Numerical modeling of rupture disk as a method of controlling pressure in oil well annulus

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Abstract. The work objective is to present a computational model for pressure control in the confined annulus of oil wells using rupture disks. Throughout an oil well's life cycle, variations in its temperature provoke pressure increases in its annular spaces, known as Annular Pressure Build-Up (APB). The pressure difference between internal and external pressures on the casing or production columns can compromise their integrity, causing burst or collapse failure. A rupture disk allows hydraulic communication between the annulus when the pressure difference exceeds the disk's collapse pressure, balancing the volume and pressure and increasing the casings' safety factors. The methodology consists of four steps: i) reviewing the literature on rupture disks in APB contexts; ii) defining and numerically implementing pressure balance models; iii) a case study on a reference well to verify pressure balance models. At this step, a parametric study calculates the safety factors according to the disk position in the casings; and iv) evaluates the disk's ability to control annular pressures and protect the casings. The results show that the proposed methodology yields good results compared to the state-of-the-art. The main contribution is to present a rupture disk model and its impact on oil well casing integrity.

Keywords: Annular Pressure Build-up (APB), Pressure control methods, Wells integrity.

1 Introduction

Geothermal gradients, associated with operations carried out in oil wells, cause pressure variations in their annular spaces, a phenomenon called APB (Annular Pressure Build-up). The APB corresponds to the pressure variation in the annulus, due to well heating or cooling as a consequence of the drilling process or fluid production/injection operations. This heating generates the confined fluids expansion and the annulus volume variation (Santos [1]).

Neglecting this phenomenon can compromise the well's integrity through collapse or rupture due to the internal pressure of columns, formation fracture, or leakage of the sealing seal. If not adequately predicted in the design phase, its occurrence can also restrict the well's production, minimize its economic return, or even make the well's construction technically and economically unfeasible (Perez [2]).

The physical mechanism of APB is already well understood and documented. However, accidents caused by APB are still recorded (Sathuvalli et al. [3]). In this sense, APB mitigation techniques and annular pressure control have been studied and developed in recent decades to ensure well's integrity and improve their production capacity (Miller et al. [4]).

In this context, a rupture disk is one piece of equipment that can control the pressure in the annulus. It consists of a device that can rupture/collapse with a specific pressure difference (Liu et al. [5]), allowing communication between annular spaces and balancing the volume and pressure between them. It can also utilized to connect the annulus and the rock formation. This way, the liquid in the annulus expands and leaks into the formation through the rupture disk, so the annulus pressure decreases (Zhang et al. [6]).

Therefore, this paper aims to contribute studies concerning APB and its pressure control techniques, specifically using rupture disks. Another objective is to evaluate the influence of rupture disks on the well casings' integrity.

2 Methodology

The methodology adopted in this work development consists of four macro steps, as illustrated in Figure 1.

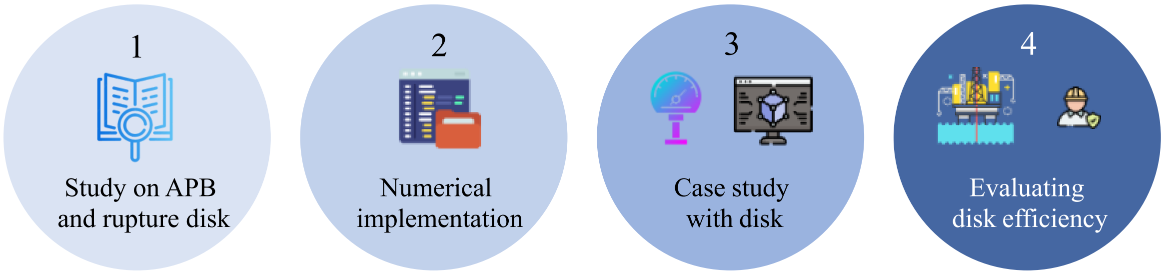


Figure 1. Methodology in this work development

The first step consists of reviewing aspects that affect the APB calculation. Regarding rupture disks, the mathematical modeling is based on Liu et al. [5]. Although the authors present three pressure balance models, only two are implemented in this work. The section 4 presents more details about disk modeling.

