

ENC-2020-0624
**THERMAL EFFECTS ON PRESSURE CHANGES OF FLUIDS
CONFINED IN PIPES**

Ricardo Knesebeck
Arthur Gaideski Portela
Alexandre Yuji Imano
Gabriel Merhy Oliveira

Cezar Otaviano Ribeiro Negrão

Research Center for Rheology and Non-Newtonian Fluids (CERNN), Postgraduate Program in Mechanical and Materials Engineering (PPGEM), Universidade Tecnológica Federal do Paraná (UTFPR), Rua Deputado Heitor Alencar Furtado, 5000 – Bloco N – Ecoville, Curitiba / PR – Brazil

knesebeck@alunos.utfpr.edu.br, portela.cernn@gmail.com, imano.cernn@gmail.com, gabrielm@utfpr.edu.br, negrao@utfpr.edu.br

Abstract. *In oil and gas exploration, the safety of pipelines sealing is assured by tightness tests. During these tests, the fluid is pressurized inside a pipeline and then confined while its pressure is measured. Authors argue that there are others effects besides leak offs that can cause a pressure drop and a false test failure. These effects can be rheological or thermal, the present paper focus on the latter. An experimental procedure was developed in order to simulate a confined fluid with controlled temperature changes and pressure measurements. It was verified that the thermal effects are, indeed, significant on the pressure change. Two numerical models were developed to predict both temperature and pressure, based on the test results, one that considers a constant volume of fluid and one that considers the deformation of the pipe's wall. Both models were simulated and compared with experimental results. It was determined that the pipe's wall deformation is very significant in the pressure prediction and must be included in order to minimize errors, as the isovolumetric model had a relative error of over 60%.*

Key words: *Thermal Expansion, Confined fluid, Tightness Test, Pressure, Temperature*

1. INTRODUCTION

Oil is a valuable resource and its increasing demand is followed by an increase in exploration. This means that wells are becoming deeper and more complex, so some physical phenomena can no longer be disregarded or approximated. In addition, safety is always a major concern during oil exploration operations, so extra care should be taken when evaluating critical components.

For instance, during the drilling phase of oil exploration, only the drilling fluid is supposed to be inside the oil well, meaning it is undesirable that the oil or gas inside the rock formation flows into the well. This occurrence is known as a kick, a sudden influx of oil or gas. If the kick reaches the surface, it becomes a blow-out, which brings risk to the equipment and the operators' lives as the highly flammable fluids enter in contact with the surface oxygen. Therefore, it must be avoided at all costs.

While the drilling fluid's pressure is constantly adjusted in order to avoid the influx of oil and gas, there is a backup equipment named BOP (Blow-Out Preventor), a mechanical valve equipment located at the wellhead (Matos, 2017). This safety device is connected to the platform through the riser and parallel pipelines, known as kill and choke lines, and is able to disconnect the drill rig from the well in case of an uncontrolled kick. Figure 1 shows a scheme of an offshore oil rig, depicting the mentioned components.

In order to assure the reliance of the BOP, tightness tests are run through pressurization of fluid in the lines, often the same fluid used to clean the well. The fluid is pre-circulated in the tested line and when pumping comes to a stop, the fluid remains pressurized according to the test norm. A certain pressure drop is allowed during a certain time window in order to validate the test. If the pressure drop is greater than that set by the norm, the test fails due to leak offs in the systems. With a continuous reliance purpose, API RP 53 limits to 21 days the maximum interval between two BOP tests (Carbognin, 2017). A problem observed by drilling engineers is a higher than expected pressure drop during the tests without signs of leak off. Some authors discuss the possibility of other effects that affect the pressure's behavior, such as the fluid's rheology and thermal expansion of both the fluid and the pipe.

The drilling fluid can be formulated with different bases, such as olefinic, paraffinic or water. These formulations are usually non-Newtonian, as their viscosities change based on the shear rate the fluid is subjected to. The fluid's rheology is a factor that contributes to a slow pressure stabilization during the tests (Knesebeck et al., 2019) (Oliveira et

al., 2015) (Santos et al., 2019), due to failure in pressure transmission in fluids with yield stress. These effects can lead to incorrect measures of pressure drops and an incorrect interpretation of the tightness tests.

