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THE RHEOLOGICAL BEHAVIOR OF DRILLING FLUIDS AT HPHT CONDITIONS: A PROPOSAL FOR A CONSTITUTIVE EQUATION FITTING METHODOLOGY

Diogo E. V. Andrade
Federal University of Rio Grande do Sul – UFRGS, Graduate Program in Mechanical Engineering – PROMEC, Rheology and Non-Newtonian Fluid Flow Laboratory – ReoSul, Rua Sarmento Leite 425, Brazil.
diogo.andrade@ufrgs.br

Luis H. Quitian-Ardila
Admilson T. Franco
Federal University of Technology-Paraná—UTFPR , Research Center for Rheology and Non-Newtonian Fluids—CERNN, Postgraduate Program in Mechanical and Materials Engineering—PPGEM, R. Deputado Heitor Alencar Furtado, 5000 Curitiba, PR 81280-340, Brazil.
luis.2019@alunos.utfpr.edu.br, admilson@utfpr.edu.br

Abstract. *In this work we performed a rheological characterization of bentonite-free water-based drilling fluid with xanthan gum under high-pressure, high-temperature (HPHT) conditions. The tests were carried out in a rotational rheometer coupled to a pressure cell. Steady-state flow curves were obtained at three temperatures (25, 55 and 100 ºC) for different pressures (100 to 800 bar). Experimental data shows that the effect of temperature on the apparent viscosity of drilling fluid depends on the magnitude of pressure experienced by the fluid, the same is true when one analyses the effect of the pressure that depends on the temperature imposed to the material. Finally, a methodology was proposed to fit an equation capable of predicting the apparent viscosity of drilling fluid under HPHT conditions. The equation showed good prediction accuracy in the fitted range. The proposal outlined in this study provides significant insights for the oil and gas industry, as predicting the rheological behavior of drilling fluid under different temperatures and pressures is critical for efficient drilling plans.*

Keywords: *HPHT condition, Drilling Fluid, Rheology, constitutive equation*

1. INTRODUCTION

The scenario of deep wells under high-pressure and high-temperature (HPHT) conditions brought significant challenges for the industry, requiring advanced technologies, improved drilling fluids, and increased knowledge to ensure safe and efficient operations (Gautam et al., 2022; Greenaway et al., 2008). One can conclude that HPHT offshore fields require extensive planning, design, and the correct determination of the drilling fluid's rheological properties under these conditions to ensure safe and effective operations (Jaculli et al., 2022). Drilling fluid is crucial in the process as it provides hydraulic pressure, help in removing cuttings, control formation pressure, and minimize formation damage from the wellbore (Agwu et al., 2021; Balhoff et al., 2011; Gautam et al., 2022; Gautam and Guria, 2020; Wang et al., 2012a; Xu et al., 2013; Zhuang et al., 2018). The incorrect drilling fluid selection can lead to high costs, drilling delays, wellbore instability, and environmental risks.

The analysis of apparent viscosity and dynamic yield stress in water-based drilling fluids with xanthan gum is well described in the literature, on the other hand, few works have studied the accuracy of apparent viscosity fit under HPHT conditions. Hermoso et al. (2014c) used two important models to represent the viscoplastic behavior in drilling fluids, the Herschel-Bulkley and Bingham models. Fakoya and Ahmed (2018) developed a generalized empirical model for oil-based drilling fluids and water-based drilling fluids with bentonite to predict apparent viscosity varying by volume fraction and temperature. The model obtains good results using multiple settings parameters and revealed the sensitivity of some rheological parameters with temperature. J. Hermoso et al., (2017a, 2017b), reported that using a modeling of the PVT (pressure-volume-temperature) behavior, it is possible to model the apparent viscosity under HPHT conditions for oil-based drilling fluids, showing a good fit. In this case, the author does not use the fitted parameters of the rheological models. Recently, our group conducted a study on the effect of High-Pressure and High-Temperature individually in water-based drilling fluids and demonstrated that the fluid underwent modifications in the microstructure and rheological properties (Quitian et al., (2022)). This study found a fit that helped to predict apparent viscosity as a function of shear rate under HPHT conditions.

The characterization of drilling fluids is essential to predict their behavior under conditions such as temperature, pressure, and composition, which are critical variables evaluated during well planning. In the open literature on drilling fluids, most studies assess these variables separately, such as thermal capacity and pressure on water-based drilling fluids under HPHT conditions in offshore wells. All indicate that the temperature increase has a viscosity-lowering effect, which is highly significant compared to pressure variations. Nevertheless, very few works evaluate these variables simultaneously.