The second step consists of the computational implementation of these two pressure balance models. The equations that govern the disk's behavior are incorporated into the APB in-house simulator, developed by the research group, and used in other works (Vasconcelos [7] and Santos [8]).

The third step involves defining a reference well scenario as a case study. Initially, a simplified version of this reference well is used to verify the pressure balance models. Next, a parametric study varies the rupture disk position to evaluate its influence on the safety factors (SF) related to the burst and collapse of the well casings.

The fourth step evaluates the disk's ability to control the well annulus pressures. Integrity analysis is also performed at this stage, i.e., whether the casings' safety factors are below the allowed limits.

3 APB formulation

The Annular Pressure Build-up (APB) is determined by equalizing the fluid volume change (ΔV_{fl}) with the annular volume change (ΔV_{an}) (Oudeman and Kerem [9]), conform the eq. (1).

$$\Delta V_{fl} = \Delta V_{an} \tag{1}$$

The fluid volume change trapped in the annular is associated with its thermodynamic properties. One of the approaches found in the literature uses the fluid thermal expansion coefficient (α_{fl}) and its compressibility (k_t) to calculate ΔV_{fl}, according to eq. (2). Where ΔT is the temperature variation and ΔP is the pressure variation.

$$\Delta V_{fl} = V_{fl} \left[\alpha_{fl} \Delta T - k_t \Delta P \right], \tag{2}$$

To consider fluid properties as constants generally appropriate when the initial temperature and pressure in the fluids distribution do not vary significantly throughout the annular volume, the difference between the initial and final fluid temperatures is small, and the temperature change is positive (Sathuvalli et al. [10]). Like these conditions are unusual in typical oil well operations, strategies that relate α_{fl} and k_t with the fluid density according to pressure and temperature conditions are used. In Zamora et al. [11] a methodology for modeling drilling fluids is described. In this sense, Perez [2], Vasconcelos [7] and Santos [8] describe expressions for updating density, coefficient of thermal expansion and compressibility.

Furthermore, ΔV_{an} is determined according to the Lamé equations for thick-walled tubes, as a consequence of the linear elasticity applied to axisymmetric solids. This approach is used to calculate the wall displacements in hollow cylinders and, therefore, the variation in their volume.

eq. (1) can be used to estimate the APB value in a single annular (single string analysis). For analyses with multiple annulars (multi string analysis), the pressure variation in one annular directly interferes with the pressures of the adjacent annular. Therefore, applying eq. (1) to each annular of the well, obtain eq. (3), whose solution provides the APB values in the annulars (Sathuvalli et al. [3]).

$$[\Delta V_{fl}] = [\Lambda][\Delta P] + [\eta][\Delta T] \tag{3}$$

In eq. (3), $[\Delta V_{fl}]$ is the vector that denotes the fluid volume change in the well annular, $[\Lambda]$ is the flexibility matrix, $[\Delta P]$ is the APB vector, $[\eta]$ is the matrix whose terms provide the annular volume change of each annulus due to the casings thermal expansion that limit it and $[\Delta T]$ is the vector of casing columns temperature changes (Sathuvalli et al. [3]).

4 Rupture disk formulation

The mathematical modeling used to reproduce the rupture disk behavior is based on Liu et al. [5]. The authors present three pressure balance models that simulate the rupture disk operation: i) piston model (Figure 2 (a)), assuming that there is no fluid exchange between two annular and provides the simplest solution; ii) fully miscible fluid model (Figure 2 (b)), which is intended for annular with the same type of fluid, but with different density values; and iii) fully immiscible fluid model (Figure 2 (c)), which is intended for annular with different types of immiscible fluids, such as oil-based mud in the inner annulus and water-based mud in the outer annulus.