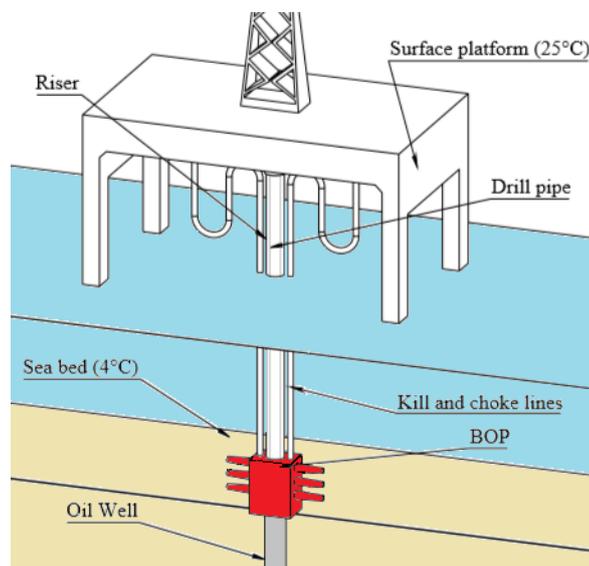


Figure 1. Drilling Rig Schematics.

For thermal effects, it is important to highlight that the fluid enters a choke or kill line at the surface, where ambient temperature varies, and goes down to the sea bed at 4°C (Khan and May, 2016). This gradient induces heat loss from the fluid to the ambient while pressure data is being acquired, contributing to errors. The heat exchanges during flow are largely discussed in numeric/analytic models since the demand for energy takes extraction to deeper waters, exploring wells with high pressure and high temperature in its inside (Khan and May, 2016), (Dokhani et al, 2016), (Harris, 2014). These wells have a thin pressure operating window between pore pressure and fracture pressure, so temperature gradients may represent danger for the well integrity and efficiency, bringing risks as fracture, circulation loss, kicks and malfunctioning of bottom hole devices. High Pressure/High Temperature (HP/HT) models use the energy balance applied for the hole well. Dokhani et al. (2016) divide the situation in four energy balances situations: drill string; annulus; formation; and between riser and seawater. The present document focus on the last situation applied to a kill line.

Other situation in which the thermal effects are largely discussed is in APB (Annular Pressure Buildup) cases. In these cases, the increase of pressure due to thermal expansion can present damage to drill pipes or the well casing (Oudeman and Kerem, 2006) (Adams and MacEachran, 1994) (Ellis et al, 2002). However, the APB modeling includes more variables than just the fluid's properties. Temperature changes are also able to change the pipe's internal volume by thermal expansion, reflecting it in a pressure decrease inside the line. In addition, the change of pressure itself can deform pipe walls and change its volume, decreasing pressure (Oudeman and Kerem, 2006).

Experimental works for confined fluids are found in the literature, but hardly have the goal of validating the numerical models. In order to validate results, Oudeman and Kerem (2006) compare the model results with a real well case study. Ellis et al. (2002) use the same comparison (Marlin A-2 case) for validation purposes, but also create an experimental section to find some thermal properties for the systems, as thermal conductivity and heat transfer coefficients, to use them as model inputs. Furthermore, there are experimental works for APB when it comes to mitigation of the problems it causes, reducing the impacts on the pipe wall stress (Peliano, 2017), (Azzola et al., 2004).

The experimental work developed in the present paper has the goal of observing the pressure and temperature relation of a confined fluid using an experimental system built at CERNN (Research Center for Rheology and Non-Newtonian Fluids), projected to test drilling fluid properties by Mitshita (2015). Furthermore, numerical models are developed in order to predict the pressure change due to thermal effects in a confined fluid. These models are simulated with the same parameters as the experimental procedure and have their results compared in order to validate them.