The current work shows a methodology based on rheometrical tests that allow analysis and a constitutive equation proposal of a drilling fluid under HPHT conditions. The main contribution of this methodology is to demonstrate the importance of simultaneously analyzes of the thermal and pressure effects on the drilling fluids' rheological behavior. In addition, we propose an equation that captures the influence of temperature, pressure, and shear rate on the apparent viscosity of the tested drilling fluid. The results call attention to the community to analyze and develop correlations for these variables acting simultaneously.

2. MATERIALS AND METHODS

A bentonite-free water-based drilling fluid with xanthan gum provided by Petrobras was used in the analysis. In Table 1 is described the main components of the drilling fluids, and the complete fluid composition can be found in our previous work (Quitian et al., 2022). A pressure cell coupled to a rotational stress-controlled rheometer was used for rheological characterization as presented in Figure 1. The equipment can achieve pressures up to 1000 bar and temperatures up to 300 °C. The experiments were performed in a Couette geometry, and before each measurement, the sample was homogenized in an industrial mixer. Table 1 presents the information on the equipment used, type of geometry, main parameters, and temperature and pressure imposed during the rheometrical tests. It is worth mentioning that the range of the shear rate used in this analysis respects the limit of the sensibility of the magnetic coupling system used in the rheometer. For shear rates lower than 50 s^{-1} the obtained results did not accurately represent the rheological behavior of the material. The configuration used for rheological tests under high temperature and high-pressure conditions and the analysis of the reliable range of shear rater also described in detail in the previous work (Quitian et al., 2022).

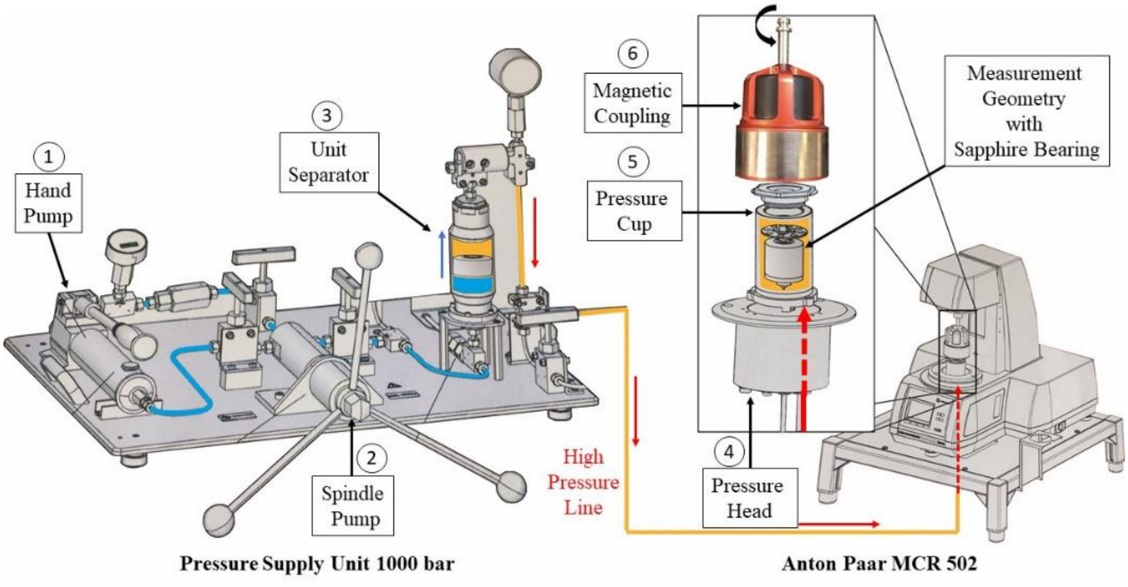

Figure 1. Pressurization system used to increase pressures up to 1000 bar, connected to the Anton Paar MCR502 rheometer, and pressure cell with magnetically coupled geometry with sapphire bearing. Adapted from the Instruction Manual C-ETD 300 / PR 1000. The drilling fluid is represented in yellow, and the pressurized oil is in blue. (Quitian et al., 2022)

The rheological data were obtained experimentally for each pressure and temperature variation. Each steady-state flow curve was fitted to the power law model, which represents quite well the behavior of this specific drilling fluid under the imposed conditions. The power model [Eq.1] is fitted using two parameters determined for the smallest possible error through a non-linear regression. The equations describing this model are as follows:

$$\tau = m[\dot{\gamma}]^n \quad (1)$$

Where τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), m is the consistency coefficient ($Pa.s^n$), and n is the flow behavior index (dimensionless), which represents the structural characteristics of the fluid (Ansari et al., 2020; Patrick et al., 2021).

