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# Parametric Analysis of the Annular Pressure Change Mitigation with Rupture Disks

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**Abstract:** *Offshore petroleum production occurs in subsea reservoirs which usually operate at high pressure and temperature conditions. Injection of fluids in the reservoir causes temperature variations in the fluids trapped in the annular layers adjacent to the injection tubing, hence, a pressure increase in these annular cavities is expected. Several mitigation procedures and devices have been developed to mitigate this pressure variations, which can be achieved by reducing the heat exchanged with the injection fluid, employing fluids with special properties, or enabling fluids' movement across the annuli. This latter involves using devices known as rupture disks, which are placed between adjacent annuli and after a sufficiently high pressure difference between the layers is attained it opens and fluid flows between layers according to the negative pressure difference. The present work employed a semi-transient uni-dimensional thermo-structural model to calculate the temperature distribution of all wellbore components; the mass transferred between adjacent annuli was calculated with a previously developed model based on a dynamic time mesh refinement, based on the physics of the phenomena. An offshore well located in a Brazilian oilfield was used on the simulations, with its fluid components thermophysical properties dependence upon their thermodynamic state being considered. All the results were evaluated with a parameter based on the pressure difference across the casing; this parameter can be evaluated as a casing failure probability, with values higher than 1 being considered as a significant risk. The present study consists on near 200 simulations which focused on two different aspects: the disk configuration (installation depth, opening load, radius) and parameter operations (inlet temperature and injection rate). The results indicated that no parameter regarding the disk configuration has any influence on the structural results. As for the injection parameters, the inlet temperature had more influence on the maximum values at the end of the simulation while the inlet flow rate controlled the growth rate of the inter-annular pressure difference and the disk opening time, respectively.*

**Keywords:** *Annular Pressure Change, Rupture Disk, Injection Well, Transient Model*

## 1. INTRODUCTION

Exploration of deepwater oil reservoirs entails special wellbore projects to avoid structural failures caused by the high-pressure/high-temperature environment. Such is the case of the phenomenon known as Annular Pressure Change (APC), which is known for over 30 years (Adams, 1991; Adams and MacEachran, 1994), but attention has been drawn towards it on the last decade (Hasan *et al.*, 2010; Hasan and Kabir, 2012), with the increase in the exploration of offshore wells. This phenomenon is characterized by the pressure variation inside the sealed cylindrical cavities adjacent to the inner tubing, where hot fluids flow upwards, production wells, or cold fluid flows downwards, injection wells; due to the heat transfer caused by this fluid flow, temperature changes both axially and radially, and this annular pressure variation is observed. Pattillo *et al.* (2004) presented a field case of casing failure due to the APC.

Oudemans and Bacarreza (1995) proposed the first mathematical model to account for the APC, their model is still widely used in most studies. The authors proposed a simple mathematical expression to account for the three main factors in the pressure change: temperature, annular volume and annular fluid mass variations. The first one is accounted for with wellbore thermal models, which predicts temperature distribution across the well during operation, while the second usually relies on structural deformation models, like the one from Halal and Mitchell (1994) and, at last, mass variations inside the annular are either neglected or the transfer from the annular space to the adjoining formation can be estimated with in-situ correlations, albeit none could be found in the literature. Hasan *et al.* (2010) estimates the thermal parcel to be responsible for 80 - 90 % of the APC, so the remaining ones can be neglected. Recent works (da Veiga *et al.*, 2022; Martins *et al.*, 2022) presented novel formulations for the APC estimation based on the fluid's mass conservation inside

the annular space.

Multiple authors (Sathuvalli *et al.*, 2016; Dong and Chen, 2017) have proposed classifications regarding mitigation techniques according to the nature of device employed or simply which phenomenon is the target of the mitigation. Among the many techniques widely available in the literature, the rupture disk stands out due to its low cost and easy installation. Liu *et al.* (2016) proposed different models to solve the pressure balance between adjacent annuli, however the authors employed arbitrary temperature curves obtained from a commercial software to simulate the fluids' behavior.

Wellbore thermal models are employed in well simulations for more than 50 years, with the seminal work by Ramey (1962) being a cornerstone for most recent models. The author proposed an analytical solution to a 1D semi-steady state energy balance equation of a fluid being injected on a well. To account for the transient nature of the formation surrounding the well the author proposed the use of so-called time functions, i.e., algebraic expressions obtained from a previous solution of the partial differential energy balance at the formation considering a set of simplifying boundary conditions. Many researchers advanced on this work, by incorporating new features, such as more robust time functions and phase change considerations (Hasan and Kabir, 1991; Chiu and Thakur, 1991; Hasan and Kabir, 2002; Hagoort, 2004; Hasan *et al.*, 2005; Cheng *et al.*, 2011; Ferreira *et al.*, 2017).

Advances on numerical techniques and computational technology enabled the development, solution and application of full transient thermal models, which presents the advantage of using variable inlet data, as usually occurs in the field, with the downside of increased computational cost when compared to the simpler semi-steady state models. Simulation of injection operations are found in the literature (de Almeida *et al.*, 2017; O'Reilly *et al.*, 2017; Yi *et al.*, 2018; O'Reilly *et al.*, 2021). Martins *et al.* (2022) coupled a one-dimensional transient thermal formulation to a structural deformation model (Halal and Mitchell, 1994) to estimate the annular pressure variation through time. The transient formulation enables the use of field data as input information and it favourably compared to the PDG pressure and temperature information of a recycled seawater injection well. The authors also developed a model for the mitigation effect of placing a rupture disk between adjacent annuli and evaluated different disk installation configurations and their results.