2. EXPERIMENTAL METHODOLOGY

In order to approximate the experimental procedure to a fluid confined in a kill line situation, some requirements must be met. First, in order to discard leak-off in the line, it is easier to work with a small-scale system where tightness can be easily assured. Second, the sea is the heat extraction source when kill line is pressurized. It implies in the use of an external heat source. For that purpose, an insulated chamber fitting the sealed line must be used. Besides that, a

pressure prediction numeric model can not use the fluid temperature as input, since this information is not available at the field. This paper will treat the heat exchanges phenomena between pipe walls and fluid, so pipe wall's temperature must be recorded. Also, the fluid temperature and pressure inside the sealed line must be captured in validation terms. Therefore, pressure and temperature sensors must be strategically positioned in the sealed line. Finally, to make that requirements guaranteed, an experimental system must be used, as describes the following item.

2.1. Experimental apparatus

Figure 2 shows the experimental unit projected to test different properties of drilling fluids. Initially, it has a fluid reservoir, which feeds a progressive cavity pump. After the pump, two lines can be followed: the first consists in a bypass pipeline, which has two valves: an electropneumatic valve V3 and a manual valve MV. The second line, described in the picture as main pipeline, is a stainless-steel helical pipeline with 50m length and 20.44mm diameter, with one electropneumatic valve at its inlet (V1) and one at its outlet (V2). Attached to the main pipeline, there are four resistive pressure transducers (P1, P2, P3 and P4), 16m apart from each other. Next to these transducers, there are four threaded connections, where type T thermocouples can be connected and make contact with the fluid inside the pipeline. The main pipeline also has adhesive thermocouples that measure directly the pipe wall's temperature. There is also a Coriolis type flow meter to measure the flow inside the pipeline. All of these components remain inside of a thermally insulated chamber, with its temperature controlled by a PID program. The program works based on the adhesive thermocouples feedback, controlling a resistance/condensation unit system. The data acquisition from the transducers, thermocouples and flow meter, as the control of the pump, the electropneumatic valves and the PID is done through a computational interface that communicate with CLP's.

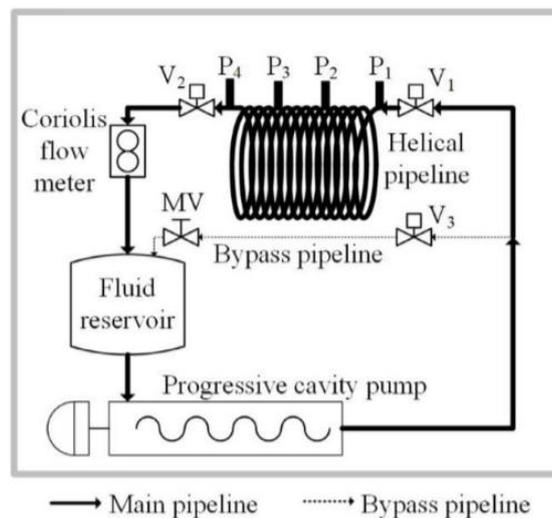


Figure 2. Experimental Unit Schematics.
Reference data: Mitishita et al. (2015)

2.2. Experimental procedure

As described, the sealable line with pressure and temperature sensors is the main pipeline. In order to assure its seal, a leak off test must be run before any test procedure starts. For that, the chamber temperature is stabilized and fluid is pressurized inside by closing V2 and turning on the pump. Then, V1 is closed to confine the fluid in its inside. Since temperature is stable, pressure is expected to be constant to discard any leak-off. After this assurance, a pressure increase in the fluid due to temperature changes can be recorded. With this goal, fits the following procedure:

- Chamber temperature stabilization at 20°C;
- Fluid pre circulation for 10 minutes;
- V2 and V1 closure;
- Data acquisition start;
- Chamber temperature increase for 26°C;
- Chamber temperature stabilization at 26°C;
- Data acquisition over time.

The procedure uses water in the line, due to its material properties being well described in literature. Also, it was realized in duplicate, in order to ensure test's repeatability.

3. NUMERICAL MODEL

In order to predict the fluid pressure behavior while confined, two numerical model were developed. One considers the pipe as rigid, so the volume of fluid is constant. The seconds considers both elastic deformation and thermal expansion of the pipeline, so the volume can no longer be considered constant.