Table 1. Experimental procedure for performed flow curves under HPHT conditions.

Drilling fluid	Water-based drilling fluid comprises xanthan gum (0.25 wt.%), NaCl brine, limestone $Ca(OH)_2$, and other components.
Fluid homogenization	At 1000 rpm for 20 minutes with Hamilton Beach HMD200
Rheometer	Rotational stress-controlled rheometer Anton Paar MCR 502
Pressure cell	C-ETD 300/PR 1000
Rotor type	A Couette serrated surface geometry (28-mm cylinder diameter, 30-mm cup diameter, 50-mm height)
Temperature (°C)	25, 55, and 100
Pressure (bar)	100, 400, 600, and 800
Shear rate (s^{-1})	50, 100, 150, 200, 250, 300, 350, and 400 for 1000 s each step

The models used to fit the rheological behavior of fluids requires physical conditions that restrict the range values of the fitting parameters. These conditions are determined by analyzing the rheological behavior of the drilling fluid. Bentonite-free water-based drilling fluid with xanthan gum exhibits a shear-thinning behavior, i.e., the higher the shear rate, the lower the apparent viscosity (here defined as $\eta = \tau/\dot{\gamma}$) (Huang et al., 2016; Quitian et al., 2022; Sofia and Djamel, 2016; Whitcomb and Macosko, 1978; Zheng et al., 2020; Zhu and Zheng, 2021b). Therefore, the fitting parameters must be conditioned in the mathematical regression so that the consistency coefficient is greater than zero ($m > 0$) and the flow behavior index is a value between zero and one ($0 < n < 1$). This process is essential to determine the rheological parameters of the power law model more accurately.

3. RESULTS

The influence of pressure and temperature on the rheological behavior of the drilling fluid was analyzed in the liquid-like regime. In Figure 2, one can see the steady-state flow curves for different pressures and three different temperatures. One can see that the higher the temperature, the lower the measured shear stress for a determined imposed shear rate. Conversely, an increase in pressure leads to a shear stress increment. These results demonstrate an essential influence of the temperature. For example, an increase in temperature from 25 to 55 °C significantly reduced shear stress. Specifically, the maximum reduction observed was 46% at a shear rate of 200 s^{-1} and a pressure of 100 bar. As the temperature increases to 100 °C, the effect becomes more pronounced, resulting in a substantial reduction in shear stress. Interestingly, the increase in pressure has an opposite influence on shear stress. The increment in pressure partially compensates for the viscosity fall imposed by the temperature. The higher the temperature, the more significant the influence of the pressure. The shear stress increased around 1.38 times at 25 °C when the pressure was increased from 100 to 800 bar, while this increment arose to 1.61 and 3.92 times, respectively, at 55 and 100 °C.

In the analyzed shear rate range, the power law model (dashed lines in Figure 2) represents the material's behavior for each tested condition quite well. The fitted parameters and the respective parameters uncertainty for each pressure and temperature condition are reported in Table 2. It is important to emphasize that the power law parameters were fitted individually for each condition. In other words, the fitting process was applied for each one of the 12 conditions analyzed.

It can be observed that the consistency coefficient (m) for HPHT data exhibited an increase with rising pressure at the three measured temperatures, albeit at varying proportions. The flow behavior index values (n) decreased as the pressure increased. The effect is more pronounced at 100 °C. In all the analyzed ranges this index varied between 0.515 and 0.319, indicating a dependence of this parameter with the changes in pressure and temperature.

Based on this analysis, one can see that the influence of the pressure on the drilling fluid's rheological behavior depends on the temperature imposed in the analysis. If one changes the temperature, the magnitude of the pressure effect also changes. The same conclusion is obtained by the impact of the temperature, which depends on the pressure experienced by the fluid. Because of this observation, both effects must be analyzed simultaneously, and this variation cannot be disregarded, particularly in offshore well operations. Establishing a relationship between the two variables is crucial to ensure that the effects of both factors are fully considered, regardless of the pressure effect being less significant than the impact of temperature. The influence of pressure and temperature can be analyzed through the fit of the experimental data. Quitian et al. (2022) employed the modified Barus model and WLF model to study separately the impact of pressure and temperature on the rheological behavior of this drilling fluid. In that previous work, we achieved this by fitting the behavior of the consistency coefficient (m) and assuming constant flow behavior index (n) obtained from the power-law model fit, i.e., $\tau = m\dot{\gamma}^n$. That hypothesis was quite good, as the effects of temperature and pressures were analyzed separately. In this current work, this hypothesis does not accurately represent the obtained results.