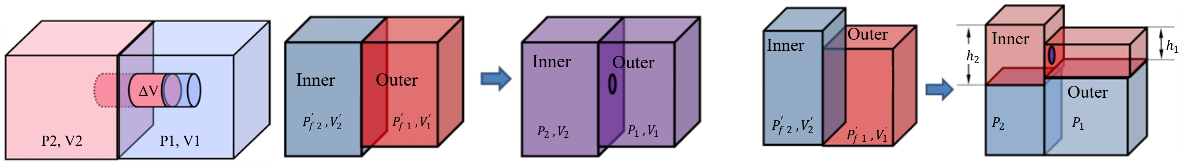


Figure 2. Pressure balance models: (a) Piston; (b) Fully miscible fluid; (c) Fully immiscible fluid. (Liu et al. [5])

In this paper, only the piston and miscible fluid models are studied. For the immiscible fluid model, Liu et al. [5] don't make explicit how the interface heights between fluids are calculated (Figure 2 (c)).

In the piston model, fluids move from the higher pressure annular to the lower pressure annular until the pressures are balanced. The volume change associated with the piston displacement, as illustrated in Figure 2 (a), is calculated with eq. (4) (Liu et al. [5]).

$$\Delta V = \Delta P_m \frac{k_{t2}V_1 \cdot k_{t1}V_2}{k_{t2}V_1 + k_{t2}V_2} \tag{4}$$

In eq. (4), k_t is the average compressibility of each fluid, and V is the annular volume considering rigid casings. After determining the piston volume change, it is possible to calculate the final APB for each annular after the pressure balance ΔP_{bld}, according to eq. (5). $\Delta P_{bld}{}'$ is the APB value if the disk had not ruptured.

$$\Delta P_{bld1} = \Delta P_{bld1}{}' + \frac{\Delta V}{k_{t1} \cdot V_1}; \Delta P_{bld2} = \Delta P_{bld2}{}' - \frac{\Delta V}{k_{t2} \cdot V_2} \tag{5}$$

The APB values are used to determine the final pressures in each annular, according to eq. (6). Note that, for this approach, the APB and pressure calculation is independent of the depth disk installation. Final pressures at all depths can be calculated using eq. (6).

$$P_{f1} = P_{i1} + \Delta P_{bld1}; P_{f2} = P_{f1} = P_{i2} + \Delta P_{bld2} \tag{6}$$

For the miscible fluid model, the internal and external fluids are assumed to be fully mixed after the rupture disk opens. Therefore, the internal and external fluids must have the same density ρ_{mix}, compressibility k_{tmix} and coefficient of thermal expansion α_{mix} (Liu et al. [5]). Therefore, these parameters are calculated with eq. (7).

$$\rho_{mix} = \frac{\rho_1 V_1 + \rho_2 V_2}{V_1 + V_2}; k_{tmix} = \frac{k_{t1} V_1 + k_{t2} V_2}{V_1 + V_2}; \alpha_{mix} = \frac{\alpha_1 V_1 + \alpha_2 V_2}{V_1 + V_2} \tag{7}$$

Similar to the piston model, the volume change is determined using the eq. (4), however, using the mixture compressibility k_{tmix}. The APB values are updated according to the eq. (5). The final pressures are determined using eq. (6), but they are only valid at the rupture disk installation depth. As illustrated in Figure 3, the final pressure profile (green line) is not parallel to the initial pressure profiles (black and red solid lines), because the fluids are completely miscible and their initial densities have been modified. In this way, the pressures at other depths (TVD - True Vertical Depth) are calculated using eq. (8), with the depths expressed in feet and the density in ppg.

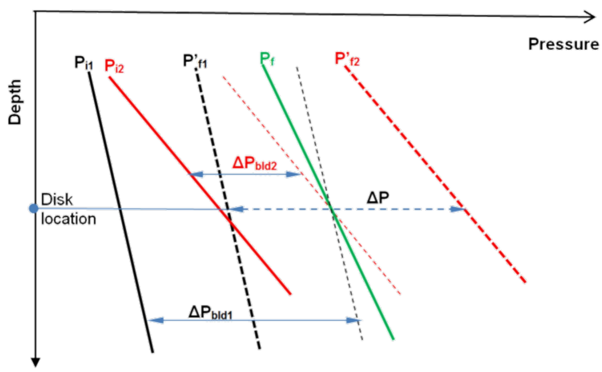


Figure 3. Pressure profiles of fully miscible fluids (Liu et al. [5])

$$P_f(TVD) = P_f(TVD_{disk}) + 0,052 \cdot (TVD - TVD_{disk}) \cdot \rho_{mix} \tag{8}$$

5 Case Study

To verify the pressure balance models and analyze the casings' integrity, a reference well is used, illustrated in Figure 4, which presents four annular wells with different boundary conditions.