3.1. Equation of state

Assuming that the fluid's density ρ is a function of the fluid's pressure P and the fluid's temperature T , this relationship can be written as Eq. (1). The first term of the right hand side represents the density variation due to the pressure variation and the second term represents the density variation due to the temperature variation.

$$d\rho = \left(\frac{\partial\rho}{\partial P}\right)_T dP + \left(\frac{\partial\rho}{\partial T}\right)_P dT \quad (1)$$

The isothermal compressibility α and the volumetric coefficient of thermal expansion β are defined by Eqs. (2) and (3), respectively. For small changes in temperature and pressure, both of these properties can be assumed constant.

$$\alpha = \frac{1}{\rho} \left(\frac{\partial\rho}{\partial P}\right)_T \quad (2)$$

$$\beta = -\frac{1}{\rho} \left(\frac{\partial\rho}{\partial T}\right)_P \quad (3)$$

By substituting Eqs. (2) and (3) into the Eq. (1), a relationship between density, pressure and temperature is given:

$$\frac{d\rho}{\rho} = \alpha dP - \beta dT \quad (4)$$

In the isovolumetric case, density is constant and a direct relationship between temperature and pressure can be obtained:

$$dP = \frac{\beta}{\alpha} dT \quad (5)$$

3.2. Pipe wall deformation (thin wall model)

In the case with pipe deformation, there is a variation of the inner volume of the pipe V_{pipe} . For this particular case, based on the work of Oudeman and Kerem (2006) for thin wall cylinders, the variation can be written as presented in Eq. (6).

$$\frac{dV_{pipe}}{V_{pipe}} = \frac{D}{Et_h} dP + \beta_{wall} dT_{wall} \quad (6)$$

The first term on the right-hand side represents the volume variation due to the elastic deformation caused by pressure, according to Hooke's law, where D is the pipe's diameter, E is the Young's module and t_h is the wall's thickness. The second term represents the volume variation due to the thermal expansion of the pipe. Since the fluid is confined, its mass is constant and the pipe's inner volume can be related with the fluid's density, so Eq. (6) can be modified:

$$\frac{d\rho}{\rho} = -\frac{D}{Et_h} dP - \beta_{wall} dT_{wall} \quad (7)$$

Substituting Eq. (7) into the equation Eq. (4), a relationship between temperature and pressure, considering the pipe's deformation, is given by Eq. (8).

$$\left(\alpha + \frac{D}{Et_h}\right)dP = \beta dT - \beta_{wall}dT_{wall} \quad (8)$$

3.3. Energy balance equation

The simplified energy balance equation (Eq. (9)), supposes that the heat only flows through conduction in the radial direction, where c_p is the fluid's specific heat and k is its thermal conductivity. This assumption is based on the temperature not varying in the axial direction and the fluid being completely stationary, ignoring convective effects.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{k}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) \quad (9)$$

Considering that T is the average temperature of the fluid, both sides of Eq. (9) can be integrated in radial direction, from 0 to the radius $D/2$ to obtain the Eq. (10). This approximation can only be used for pipes with small diameters, as the radial temperature gradient can be considered small. Note that this integrated equation just depends on the time variation.

$$\frac{dT}{dt} = \frac{8}{D^2} \frac{k}{\rho c_p} (T_{wall} - T) \quad (10)$$

3.4. Numerical solution

To solve the system formed by Eqs. (5), (8) and (10), with pressure, temperature and time as variables, the backward differences method was used. Pressure and temperature are calculated based on the previous time instant data. For both the isovolumetric and the wall deformation numerical models, the Eq. (11) is used to compute the temperature after a time interval of Δt . The index $n+1$ refers to the current time node, while the index n refers to the previous one.

$$T_{n+1} = \frac{8}{D^2} \frac{k}{\rho c_p} [T_{wall,n} - T_n] \Delta t + T_n \quad (11)$$

In the isovolumetric model, pressure is given by equation Eq. (12), while in the thin wall deformation model, by the Eq. (13).

$$P_{n+1} = \frac{\beta}{\alpha} (T_{n+1} - T_n) + P_n \quad (12)$$

$$P_{n+1} = \frac{\beta(T_{n+1} - T_n) - \beta_{wall}(T_{wall,n+1} - T_{wall,n})}{\left(\alpha + \frac{D}{Et_h}\right)} + P_n \quad (13)$$

To obtain results comparable to the experimental ones, the same geometry and fluid were used. Table 1 shows the geometrical and material parameters inputted into the model. The wall temperature from the experimental results is also used as an input for the mathematical model.