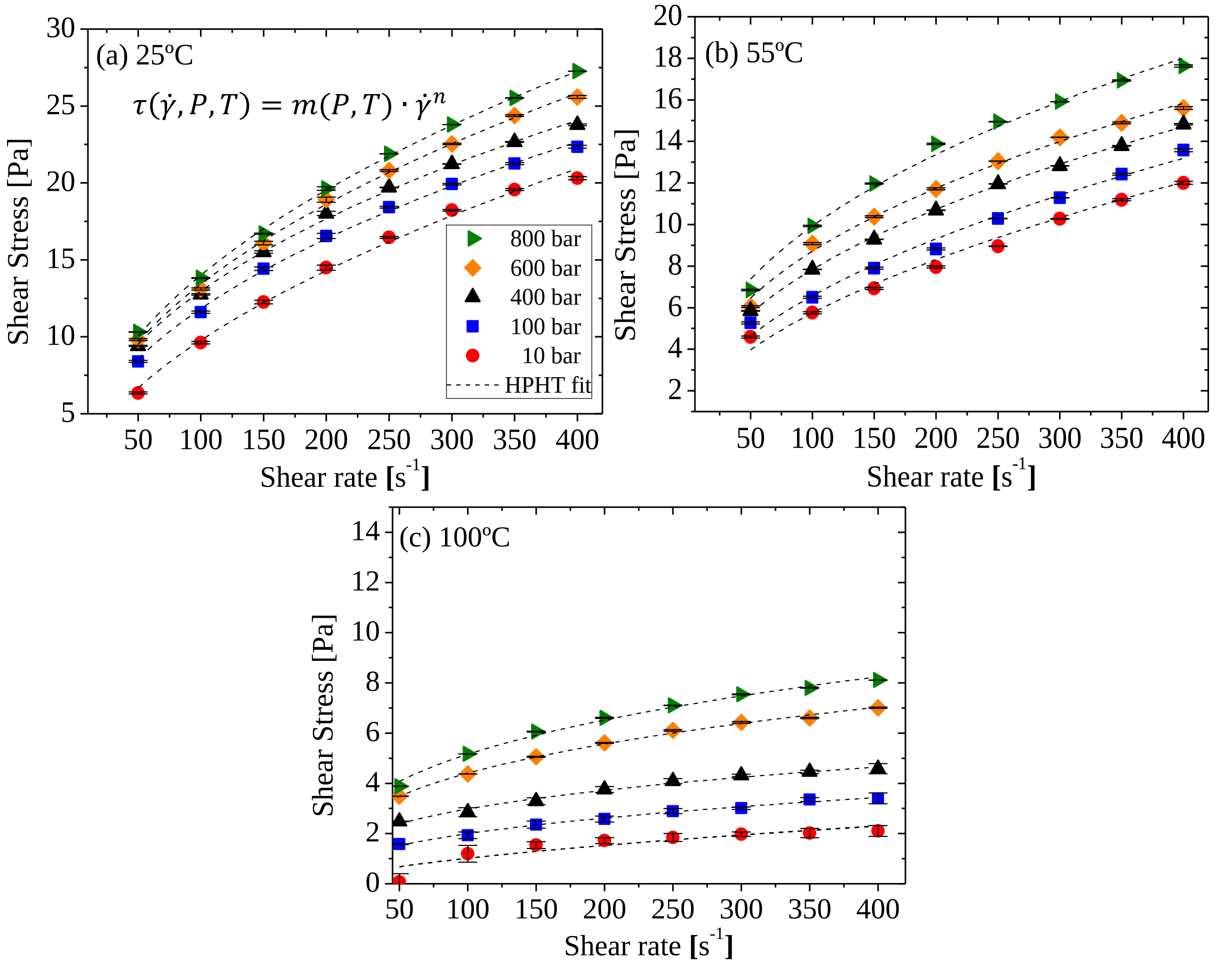

Figure 2. Steady-state flow curve for (a) 25°C, (b) 55°C and (c) 100°C at a different pressure from 10 to 800 bar were measurements on Anton Paar with Pressure Cell configuration, applicating shear rate 400–50 s^{-1}. Experimental data were fitted along with the best fit of the Power-law equation (dashed line). The error bars denote the standard deviation of experiments performed in triplicate.

