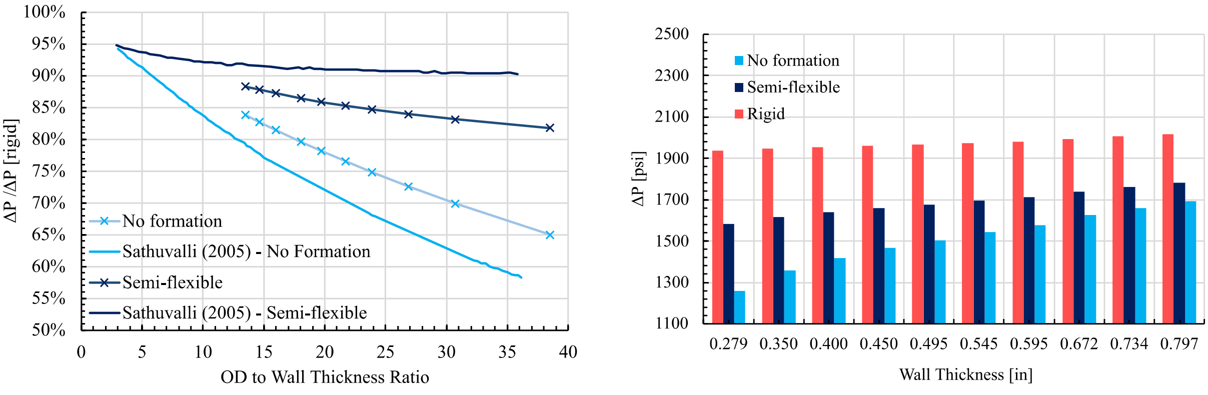

Figure 4. Results: (a) Effect of wellbore flexibility on APB; (b) Absolute APB in three scenarios

6 Conclusions

With the application of the methodology, it was possible to reproduce the case study, with the results presenting a difference of 1.115% in the calculation of the APB. Thus, the implementation was used to simulate variations of the case study, varying the stiffness of the geological formation. For the reference scenario, it was observed that the value of the formation elasticity modifies the APB level by up to 35%. In this context, accuracy on the prediction of the formation mechanical behavior is very relevant to avoid operational problems related to the casing under-dimensioning, providing gains in terms of operational safety, specially for thinner walls of casings where the variations are higher.

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