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MODELING FLOW RESTART EFFECTS ON ANNULAR PRESSURE BUILD-UP

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Abstract. *During oil well drilling, metal casings are attached to the wellbore to ensure its structural stability and prevent fluid leaks into the rock formation. Consequently, fluid ends up confined in the annular spaces between the casings and is subject to an increase in pressure known as annular pressure build-up (APB) due to temperature increase. APB is mainly caused by the temperature variations that the well undergoes throughout its life cycle, due to geothermal gradients and fluid flow. Several studies have focused on predicting and mitigating its causes and effects, usually calculating the well temperature and relating it to the confined fluid's density and volume variations. However, most studies consider a constant operating condition to obtain the steady state condition of pressure and temperature, while transient analysis are relatively recent. The present work proposes a one-dimensional transient mathematical model to predict annular pressure changes due to temperature changes in a well's cross section, caused by flow restart after a well shut-in. A transient heat transfer model is coupled to linear elasticity model and solved by using the finite-differences method. Results show the pressure variations in the annuli following a flow restart, where the innermost annulus experiences the most pronounced pressure variation. The abrupt pressure difference causes a stress peak on the innermost casing, presenting concern for casing integrity. Observed effects emphasize the transient nature of APB and the need for modeling of varying operational conditions. In conclusion, the one-dimensional approach provides valuable insight in transient APB while being computationally fast and easy to implement. The main factors that affect APB can be categorized in: well's geometry, material properties and operating conditions. Well design and operational procedures must be based on each well's unique circumstances.*

Keywords: *annular pressure build-up, transient, oil well, casing stress*

1. INTRODUCTION

During the well drilling phase of oil and gas exploration, metallic casings are inserted into the borehole to ensure the system's structural integrity. Several casings may be placed sequentially, one inside another, and the resulting annular spaces between them remain filled with cement or drilling fluid during the well's remaining life cycle. The increase of pressure in these annular spaces is known in the industry as APB (annular pressure buildup) and occurs due to the expansion of the trapped fluid in the annulus subjected to temperature variation. These pressure variations are concerning to well safety, as there have been reports of APB related well failure during oil and gas production (Bradford et al., 2004; Pattillo et al., 2007; Vargo et al., 2002) and even during the drilling phase (Pattillo et al., 2006).

Multiple factors contribute to thermal variations within the system. Mainly, there is the geothermal gradient, where temperature rises with increasing depth, and the fluid flow along the well, which facilitates thermal exchange between different regions (Holmes and Swift, 1970). One critical scenario is the flow restart after a pause in production. Hot oil and gas originating from the reservoir come in contact with regions that have stablished thermal equilibrium with the geothermal gradient, potentially causing a thermal shock that may be critical to APB.

APB prediction typically involves using the well's thermal profile and thermodynamical relationships to calculate the pressure in the annuli. If the temperature profile is known, pressure within the annuli can be determined by thermodynamical relationships between pressure, temperature and annulus volume. Several studies have shown that each annulus has an impact on adjacent ones, so all the systems must be computed simultaneously. This methodology is known as the multi-string approach (Adams, 1991; Adams and MacEachran, 1994; Halal and Mitchell, 1994; Oudeman et al., 1995).

However , numerous APB studies made their analysis on steady state temperature regimes, often assuming a constant flow rate on the production tubing (Alcofra, 2014; Sathuvalli et al., 2005; Yang et al., 2013). The analysis of the transient periods, such as well shut-in and flow restarts, is a relatively recent development, enabled by the advance of computational technology, which allowed the simulation of more complex models (Barcelos et al., 2017; Hafemann, 2015; Martins et al., 2023, 2022). Additionally, most studies have not delved into the analysis of casing stresses or failure criteria, limiting their scope to the determination of the pressure variations in the annuli due to APB.

The objective of this work is to propose a mathematical model that simulates APB caused by a flow restart condition. A one-dimensional, transient approach is used to predict temperature and pressure behavior in typical well geometries. The thermal energy and force balance equations are applied on a multi-layered system representing a well to identify which parameters are critical to APB analysis.

2. MATHEMATICAL MODEL

Due to their complexity, wells are generally modeled at least as two-dimensional. However, introducing transient effects would require a coarse mesh or extensive computational times. Considering only a cross section of the well, it is possible to solve the problem in one dimension with a refined radial mesh and analyze the system's overall behavior during rapid transient time scales. In this context, axial variations are disregarded and axial symmetry is considered. The system can then be divided into layers, each with its own homogeneous material, where the thermal energy and force balance are applied. Consider the system with N non-uniform layers in the radial direction r, as shown in Figure 1.