The present study focused on a parametric analysis concerning the disk parameters (opening radius and load and installation depth) along with the inlet conditions (temperature and flow rate). The results will be analyzed with the dimensionless parameter proposed by Martins *et al.* (2022).

## 2. WELLBORE DESCRIPTION

The injection wellbore studied in Martins *et al.* (2022) was also studied in the present work and it is shown in Fig. 1. This well is composed by three annuli, namely A, B and C, comprised by a mixture of water and glycol 50/50 %wt, 1103 kg m<sup>-3</sup> brine and seawater, respectively; the injection fluid is also seawater, modeled as a mixture of water and sodium chloride 95/5 % wt. A cementation discontinuity is located under Annulus B and was filled with oil diesel. The seabed depth is 1348 m and the well is 2790.33 m long.

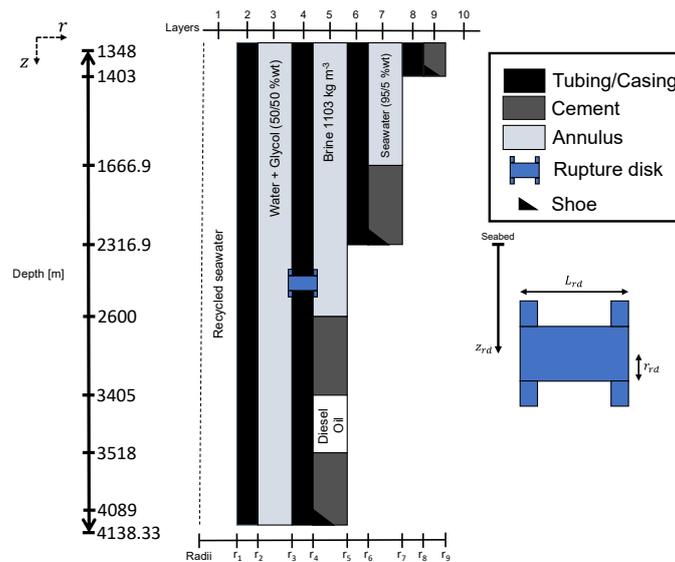


Figure 1: Wellbore diagram

Note that the rupture disk is placed between Annuli A and B, and three geometric parameters are important in its description: its length,  $L_{rd}$ , is determined by the installation casing thickness, and its installation depth,  $z_{rd}$ , and radius,  $r_{rd}$ , will be parametrized in the current work.

### 3. MATHEMATICAL MODEL

The present section describes the mathematical model employed on the simulations. All differential equations were solved with the finite difference method in a computer code developed on the language Python 3 (Van Rossum and Drake, 2009).

#### 3.1 Energy and Momentum Balance

Aside from the momentum balance expressions, due to the time scale of the phenomena, all conservation equations were obtained in a transient formulation. Equation 1 is used to estimate the pressure drop at the injection fluid layer and is composed by three different terms, right side of the equation, gravity, friction and acceleration terms, respectively. Note that the some parameters, like friction coefficient, depend on the flow regime. The present study considered single-phase flow and  $f$  was estimated via the correlation from Pritchard (2011).

$$\frac{\partial p_1}{\partial z} = \rho_1 g \sin \theta - \frac{f_1 \rho_1 v_1^2}{4r_1} - \rho_1 v_1 \frac{dv_1}{dz} \quad (1)$$

where  $p$  is pressure,  $z$  is axial distance to the seabed,  $\rho$  is density,  $g$  is gravity,  $f$  is friction coefficient,  $\theta$  is the angle between the seabed and the well,  $v$  is velocity,  $r$  is radius and the subscript 1 refers to the flowing fluid.

The thermal model geometry is a set of axis-symmetrical cylinders, with each one comprised of a different material composing the well (injection fluid, tubing, annulus A and so on). An energy balance in a generic element yielded Eq. (2),

$$\rho_i c_{p,i} \frac{\partial T_i}{\partial t} + \rho_i c_{p,i} v_i \frac{\partial T_i}{\partial z} = \frac{\partial}{\partial z} \left( k_i \frac{\partial T_i}{\partial z} \right) + K_{i/i+1} (T_{i+1} - T_i) - K_{i-1/i} (T_i - T_{i-1}) + (1 + \rho_i \gamma_{J,i} c_{p,i}) \left( \frac{\partial p_i}{\partial t} + v_i \frac{\partial p_i}{\partial z} \right) + \frac{P_i}{A_i} \Upsilon_i v_i, \quad (2)$$

where  $c_p$  is specific heat,  $T$  is temperature,  $t$  is time,  $k$  is conductivity,  $K$  is thermal conductance,  $\gamma$  is Joule-Thomson coefficient,  $P$  is wetted perimeter,  $A$  is area,  $\Upsilon$  is frictional pressure drop (third term on the right side of Eq. (1)) and the subscript  $i$  refers to the layer in which the equation is being applied.