Table 1 presents the specifications of the analyzed well. The well has a rotary table height of 25,00 m and a water depth of 2138.00 m. A single shale layer with behavior in a linear elastic regime is adopted. The packer depth in the first annulus is 4771,78 m.

Table 1. Application well specification

Name	Type	Top (m)	Bottom (m)	TOC (m)	ID (pol)	OD (pol)	Hole Size (pol)	Linear weight (lbf/pé)	Grade
Conductor	Casing	2163,00	2247,92	2163,00	33,00	36,00	42,00	554,00	L80
Surface	Casing	2163,00	3350,45	2816,00	18,00	20,00	26,00	203,11	L80
Intermediate	Casing	2163,00	4794,17	4202,00	12 3/8	13 5/8	16,00	88,20	L80
Production	Casing	2163,00	4999,73	4270,00	9,56	10 3/4	12,25	65,70	L80
Production	Tubing	2163,00	4893,41	-	6,05	6 5/8	-	20,00	L80

The reference well simulates a 3000 m³/day oil production operation. The simulation considers that, initially, the well is in geothermal equilibrium and obtains steady-state temperature profiles from the well production. The thermal simulation results are presented in the graphs in Figure 5.

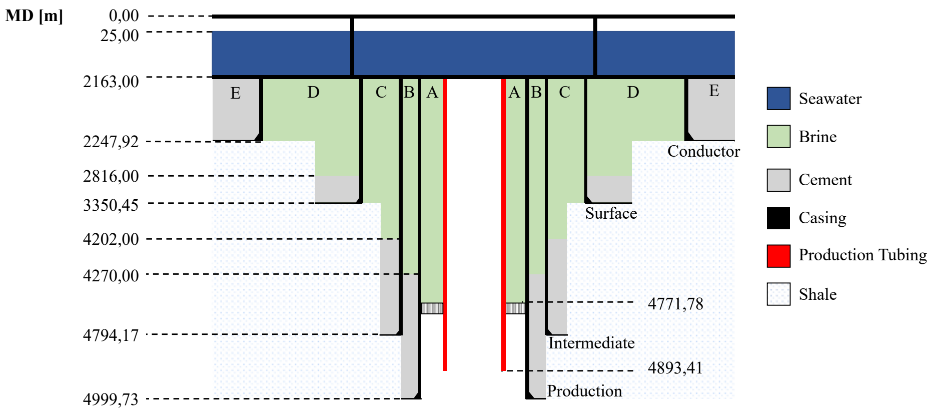
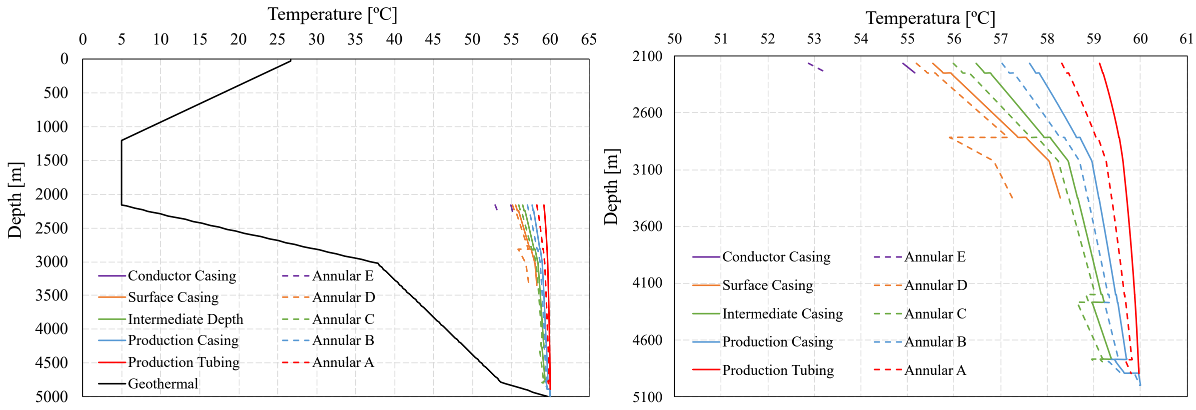