Table 1. Input Parameters for the Numerical Models.

Parameter	Symbol	Value	Unit
Pipe's Diameter	D	0.02044	[m]
Pipe's Wall Thickness	t_h	0.00311	[m]
Stainless Steel Elastic Modulus	E	1.93×10^{11}	[Pa]
Stainless Steel Volumetric Thermal Expansion Coefficient	β_{wall}	5.10×10^{-5}	[K ⁻¹]
Water Density	ρ	999	[kg/m ³]
Water Thermal Conductivity	k	0.61	[W/m.K]
Water Specific Heat	c_p	4186	[J/kg.K]
Water Isothermal Compressibility	α	4.59×10^{-10}	[Pa ⁻¹]
Water Volumetric Thermal Expansion Coefficient	β	2.07×10^{-4}	[K ⁻¹]

4. RESULTS AND DISCUSSIONS

The results accomplished with the experimental procedure follow at item 4.1, and the comparison with numerical model are in item 4.2.

4.1. EXPERIMENTAL RESULTS FOR PRESSURE AND TEMPERATURE OVER TIME

Figure 3 shows the obtained experimental results. X-axis present the test time, beginning when data started to be recorded. At the left hand Y-axis, is possible to observe pressure data, marked with a triangle symbol, starting constant and then responding to the chamber's temperature increase. In its turn, right hand Y-axis shows the temperature profiles of both the wall and the fluid. The line marked with a diamond symbol refers to the measured pipe wall temperature. The square-marked line represents the thermocouple connected to the pipeline interior, picturing the fluid behavior.

Pressure does not increase linearly in the pipeline, due to effects as the thermal expansion of the pipe wall, composed by stainless steel, and the water thermal inertia.

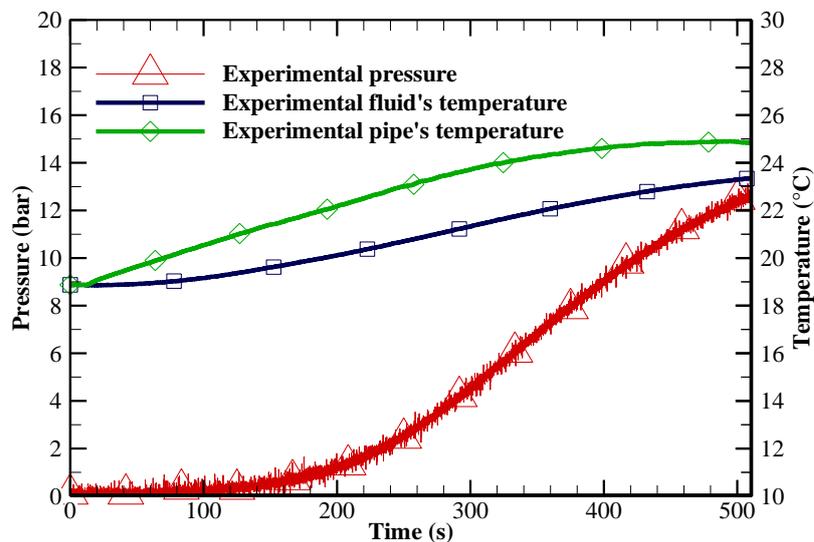


Figure 3. Experimental temperature and pressure of confined water over time.

4.2. NUMERICAL RESULTS AND COMPARISON

With the data from the experimental results, the numeric models were used to simulate the same conditions. The main outputs from the simulations were the temperature and pressure profiles over time. Figure 4 shows that the simulated temperature profile follows closely the experimental profile. This shows that the assumptions made to the energy balance equation are good approximations.