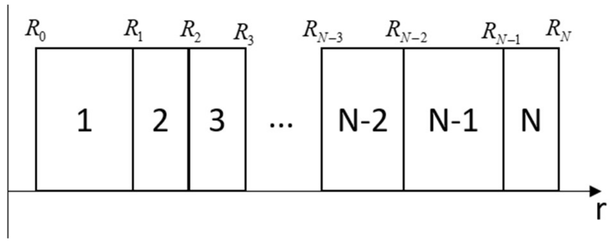

Figure 1. Schematic of the multi-layered one-dimensional system

2.1 Thermal energy balance

To determine the temperature profile, the thermal energy balance is applied to the system. Considering constant properties and disregarding the convection of trapped fluids (due to their high viscosities and gel properties), the problem is reduced to the one-dimensional transient heat diffusion (Incropera and DeWitt, 2008), expressed as:

$$\frac{\partial T}{\partial t} = \frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r} \right) \tag{1}$$

where T is temperature and α is the thermal diffusivity. Eq. (1) can then be solved by the finite differences method to obtain the radial temperature profile over time.

2.2 Force balance

The pressure and stress profiles within the well are derived from the force equilibrium. It is assumed that shear stresses are negligible and considering the fluid completely trapped in the annulus. Considering Hooke's law for linear elasticity with thermal deformation (Timoshenko and Goodier, 2010):

$$\varepsilon_r = \frac{1}{E}\left[\sigma_r - \nu\left(\sigma_\theta + \sigma_z\right)\right] + \beta\left(T - T_{amb}\right) \tag{2}$$

$$\varepsilon_\theta = \frac{1}{E}\left[\sigma_\theta - \nu\left(\sigma_r + \sigma_z\right)\right] + \beta\left(T - T_{amb}\right) \tag{3}$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu\left(\sigma_r + \sigma_\theta\right)\right] + \beta\left(T - T_{amb}\right) \tag{4}$$

where ε is the strain, E is the elasticity modulus, σ is the normal stress, β is the linear thermal expansion coefficient and T_{amb} is the ambient temperature. Lamé's solution (Timoshenko and Goodier, 2010) for the stress and profiles in a thick cylinder wall is given by:

$$\sigma_r = A + \frac{B}{r^2} \tag{5}$$

$$\sigma_\theta = A - \frac{B}{r^2} \tag{6}$$

$$\sigma_z = 2\nu A + E\left[\varepsilon_z - \beta\left(T - T_{amb}\right)\right] \tag{7}$$

where A and B are coefficients to be determined through boundaries and coupling conditions, specific to each well geometry. Note that for a fluid layer, all three normal stresses are equal and related to its pressure P as:

$$\sigma_r = \sigma_\theta = \sigma_z = -P \tag{8}$$

Note the negative sign, which indicates that pressure is a compressive stress. Finally, the fluid pressure in each annulus can be related to its temperature and volume V through (Oudeman and Bacarreza, 1995):

$$\Delta P = \frac{\kappa_P}{\kappa_T}\Delta T - \frac{\Delta V}{k_T V} \tag{9}$$

where κ_T and κ_P are the fluid's isothermal compressibility and isobaric thermal expansion coefficients, respectively. With these considerations, any fluid layer may be solved within the same equation system, so stresses and pressures in casings and annuli must be solved simultaneously.

2.3 Initial condition

Before the flow restart, the well is assumed to have reached thermal equilibrium with the geothermal system, which is considered to be at the temperature T_0.

$$T\left(r, t = 0\right) = T_0 \tag{10}$$

As the stresses do not depend directly on time, the initial stress condition is determined by the initial temperature.

2.4 Boundaries conditions

At the innermost radius, the first wall exchanges heat with the flowing fluid. Therefore, the first boundary condition is assumed as convection heat transfer:

$$-k_1 \left.\frac{\partial T}{\partial r}\right|_{r=R_0} = -h\left[T\left(r = R_0\right) - T_{fluid}\right] \tag{11}$$

where k_1 is the first layer's thermal conductivity, h is the convection coeficient between the first layer and the production fluid at constant temperature T_{fluid}. For each subsequent layer n, the thermal conditions at the outer interface are:

$$T_n\left(r = R_n\right) = T_{n+1}\left(r = R_n\right) \tag{12}$$

$$k_n \left.\frac{\partial T_n}{\partial r}\right|_{R=r_n} = k_{n+1} \left.\frac{\partial T_{n+1}}{\partial r}\right|_{r=R_n} \tag{13}$$