Equation (2) is composed of the transient and axial advective heat transfer terms on the left side and conductive heat transfer, radial heat transfer, expansion and viscous heat dissipation terms on the right side. Note that this equation must be adapted to the layers it will be applied to; for instance: when applied to layer number two, tubing, the axial advective heat transfer, expansion and viscous dissipation will be dropped.

Thermal conductance depend on the thermal resistance between the center of two adjacent layers and must represent the heat transfer mechanism present between them. The convective heat transfer between the injection fluid employed the correlation from Sieder and Tate (1936) and natural convection in the annular fluids was estimated with the correction term proposed by Zhou (2013). A complete description of the thermal conductance terms is shown in Martins (2022).

#### 3.2 APC Mitigation with a Rupture Disk

The APC is indirectly obtained with Eq. (3),

$$m(t=0) + \Delta m(t) - \int_{z=0}^{z=L} \rho(T, p + \delta p) A dz = 0 \quad (3)$$

where  $m$  is mass,  $L$  is the annulus length and  $\delta p$  is the APC. This expression is based on the mass conservation inside the annulus, with the first term being the mass calculated at the start of the simulation, the second term is the instantaneous accumulated mass entering (or leaving) the annulus and the third term refers to the fluid density changes with temperature and pressure, with the former calculated with Eq. (2) and the latter the initial value given by the operator.  $\delta p$  is obtained from Eq. (3) with a non-linear root finder from the SciPy package (Jones *et al.*, 2001–). The density behavior as function of temperature and pressure was calculated using the commercial software Multiflash (Infochem/KBC, 2018).

In a typical scenario of sealed annuli, the second term of Eq. (3) is dropped but in the presence of rupture disks that enables fluid flow between adjacent annuli it must be preserved. Equation (4) calculates the mass flow between both ends of a channel when subjected to a pressure difference,

$$\dot{m} = \begin{cases} -C_D \pi r_{rd}^2 (2\rho \Delta p)^{1/2} & \Delta p > 0 \\ C_D \pi r_{rd}^2 (2\rho |\Delta p|)^{1/2} & \Delta p < 0 \end{cases} \quad (4)$$

where the density term in this equation is referring to the flowing fluid, i.e., that at a higher pressure. Note that Eq. (4) is separated in two sentences, depending on the pressure variation signal. The computational code counts the annular layers outward. For example, considering a disk positioned at the casing separating annuli A and B, a positive pressure change, calculated with  $\Delta p = p_A(z_{rd}) - p_B(z_{rd})$  with  $z_{rd}$  standing for the disk installation distance from seabed, indicates a higher Annulus A pressure, so there will be a mass flow towards Annulus B, represented by the negative mass flux obtained from this equation.

The mass flow through the disk occurs at significantly lower time-scale than the heat and momentum transfer described by Eqs. (1) and (2). This means that considering  $\dot{m}$  constant during the  $\Delta t$  interval during subsequent time steps would lead to severe a pressure change over(under)-estimation. However, reducing the time step of the thermo-structural model to the same required by the annuli mass transfer would increase the computational cost without producing better results.

To circumvent this issue, Martins *et al.* (2022) proposed an adaptive refinement for the temporal mesh only, with this refinement being dependent uniquely by the physics phenomenon without any input from the operator. The authors defined that instead of modeling the mass transfer during subsequent time steps as continuous with a constant value, it would be considered as a sequence of mass ‘pulses’ and by the end of the interval, the APC registered at this time step would be the last one, calculated with the accumulated mass transferred during the interval.

At the start of a given time step, the code checks whether the disk is open or not, if it is closed, there will be a second check if the pressure difference across the disk is higher than the disk opening load. If the disk is opened, the mass flow rate and the velocity across the disk length is calculated with Eqs. (4) and (5), then the pulse duration is calculated with Eq. (6). Note that in the pulse duration calculation the distance traveled by the fluid package is taken as the difference between outer and inner casing radii, i.e. the casing thickness. The mass transferred at the present pulse is calculated with  $\delta m(\tau) = \dot{m}\tau$  and the APC is calculated with Eq. (3), with  $\Delta m(t)$  taken as the sum of all pulses at the present loop. After defining the APC, the annular pressure profiles and disk load must be recalculated with the new APC. In order to check if the loop must be repeated, the sum of all pulses duration must be the same as the time step interval, defined by the code operator. A novel addition to the methodology proposed by Martins *et al.* (2022) is that if the radial load is lower than 1 kPa the loop can be broken, as previous tests concluded that at pressure differences lower than this value, the mass transferred was considered to be negligible as the pressure change scale was significantly lower than the absolute value. The procedure described in this paragraph is summarized in Fig. 2.