Figure 4. Reference well



(a) (b)

Figure 5. Temperature gradients: (a) Thermal profiles; (b) Thermal profiles of casing and annulars

6 Results

The APB formulation, presented in section 3, had already been computationally implemented in C++ code in the APB simulator developed by Vasconcelos [7]. In this sense, the rupture disk formulation, presented in section 4, is integrated into the same simulator.

The two pressure balance models are applied to a simplified representation of the reference well to validate the implementation, considering annular containers A and B, with the one rupture disk presence, as illustrated in Figure 6.

In the piston model, annular A and B contain fluids of the same base type and density (8,6 ppg). In the miscible fluid model, the base type of the fluids in both annular A and B stays the same. However, the fluid density in annulus B increases to 10,0 ppg. This difference in density between the annulus creates a miscible fluid effect, where, after the disk ruptures, there is a mixing between the annular fluids.

Figure 7 presents the results, using the piston model (Figure 7 (a)) and using the miscible fluid model (Figure 7 (b)). The solid red and black lines represent the initial pressures in annulus A and B, respectively. The dashed lines represent the final pressures in annulus A and B, where the rupture disk is not ruptured. These final pressures indicate the condition without pressure equalization between the annulus, that is, without the effect of the rupture disk. Finally, the green line represents the equilibrium pressure profile after the rupture disk opens. This line represents the condition where the pressure in annulus A equals the pressure in annulus B due to the rupture disk action.

In the piston model analysis (Figure 7 (a)), the pressure profile of each fluid is identical. Hence, no pressure differential is exerted across the steel barrier separating the two annuli. In the final condition, if the rupture disk is not ruptured, a pressure differential of 3538,26 psi is observed on the steel.

For the miscible fluid model (Figure 7 (b)), a maximum pressure differential of 1034,03 psi is observed in the initial condition. In the final condition, disregarding the rupture of the disk, there is a minimum pressure