For the last temperature condition, it is assumed that at a far enough radius, temperature remains unaffected by the system:

$$T\left(r \to \infty, t\right) = T_0 \tag{14}$$

The first stress boundary condition, at the innermost radius, considers that there is free radial deformation. Therefore, the reacting stress must be null:

$$\sigma_r\left(r = R_0, t\right) = 0 \tag{15}$$

For each intermediate interface, the stress and deformation must be continuous:

$$\sigma_{r,n}\left(r = R_n\right) = \sigma_{r,n+1}\left(r = R_n\right) \tag{16}$$

$$\varepsilon_{\theta,n}\left(r = R_n\right) = \varepsilon_{\theta,n+1}\left(r = R_n\right) \tag{17}$$

At the last region, there is no strain at a far enough radius.

$$\varepsilon_\theta\left(r \to \infty, t\right) = 0 \tag{18}$$

Additionaly, the system is considered to be axially bound, so there is no axial strain at any layer:

$$\varepsilon_z = 0 \tag{19}$$

2.5 Von Mises stress failure criteria

To evaluate stresses and identify potential failure due to APB, the von Mises criteria were employed (Timoshenko, 1940). The criteria combine the three normal stresses into a single stress σ_{vm}, which may be compared directly to a material's yield stress.

$$\sigma_{vm} = \sqrt{\frac{\left(\sigma_r - \sigma_\theta\right)^2 + \left(\sigma_\theta - \sigma_z\right)^2 + \left(\sigma_z - \sigma_r\right)^2}{2}} \tag{20}$$

3. CASE STUDY

A particular case was studied to understand the behavior of APB during the flow restart and illustrate the practical application of the proposed model. The chosen geometry is based on a typical well configuration, considering the production tubing and three steel casings. The three resulting annuli are assumed to be filled with synthetic based drilling fluid (Zamora et al., 2013). The dimensions used to simulate the well are shown in Table 1.

Table 1. Well's geometries and dimensions

Geometry	Inner Radius [m]	Outer Radius [m]
Production tubing 5 1/2"	0,030	0,035
Production casing 9 5/8"	0,057	0,061
Intermediate casing 13 3/8"	0,080	0,085
Surface casing 20"	0,114	0,127

The flow restart condition was imposed, where the production fluid was assumed to be at a constant temperature of 72ºC. Figure 2 illustrates the pressure variations in the annuli after the flow restart. As expected, pressure builds up in the annuli over time and the innermost annulus has the highest and fastest increase, as it is the closest to the heat source. The second and third annuli follow the same behavior, but delayed due to their increasing distance to the center. As the system approaches a steady state regime, the rate of pressure increase slows down. The observed pressure variations emphasize the transient nature of APB during flow restart, highlighting the significance of modeling and predicting APB effects during such operations.

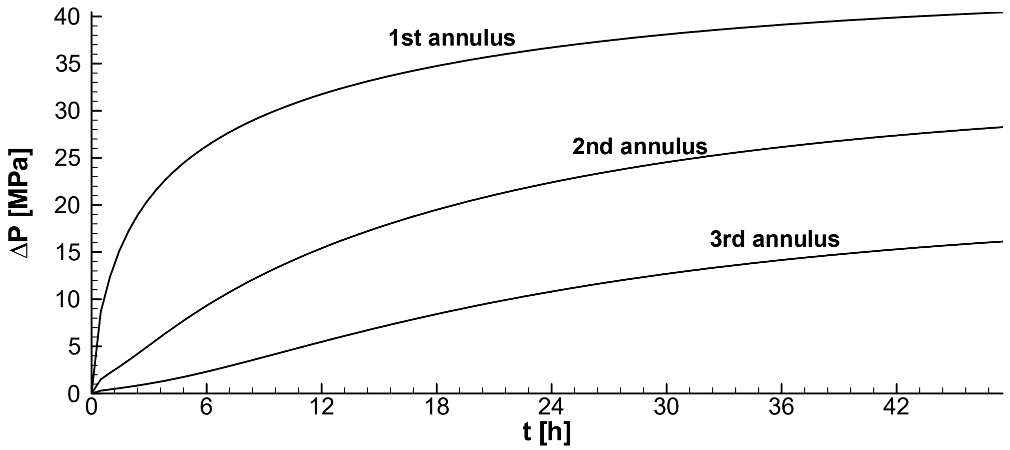

Figure 2. Pressure variation in the annuli after flow restart

For the failure analysis, the von Mises stresses are shown in Figure 3. Note the stress peak at the innermost casing, occurring around 6 hours after the flow restart. This peak surpasses the yield stress σ_y for oil and gas tubing, typically aroung 245MPa (API, 2004). The stress peak is directly related to the pressure difference between the first and second annuli, which is highest during this time frame. In this particular case, the intermediate and surface casing did not display a stress peak, but it is essential to emphasize that real-world field conditions may vary due to several factors, and thus, case-specific analysis must be made.