$$v = \sqrt{\frac{2|\Delta p|}{\rho}} \quad (5)$$

$$\tau = \frac{L_{rd}}{v} \quad (6)$$

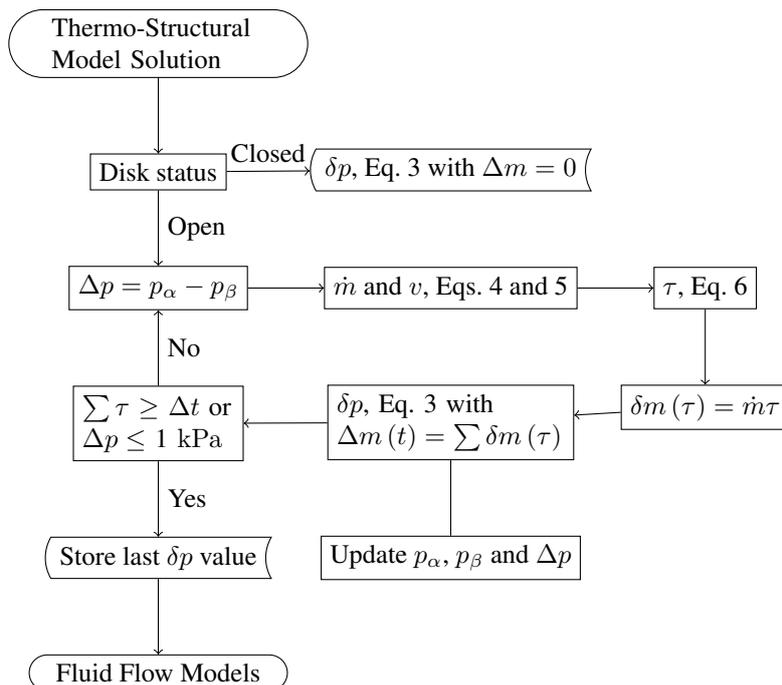


Figure 2: Flowchart of the rupture disk solution numerical procedure

More important than the APC results themselves is the difference between the pressure on both sides of a given casing, so the results will be cast in terms of a dimensionless parameters based on this pressure difference (Martins *et al.*, 2022),

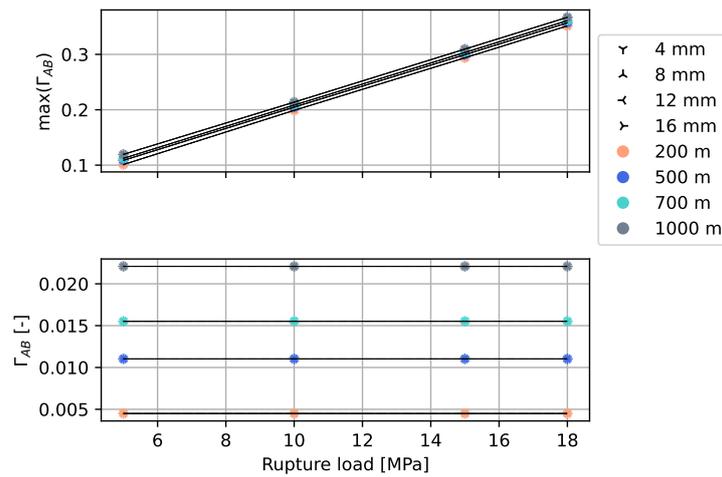
$$\Gamma_{\alpha\beta} = \frac{\max(|p_{\alpha} - p_{\beta}|)}{p_{\alpha\beta}^{cr}} \quad (7)$$

where the subscripts  $\alpha$  and  $\beta$  refer to generic adjacent annuli and the superscript *cr* refers to a radial pressure difference between both sides of a casing that will cause a failure. This failure can be of two kinds: burst and collapse, with the former occurring when inner pressures are higher than the outer ones and the latter the other way around. For the present well, the burst pressures are 73.5 and 21.1 MPa for casings AIB and BIC, respectively and the collapse pressures are 51.8 and 10.3 MPa for the same casings.

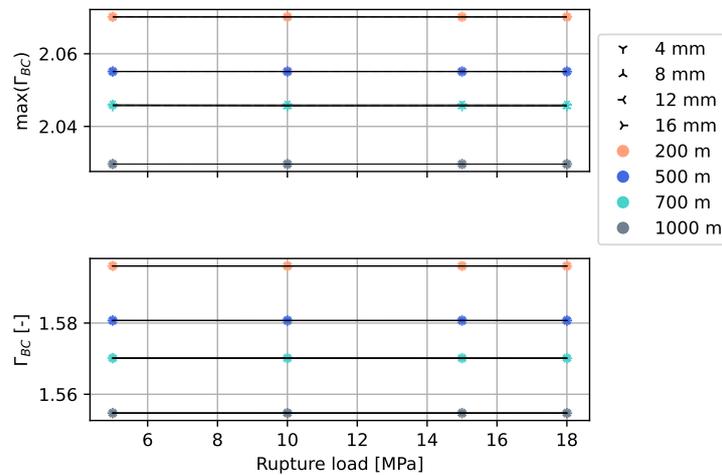
## 4. RESULTS

### 4.1 Installation Parameters

Figure 3 was obtained after a total of 64 simulations and shows  $\Gamma$  calculated both at the end of the simulation period and the maximum value during it for both casings. Note that three parameters were evaluated: rupture load, disk radius and installation depth. Note that there are no influence on the results from any parameter, except from the opening load on the maximum  $\Gamma_{AB}$ , which occurs because this maximum value occurs right at the moment preceding the disk opening, as the opening load was attained.