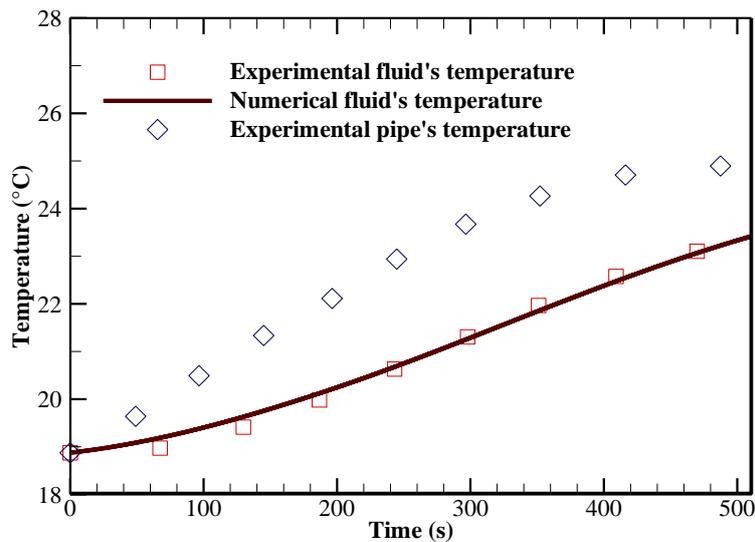


Figure 4. Experimental and numerical comparison of the temperature profile over time.

Figure 5 shows both pressure prediction models profiles in comparison to the experimental results. The model considering the pipe deformation (case 2) had a much better approximation than the constant volume one (case 1), which overestimated the final pressure in over 60%.

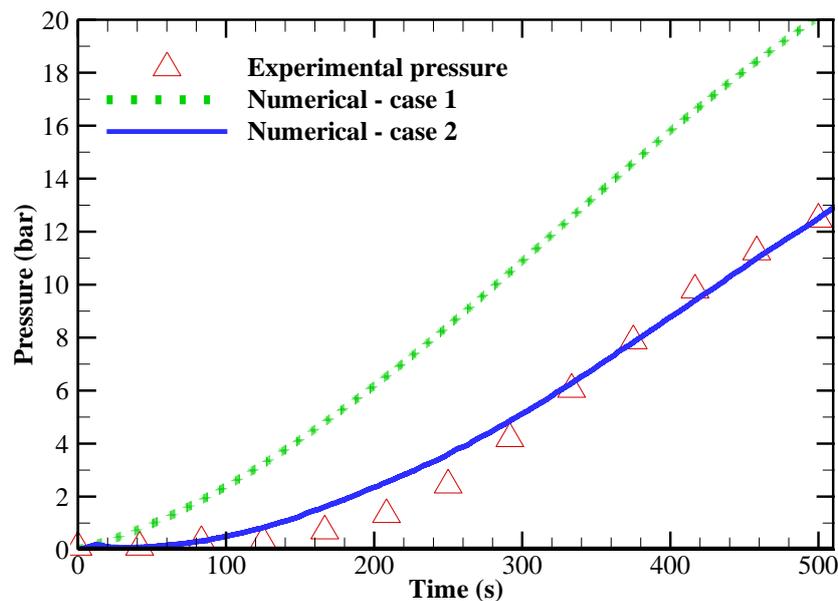


Figure 5 - Experimental and numerical comparison of the pressure profile over time.

5. CONCLUSIONS

The effects of temperature change on the pressure of a confined fluid were experimentally verified. Two models to predict this pressure change were developed, one considering constant inner pipe volume and the other considering volume change due to elastic deformation and thermal expansion of the pipe.

Experimental results showed that thermal effects can largely contribute to pressure changes, and consequently to a pressure drop higher than expected in a BOP test. Numerical results showed good agreement with the experiments when predicting the temperature profile. For the pressure profile, pipe deformation must be taken into account in order to avoid errors. While the model showed good results for the studied case, several improvements can be made in order to expand its applicability, in particular to higher pressure and temperature changes, larger diameter pipes or even annular spaces, as the ones seen in oil exploration. Some future improvements:

- Including the thick wall deformation model in order to simulate thicker pipes, as the ones found in real life applications;
- Considering a variable radial temperature inside the fluid, for larger diameter pipes or less conductive fluids;
- Adding pipe and annular superposition of models, so more complex geometries can be studied;
- Considering axial temperature and pressure variations, so more complex boundaries conditions can be applied, such as a geothermal gradient;
- Utilizing pressure and temperature dependent isothermal compressibility and thermal expansion coefficient in order to simulate a compressible fluid better for higher variations of pressure or temperature.