Table 2. Parameters of the power-law equation fitted for different pressures and temperatures. Consistency coefficient (m) and flow behavior index (n) were used to fit the behavior of pressure and temperature.

Temperature [ºC]	**Pressure [bar]**	*m* [Pa.s^n]	*n* [-]	R^2
25 °C	**100**	1.029	0.515	0.997
	400	1.256	0.492	0.997
	600	1.384	0.487	0.998
	800	1.554	0.471	0.998
55 °C	**100**	0.663	0.490	0.983
	400	0.926	0.452	0.958
	600	1.113	0.447	0.983
	800	1.463	0.432	0.998
100 °C	**100**	0.254	0.447	0.971
	400	0.459	0.383	0.964
	600	0.895	0.337	0.998
	800	1.194	0.319	0.981

3.1 Rheological parameters fit process

In order to predict the shear stress or the apparent viscosity values as a function of pressure, temperature, and shear rate is crucial to propose an equation that takes into account the simultaneous effect of the parameters on the rheological behavior of the drilling fluid. To accomplish this goal, the fitting parameters of the power law model for different HPHT conditions were correlated through models with physical significance, obtaining a fitted consistency coefficient (m_{HPHT}) and fitted flow behavior index (n_{HPHT}) in HPHT conditions. The idea of this methodology is to propose a power law equation in which both parameters are dependent on the pressure and temperature experienced by the fluid. Based on that, the predicted shear stress values as a function of pressure, temperature, and shear rate can be determined by Eq. (2).

$$\tau = m_{HPHT} \cdot \dot{\gamma}^{n_{HPHT}} \tag{2}$$

The subscribed HPHT in the constants means that the fitted parameters consider the influence of both temperature and pressure. With the shear stress value determined by Eq. (2), one can easily determine the apparent viscosity of the fluid since $\eta = \tau/\dot{\gamma}$. The m_{HPHT} and n_{HPHT} fitted following the methodology that begins with the treatment and fitting of the rheometrical tests being fitted to the power law model, thus determining the different m and n for each measured condition. These are the results already presented in Table 1. Afterward, the values of m and n were fitted individually as a function of pressure, obtaining two empirical constants for each parameter ($n_{HT}, \alpha, m_{HT}, \beta$). Then, these constants are fitted as a function of temperature, determining a total of seven empirical constants that represent the material's behavior as a function of temperature, pressure, and shear rate. The fitted model employed for each parameter is described below.

First, we fit m_{HPHT} values using exponential equation [Eq. (3)], which is composed of WLF model [Eq. (4)] (Fakoya and Ahmed, 2018; Fillers and Tschoegl, 1977; Hermoso et al., 2017b; Tschoegl et al., 2002; Williams, 1964), that was proposed initially to determine the influence of temperature on the rheological behavior of polymers, and the Barus model [Eq. (5)] (Chaudemanche et al., 2009; Hermoso et al., 2017b), that represents the piezoviscous effect on the fluid (Bair and Qureshi, 2003; Chaudemanche et al., 2009; Hermoso et al., 2014a; Tschoegl et al., 2002).

$$m_{HPHT}(P,T) = m_{HT}(T) \cdot Exp[\beta(T) \cdot P] \tag{3}$$

$$m_{HT}(T) = m_0^* \cdot 10^{\left[\frac{C_1\{T-T_0\}}{C_2+\{T-T_0\}}\right]} \tag{4}$$

$$\beta(T) = \beta_0 + \beta_1 \cdot \{T - T_0\} \tag{5}$$

Where m_0^* is the consistency coefficient at a reference temperature T_0 and pressure P_0. $C_1$and C_2 are empirical constants. Within the factor that represents the effects of pressure, there is a variable $\beta(T)$ which is the piezoviscous coefficient, expressed through the form of a linear model using two parameters that are β_0 and $\beta_1$as a function of the temperature. The fit of the flow behavior index follows the same procedure. The n_{HPHT} is determined by Eq. (6). The influence of temperature on the flow behavior index was inspired by the Arrhenius equation, as can be seen in Eq. (7). The index $\alpha(T)$ [Eq. (8)] is fitted by a linear equation as a function of temperature.

$$n_{HPHT}(T,P) = 1 - n_{HT}(T) \cdot P^{[\alpha(T)]} \tag{6}$$

$$n_{HT}(T) = n_0^* \cdot Exp\left[B\left\{\frac{1}{T} - \frac{1}{T_0}\right\}\right] \tag{7}$$

$$\alpha(T) = \alpha_0 + \alpha_1\{T - T_0\} \tag{8}$$

where n_0^* is the flow behavior index at a reference temperature T_0 and pressure P_0. B, α_0 and α_1 are empirical constants. Table 3 presents the fitted parameters of the fits of m_{HPHT} and n_{HPHT} with pressure, temperature, as well as, parameter uncertainties, Mean Absolute Percentage Error (MAPE), and correlation coefficient (R^2).