(a) Casing AIB



(b) Casing BIC

Figure 3: Maximum and last calculated  $\Gamma_{AB}$  and  $\Gamma_{BC}$  values for 64 different disk configurations. Different geometric shapes account for disk opening radius and different colors for the installation depth

## 4.2 Inlet Parameters

In the present subsection, the analyzed results are from a new set of simulations, where the temperature and inlet mass flow rate were altered to assess their importance when combined with a disk placed on casing A1B 1000 m below the wellhead, with an opening radius of 8 mm and 10 MPa load. Inlet temperature and mass flow rate ranged from 4 to 94 °C and from 5 to 357 kg s<sup>-1</sup>, respectively, with a total of 132 simulations. The results in the present paper considered only the outer casing, as the presence of a rupture disk in the inner casing results in the  $\Gamma_{AB}$  drop to zero after its opening, as reported in Martins *et al.* (2022).

A first analysis of the results was carried out considering the mass flow rate influence, with the temperature set at 33 °C, and the  $\Gamma_{BC}$  results over time are shown in Fig. 4. There is a sharp increase in the dimensionless pressure difference after one day, a consequence of the disk opening, which caused Annulus B pressure to decrease, due to the fluid flow towards Annulus A, thereby increasing the pressure difference between Annuli B and C. Note that after the disk opens,  $\Gamma_{BC} \geq 1$ , meaning unsafe conditions for the well operation, as the pressure difference across the annulus is higher than its failure pressure. Also note in this figure the little influence the mass flow rate has on the results, with changes appearing mostly as time progressed on the simulation and that the higher  $\Gamma_{BC}$  occurred at lower flow rate values, which can be attributed to the differential cooling (heating) rate across the annuli, which leads to higher pressure differences.

Figure 5 presents the temperature influence over time on dimensionless pressure difference at Casing B1C with an inlet flow rate of 123 kg s<sup>-1</sup>. In this figure, the temperature influence is clearly seen, specially at longer times ( $t > 5$  days), with highest  $\Gamma_{BC}$  values occurring at lower temperatures. This can be attributed to more energy being removed from the annuli, specially those located closest to the injection stream, resulting in lower temperatures, consequently lower pressures, at the inner annuli.

Figures 6 to 9 presents the  $\Gamma_{BC}$  behavior with temperature and mass flow rate variations at fixed times, ranging from one to seven days. These figures reinforce previous conclusions, specially lower temperatures and mass flow rates causing higher  $\Gamma_{BC}$ . Also note that as time advances higher dimensionless pressure difference values occur in all figures. In Figs. 6 and 7, for higher temperatures,  $\Gamma_{BC} \approx 0$  due to the lower temperature differences between Annuli B and C, as these two are more removed from the injection stream, and as time progresses these regions gradually disappears as the pressure differences increase.

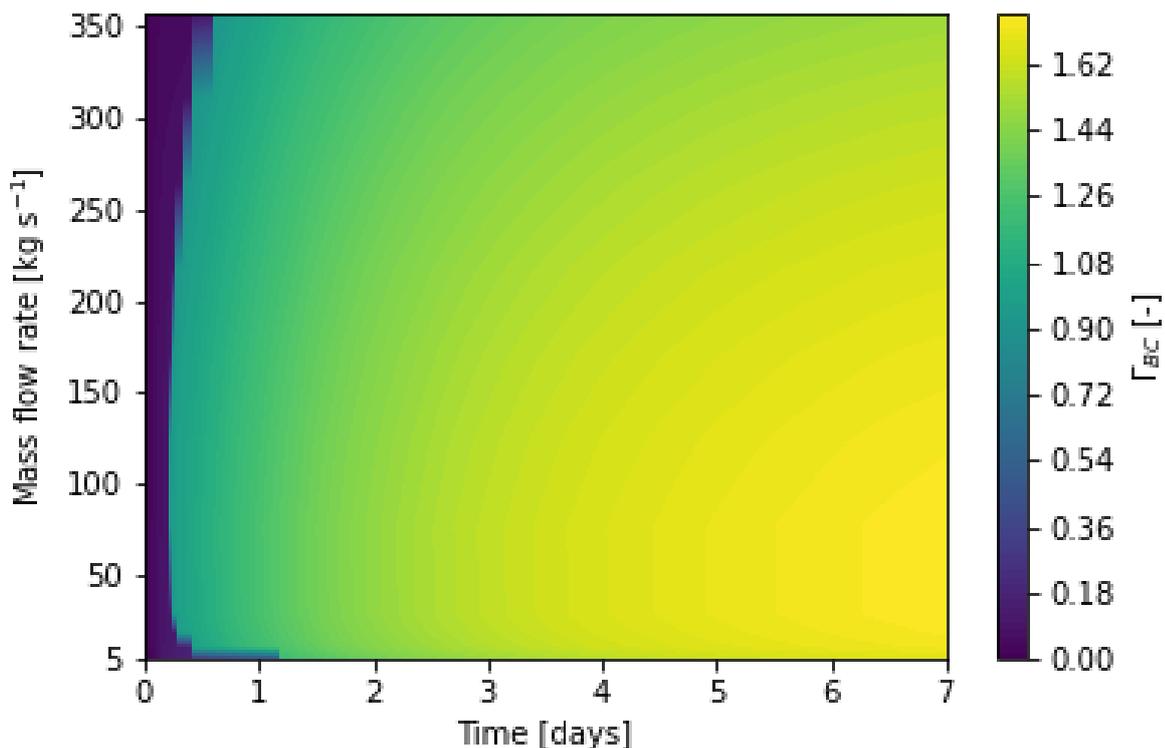


Figure 4:  $\Gamma_{BC}$  behavior as function of time and mass flow rates with an inlet temperature of 33 °C