6. ACKNOWLEDGEMENTS

The authors are grateful to Petrobras S.A., ANP and PIBIC (CNPq) for the financial support towards this project.

7. REFERENCES

- Adams, A. J., MacEachran, A., 1994. "Impact on Casing Design of Thermal Expansion of Fluids in Confined Annuli". *SPE Drilling & Completion*, 9(03), 210–216.
- Azzola, J., Tselepidakis, D., Pattillo, P. D., Richey, J. F., Tinker, S. J., Miller, R., & Segreto, S. J., 2007. "Application of Vacuum Insulated Tubing to Mitigate Annular Pressure Buildup". *SPE Drilling & Completion*, 22(01), 46–51.
- Carbognin, B., 2017. *Metodologia de verificação de sequência operacional em completção de poços baseada em interdependências*. 209 f. Dissertação (Mestrado) - Curso de Engenharia Mecânica, Engenharia de Petróleo, Universidade Estadual de Campinas, Campinas.
- Dokhani, V., Ma, Y., & Yu, M. (2016). "Determination of equivalent circulating density of drilling fluids in deepwater drilling". *Journal of Natural Gas Science and Engineering*, 34, 1096–1105.
- Ellis, R. C., Fritchie, D. G., Gibson, D. H., Gosch, S. W., & Pattillo, P. D. (2004). "Marlin Failure Analysis and Redesign: Part 2 – Redesign". *SPE Drilling & Completion*, 19(02), 112–119.
- Harris, O., 2004. *Evaluation Of Equivalent Circulating Density Of Drilling Fluids Under High Pressure-High Temperature Conditions*. 1 v. Dissertação (Mestrado) - Petroleum Engineering Course, University Of Oklahoma, Norman, 2004
- Khan, N. U., & May, R. (2016). "A generalized mathematical model to predict transient bottomhole temperature during drilling operation". *Journal of Petroleum Science and Engineering*, 147, 435–450.
- Knesebeck, R., Portela, A. G., Neia, O. A. F., Merhy, G. O., & Negrão, C. O. R. (2019). "Numeric and Experimental Study of Pressure Transmission in Drilling Fluid". In: *Encontro Nacional de Construção de Poços de Petróleo e Gás. Proceedings of ENAHPE 2019* - 073.
- Matos, J. H F. *Análise de riscos para a ocorrência de blowouts no processo de perfuração de poços de petróleo offshore*. 101 f. TCC (Graduação) - Curso de Engenharia de Produção, Engenharia de Produção, Universidade Federal Fluminense, Rio das Ostras, 2017.
- Mitishita, R. S.. *Avaliação Experimental Da Transmissão De Pressão Em Tubulações Preenchidas Por Fluidos Viscoplásticos*. 2015. 184 f. Dissertação (Mestrado) - Curso de Engenharia Industrial Mecânica, PPGEM, UTFPR, Curitiba, 2015.
- Oliveira, G. M.; Santos, T. G. M.; Franco, A. T.; Negrão, C. O.R., 2015. "Pressure Transmission in Visco and Pseudoplastic Fluids During Closed Well Operations". In: *VII Brazilian Conference on Rheology*, Curitiba.
- Oudemans, P., Kerem, M., 2006. "Transient Behavior of Annular Pressure Build-up in HP/HT Wells". *SPE Drilling & Completion*, 21(04), 234–241.
- Peliano, S. V., 2017. *Mitigação de APB pelo método da sapata aberta*. 82 f. TCC (Graduação) - Curso de Engenharia de Petróleo, Engenharia de Petróleo, Universidade Federal Fluminense, Niterói, 201
- Santos, E. M. I. R., Pereira, L. G., Santos, T. G. M., Negrão C. O. R., 2019. "Análise experimental da transmissão de pressão em um fluido tixotrópico aplicada ao teste de BOP". In: *Encontro Nacional de Construção de Poços de Petróleo e Gás. Proceedings of ENAHPE 2019* - 055.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.