Table 3. Fitted parameters of the m_{HPHT} and n_{HPHT} models for different temperatures and pressures.

Fitting parameters with pressure and temperature					
m_{HPHT}		$\delta_{\text{parameter}}$	n_{HPHT}		$\delta_{\text{parameter}}$
m_0^* [Pa.s^n]	0.970	0.054	n_0^* [bar^{-1}]	0.398	0.001
c_1 [-]	127.56	3.655	B [ºC]	3.475	0.083
c_2[ºC]	-18240.8	422.33	α_0 [-]	4.26E-02	0.003
β_0 [bar^{-1}]	6.05E-04	4.587E-4	α_1 [ºC^{-1}]	6.80E-04	5.451E-4
β_1 [ºC^{-1}.bar^{-1}]	1.61E-05	0.021			
R^2	0.951	-	R^2	0.975	-
$MAPE$ [%]	7.229	-	$MAPE$ [%]	1.859	-

* Fitting parameter at temperature T_0=25 ºC and P_0= atmospheric pressure.

The model exhibits a highly favorable behavior in describing the m_{HPHT} changes with pressure and temperature, as evidenced by a high correlation coefficient value (R^2=0.951), indicating a good predictive capability of the m_{HPHT} values. The most significant deviations were observed at 100 and 400 bar for the temperature of 100 °C. The data for n_{HPHT} exhibited a significantly higher correlation coefficient of R^2=0.975, indicating a strong association between the observed and predicted values. The model demonstrated an accurate representation of n_{HPHT} behavior across a range of pressure and temperature values.

Therefore, the two models of m_{HPHT} and n_{HPHT} were combined with the power law equation as presented in Eq. (3). The cross-plots were used to evaluate the reliability of the proposed methodology correlations. Predicted shear stress data (Eq. 3) were compared to the experimental shear stress to assess the model's accuracy. The graphical representation in Figure 3 highlights that the testing and predicted values were closely matched across all pressure and temperature conditions, indicating high predictability. The points at 100 bar and 100 °C slightly deviate from the 15% of accuracy.

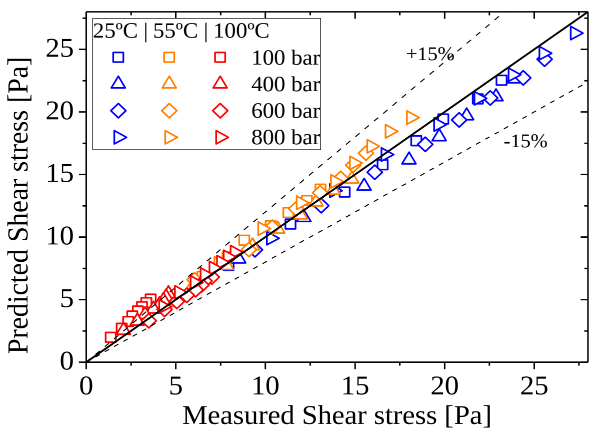

Figure 3. Comparison of the predicted and measured shear stress values in the pressure and temperature model.

4. CONCLUSIONS

The main conclusions can be summarized as:

- Steady-state shear stress of bentonite-free WBDF with xanthan gum varied with pressure and temperature. The influence of pressure and temperature must be analyzed simultaneously since the magnitude of the pressure effects depends on the analyzed temperature, and the opposite is also true.

- The proposed equation using the power law model's fitting parameters (m and n) to fit the pressure and temperature simultaneously is valid for pressures from 100 bar to 800 bar. The fit showed good prediction of shear stress values.

Based on the results presented, one can see that the proposed methodology to predict the behavior of the fluid in HPHT conditions was successful. The insights gained from this study are expected to have significant implications for the design of wells in offshore fields. In future works, this fitting methodology must be extended for other types of drilling fluids in HPHT conditions and for different compositions of Betonite-free water-based drilling fluids.

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