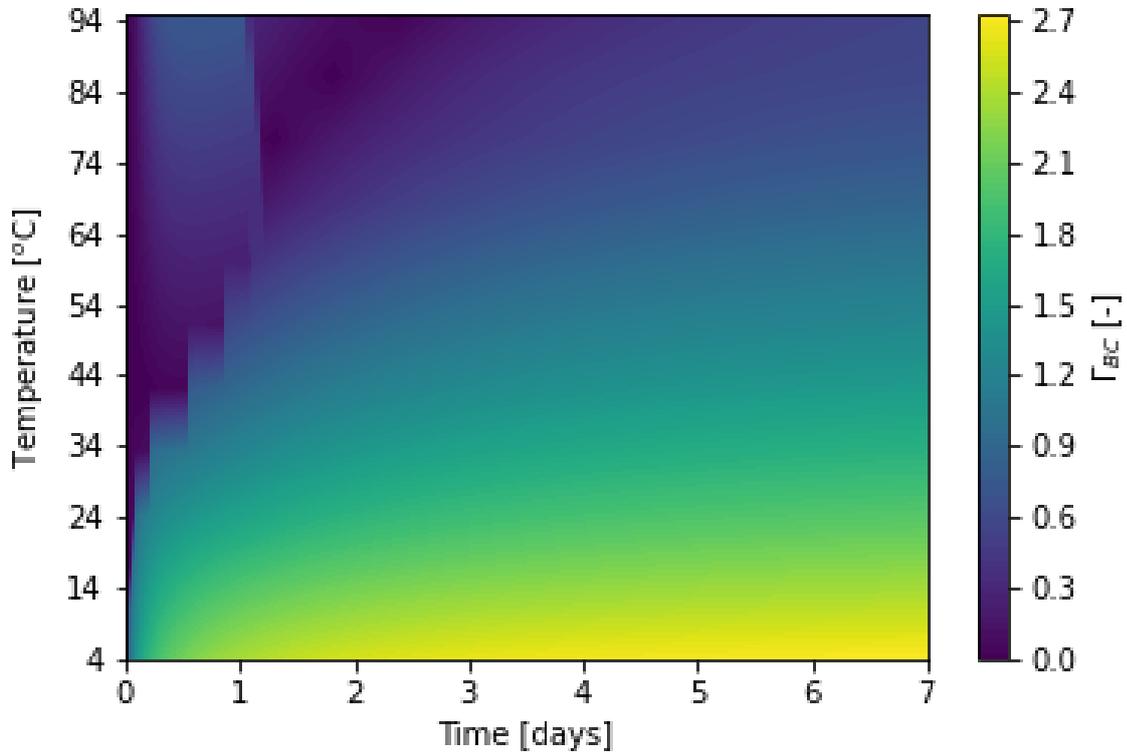


Figure 5:  $\Gamma_{BC}$  behavior as function of time and temperature with an inlet mass flow rate of  $123 \text{ kg s}^{-1}$