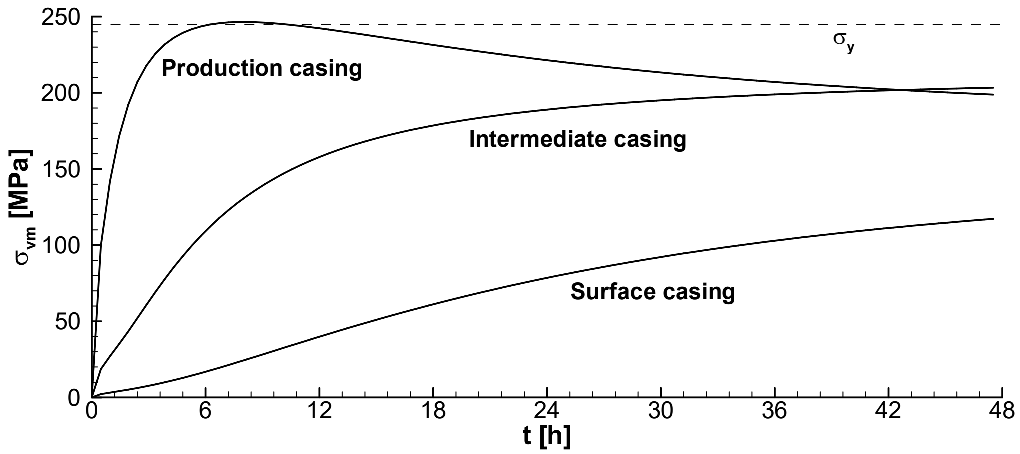

Figure 3. Casing von Mises stresses after flow restart

The potential for casing failures highlights the need for well design and operational practices that can alleviate excessive stress levels. Based on results obtained by the proposed model, it has been identified three main factors that govern APB and casing stresses:

- **Geometry** – Due to the multi-string complexity of the problem, the dimensions of the casings are fundamental to the result. Each layer's width will influence on the heat transfer rate to the adjacent layers, as well as the stress distribution for solid layers and available space for fluid compression.
- **Material properties** – While the casings are usually made of steel, the trapped fluid may vary in properties, due to the many different formulations used in the industry. Furthermore, wells go through different types of rock formations, depending on location, geology and depth. Differences in thermal diffusivity, thermal expansion and compressibility among various different types of materials can lead to varying APB behaviors.
- **Operating condition** – APB is dependent on the well's thermal history, so any operation that may alter the temperature profile, such as shut-ins and flow restarts, are critical. Changes in fluid flow rate can influence convection coefficients and, consequently, heat transfer rate to the annuli.

Therefore, to minimize the risk of APB associated failure, it is important to consider casing design and operational procedures based on specific conditions of each well.

4. FINAL REMARKS

In conclusion, this study proposes a one-dimensional transient model to predict annular pressure build-up during flow restart in oil wells. The thermal energy balance and force equilibrium equations are combined to compute temperature, pressure and stress distribution across a well's cross-section. Through a case study, a stress peak was observed during flow restart after a shut-in, with potential risk of casing failure. Results highlight the transient nature of APB and the need for transient models to predict it.

The simulation of an entire well is a complex problem that would require at least a two-dimensional approach. Nevertheless, the one-dimensional approach can provide valuable insight into the overall behavior of the system when varying parameters, while being computationally fast and easy to implement. Three main factors were identified to govern APB and casing stresses: well's geometry; material properties (casings, fluids and rock formations); and operating conditions. Since each well is unique, its design and operational protocols must be done case-by-case.

Transient models, coupled with field data, are key in optimizing well design and operational practices to mitigate APB related risks. Continuous monitoring and real-time analysis of well conditions are of utmost importance to ensure well integrity. Further research can be done by expanding the model's applicability to a broader range of well configurations, fluid and geological formation, as well as the inclusion of various operational scenarios and conditions.

5. ACKNOWLEDGMENTS

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