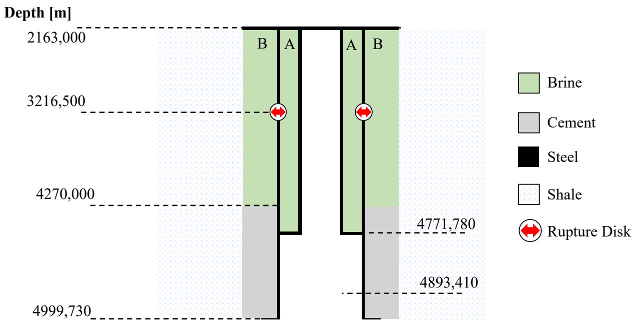


Figure 6. Simplified representation of the reference well with rupture disk

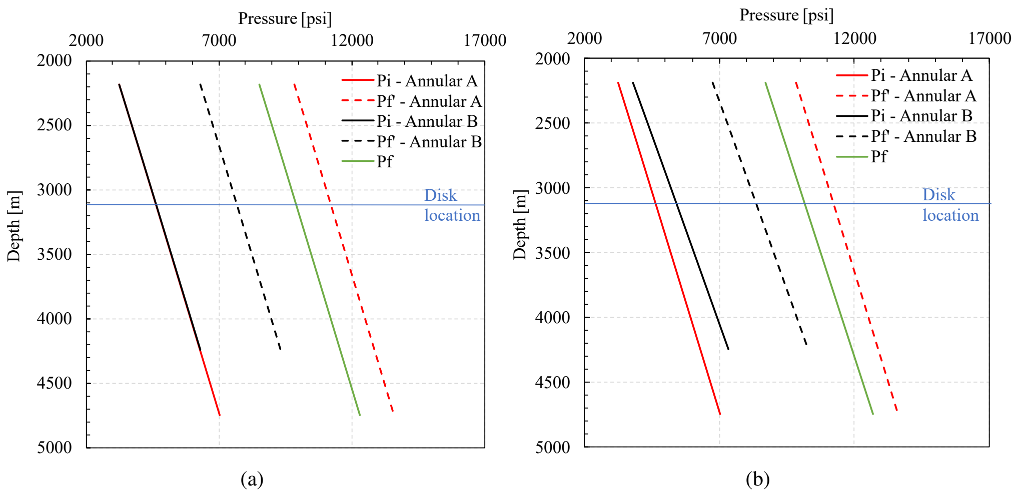


Figure 7. Pressures for the simplified model: (a) Piston model; (b) Miscible Fluid Model

differential on the steel of 3088,17 psi.

Therefore, a burst pressure of 1050,00 psi has been set for the disk. It is a suitable choice as it ensures that the rupture disk remains inactive in the initial condition of both models. This value is lower than the pressure differentials of 3538,26 psi and 3088,17 psi observed in the final condition in the respective scenarios, signaling that the disk is activated when the pressure differential in the casing reaches the disk burst pressure. Liu et al. [5] suggest that the burst pressure be equal to or greater than 1000.00 psi, reinforcing the adopted value adequacy.

After verifying the implementation, a parametric study evaluates the safety factors casings. A scenario is generated, called a modified well, where the surface casing of the reference well is replaced by a casing of lower resistance. Steel grade H40 and a thickness of 0.563 in is adopted for this casing. Additionally, variations in the positioning of the rupture disk in the modified well are considered.

Most companies do not publish their safety factors. Sometimes, they also vary the factor according to the type of load. This paper uses the values presented in Bellarby [12], where the casings are in the safe region when the SF is greater than 1,0 and 1,1 for collapse and burst, respectively.

Table 2 presents the comparison of safety factors for all evaluated scenarios. The results indicate that the base model casings are in the safe region, even without rupture disks. However, replacing the surface casing with a casing of lower resistance takes this casing for the failure region.

Table 2. Safety factors comparison

Well	Rupture Disk		SF (Fail mode)	
	Intermediate casing	Surface casing	Intermediate casing	Superface casing
Reference	Absent	Absent	2,68 (Burst)	4,34 (Collapse)
Modified	Absent	Absent	3,61 (Burst)	0,87 (Collapse)
Case 1	Present	Absent	347,09 (Burst)	1,06 (Collapse)
Case 2	Absent	Present	15,35 (Burst)	407468,13 (Collapse)
Case 3	Present	Present	8370,22 (Collapse)	1280221,49 (Burst)

According to the results, a rupture disk can enhance the surface casing integrity, increasing its safety factor to a safe value. This demonstrates that rupture disks can effectively safeguard casing, especially when there are variations in their resistance.

In some cases, it is possible to observe high values for the safety factor due to the equalization of pressures in the annulus through the use of rupture disks. When the disks are ruptured, they allow fluid flow between the annuli, equalizing pressures and reducing pressure differentials across the liners. As a result, casings are better protected, and well integrity is better preserved.

7 Conclusion

This paper presented an approach for numerical APB simulations and pressure control in annulus using rupture disks. The results suggest that by opting for a lower stell's grade or thinner casing, which are generally more economical, and combining them with the protection provided by rupture disks, it is possible to obtain an efficient and economically viable solution. It is worth mentioning that the APB simulator used in this work doesn't calculate the APB in a transient regime. In real scenarios, pressure increases in the initial moments can cause the disk to rupture before the pressures reach a steady state. Therefore, the transient calculation must be considered in real cases so that the safety factors are not exceeded.

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