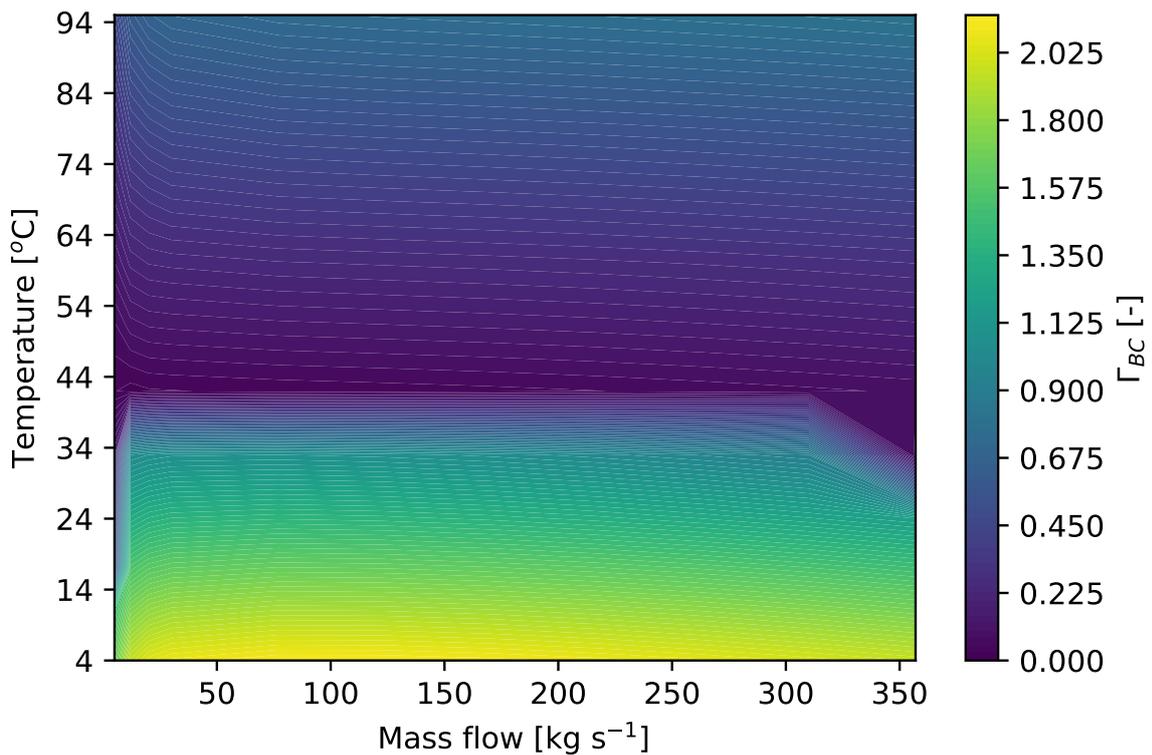


Figure 6:  $\Gamma_{BC}$  values after twelve hours

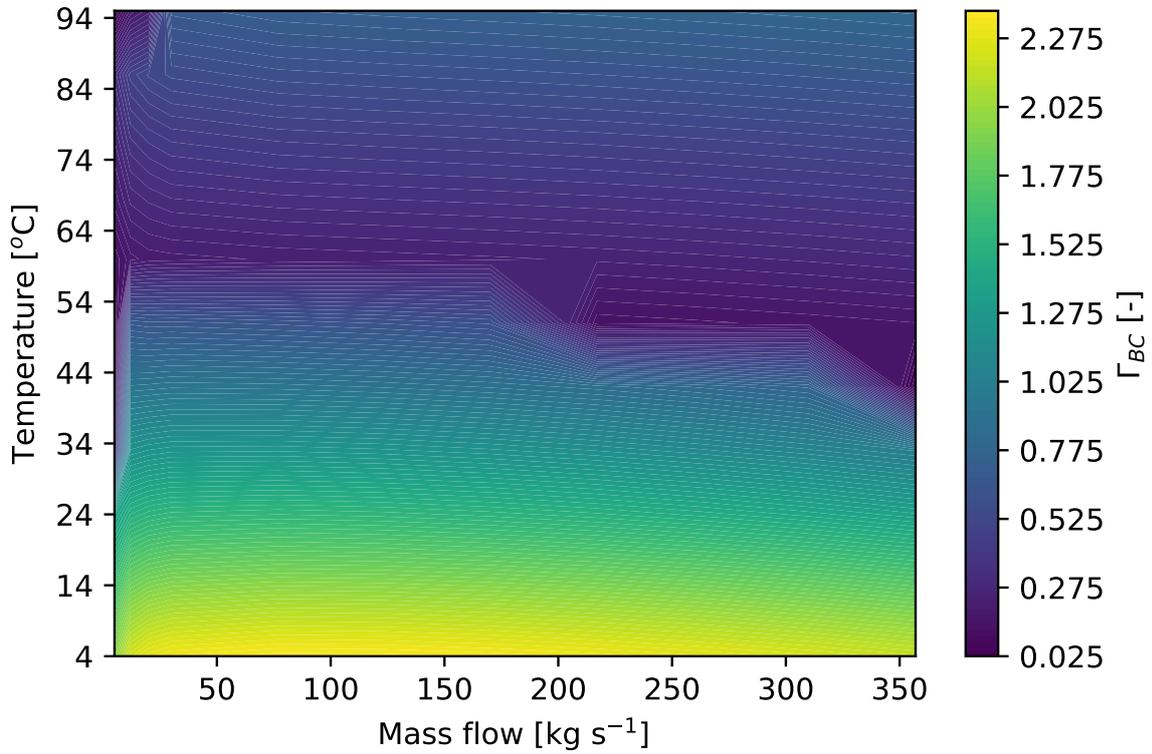


Figure 7:  $\Gamma_{BC}$  values after one day

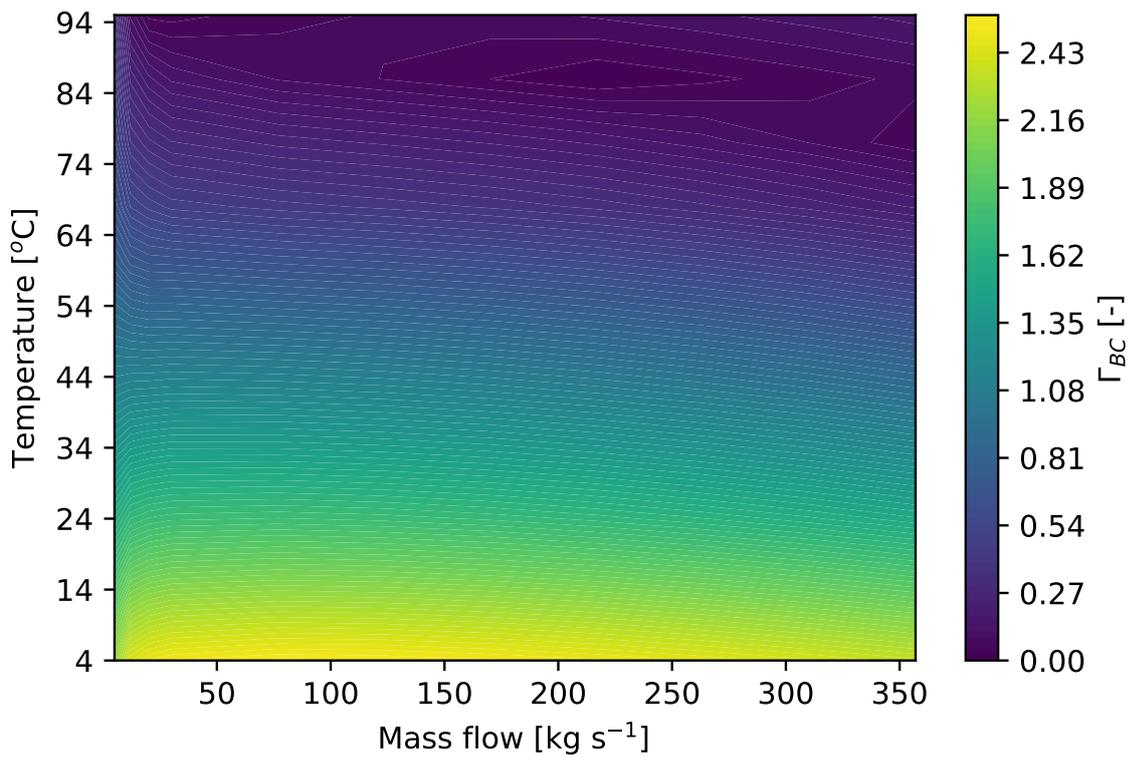


Figure 8:  $\Gamma_{BC}$  values after two days

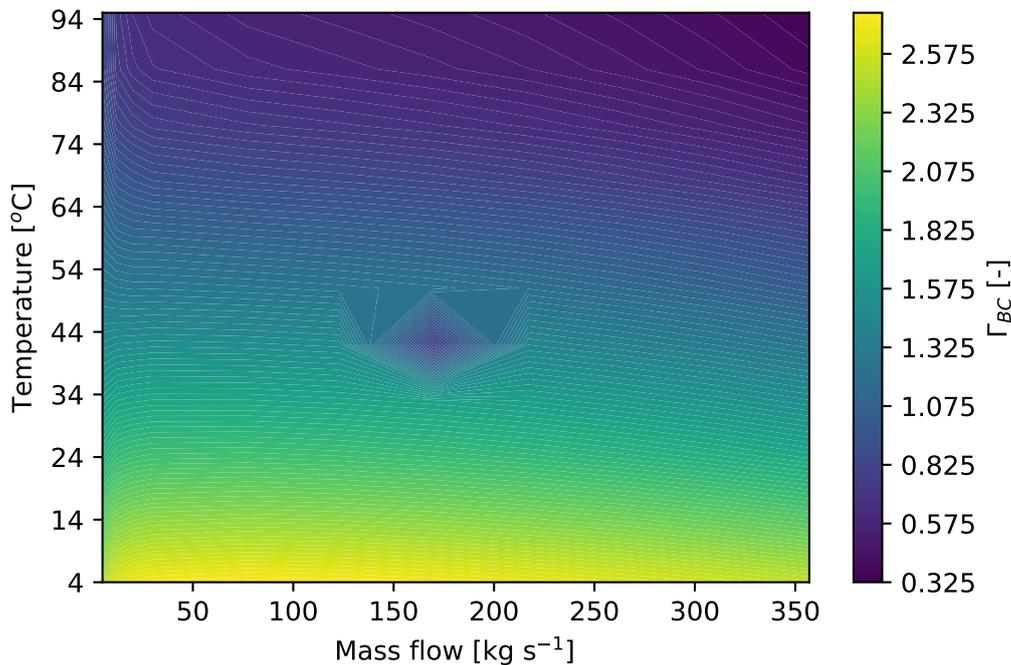


Figure 9:  $\Gamma_{BC}$  values after seven days

## 5. CONCLUDING REMARKS

The present study performed a parametric analysis on a rupture disk installation during an injection operation at an offshore well using a semi-transient thermo-structural model, with results being analyzed through a dimensionless variable which is a safety quantification, with  $\Gamma \geq 1$  deemed as a dangerous scenario. Results indicate that the disk installation parameters did not have significant influence in the operation, likely due to the long operation times. Injection parameters (temperature and mass flow rate) presented significant influence on the results, specially temperature with higher values occurring with lower temperatures. Higher  $\Gamma_{BC}$  values occurred at longer times, as more energy was being supplied (removed) from the well, resulting in the higher pressure difference across it. In a final note, a sharp increase occurred in  $\Gamma_{BC}$  at the moment when the disk opened, as it caused a near equalization between the pressures in Annuli A and B ( $\Gamma_{AB} \approx 0$ ) at the cost of an increase in the pressure difference of Annuli B and C.

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