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ANALYSIS OF STRESS OVERSHOOT FITTING IN FLOW START-UP TESTS FOR DIFFERENT DRILLING FLUIDS

Luis H. Quitian-Ardila

Elis Wendt

Leonardo de Souza Santos

Federal University of Technology-Paraná – UTFPR, Department of Mechanical Engineering – DAMEC, Postgraduate Program in Mechanical Engineering and materials – PPGEM, Research Center for Rheology and Non-Newtonian Fluids – CERNN, Rua Deputado Heitor Alencar Furtado, 5000 Curitiba, PR 81280-340, Brazil.
luis.2019@alunos.utfpr.edu.br, yamidblanco@alunos.utfpr.edu.br

Diogo E. V. Andrade

Federal University of Rio Grande do Sul - UFRGS, Department of Mechanical Engineering – DEMEC, Postgraduate Program in Mechanical Engineering – PROMEC, Rheology and Non-Newtonian Fluid Flow Laboratory – ReoSul, Porto Alegre, RS, Brazil
diogo.andrade@ufrgs.br

Admilson T. Franco

Federal University of Technology-Paraná – UTFPR, Department of Mechanical Engineering – DAMEC, Postgraduate Program in Mechanical Engineering and materials – PPGEM, Research Center for Rheology and Non-Newtonian Fluids – CERNN, Rua Deputado Heitor Alencar Furtado, 5000 Curitiba, PR 81280-340, Brazil.
admilson@utfpr.edu.br

Abstract. *Drilling fluids play a crucial role in the oil and gas industry for the drilling process. One of their essential functions is to maintain the cutting's suspension during process stoppages. These fluids exhibit a gel-like behavior at rest and a liquid-like behavior during shearing. To flow start-up, higher than normal pressures are necessary to disrupt the gelled structure. Drilling fluids are categorized as non-colloidal suspensions in various matrices, such as oil or aqueous solutions containing suspended particles larger than 10 μm . These materials exhibit non-Newtonian rheological behavior, displaying properties such as yield stress and thixotropy. The impact of stress overshoot on different drilling fluids (bentonite suspension, Olefin based suspension with NaCl, water-based suspension with xanthan gum, and olefin-based suspension with a 60/40 oil/water ratio) was analyzed using rheometric data obtained from start-up flow tests. Anticipated outcomes suggest that aging time significantly impacts not only stress overshoot but also the shear strain required to disrupt the gelled structure of a material. Precisely, the prolonged aging time is predicted to decrease the strain necessary to break up the structure, indicating a negative correlation between aging time and stress overshoot. Furthermore, the fitted models demonstrate a high level of correlation with the experimental data, thus providing a reliable basis for utilizing these correlations in the planning and simulation of drilling operations in offshore fields.*

Keywords: *drilling fluid, non-colloidal suspension, cutting's suspension, non-Newtonian fluids, yield strength.*

1. INTRODUCTION

The oil and gas (Calcada et al., 2015) industry heavily relies on drilling fluids for the efficient and successful execution of the drilling process (Gautam et al., 2022). These fluids play a crucial role in various aspects, and one of their fundamental functions is to maintain the suspension of cuttings during process stoppages (Ragouilliaux et al., 2006). The ability of drilling fluids to exhibit gel-like behavior at rest and quickly transform into a liquid-like state during shearing is paramount for smooth drilling operations. However, during flow start-up, these fluids require higher than normal pressures to disrupt their gelled structure (Balhoff et al., 2011), making the understanding of their rheological behavior and stress overshoot phenomenon of significant importance (Negrão et al., 2011). Drilling fluids are typically categorized as non-colloidal suspensions found in matrices, such as oily or aqueous solutions containing suspended particles larger than 10 μm (Tanner, R. I., 2018). This complex composition gives rise to their unique non-Newtonian rheological behavior, characterized by properties such as yield stress and thixotropy (Bonn et al., 2015). Understanding these rheological properties is essential as they directly influence the performance and efficiency of drilling operations.

The stress overshoot phenomenon, which refers to the transient increase in stress experienced by the fluid when subjected to rapid deformation, valuable insights can be gained into the behavior of these drilling fluids during critical operational stages (Dullaert and Mewis, 2006). Moreover, aging time is an essential parameter that affects the rheological properties of drilling fluids. Aging refers to the time interval between the preparation of the drilling fluid and its usage in the field (Negrão et al., 2011). The influence of aging time on stress overshoot and the required deformation to disrupt the gelled structure is investigated in this study. Understanding the effect of aging time is crucial as it directly impacts the performance and stability of drilling fluids during the drilling process (Bourgoyne et al., 1991; Livescu, 2012).

The stress overshoot phenomenon, resulting from the interplay of material elasticity and thixotropy, has been well-documented. This behavior becomes evident in experiments where shear rates are controlled and monitored using rotational rheometers, with notable studies by Speers et al. (1987) corroborating these findings. To delve deeper into this phenomenon, structural kinetic models have been proposed by notable researchers. These models introduce a structure parameter, which serves as a metric to gauge the degree of material structuring. Shear rate varies from zero, representing a completely unstructured material disrupted by shear, to a finite value, indicating a fully structured material that has been allowed to rest. This parameter aids in quantifying the extent of material structuring and provides insights into the reversible alterations in material behavior under varying shear and rest conditions. In pursuit of a comprehensive understanding of the rheological behavior of elasto-viscoplastic thixotropic materials, some researchers have dedicated their efforts to fitting structural kinetic models. Their model exhibited strong agreement with rheometric data, not only in steady states but also during transient phases. In a similar, Negrão et al. (2011) applied Dullaert and Mewis's (2006) model to rheometric data concerning an oil-based drilling fluid. Employing a shear rate-controlled test to simulate the initiation of the gelled material, they found that the start-up stress overshoot could be accurately predicted with slight modifications to the model. However, it is worth noting that the model faced challenges in accurately forecasting the overshoot time, which consistently appeared shorter than the computed values. However, there are few studies that combine the rheological characteristics of simple rheology models (power-law, Herschel-Bulkley, Casson, and Bingham Plastic Models) with a time variable for use in straightforward prediction processes of conditions that are measured outside the laboratory. The need in the oil and gas industry for a simple model for oil well planning, especially under adverse conditions of high pressure and temperature (Quitian et al., 2022), is significant.

The objective of this work is to fit the experimental data obtained from the flow restart test with an equation that has few parameters, making it easier to fit and use on oil platforms. The fitting was carried out based on the Herschel-Bulkley model. A function of rest time was chosen to multiply the Herschel-Bulkley equation and thereby fit the shear stress data as a function of two variables: rest time and shear rate. Precisely, the findings are expected to reveal a correlation between aging time and stress overshoot, indicating that longer aging times may result in decreased deformation necessary to disrupt the gelled structure. The high level of correlation between the experimental data and the fitted models provides a reliable basis for utilizing these correlations in the planning and simulation of drilling operations in offshore fields.

2. MATERIALS AND METHODS

2.1 Materials

Rheological measurements were carried out using various drilling fluids formulated and supplied by Petrobras. These fluids encompassed a Bentonite suspension, an oil-based drilling fluid containing sodium chloride (NaCl), a water-based drilling fluid with xanthan gum, and lastly, an oil-based drilling fluid with a 60/40 oil/water ratio and a barite concentration of 11.5 pounds per gallon (ppg). In Table 1, each fluid is presented alongside its respective rheometer, where the rheological properties were measured, along with some specifications prior to the tests.

2.2 Rheological tests

Steady-state flow curves were generated to characterize the various drilling fluids by imposing different shear rates for 1000 seconds. A criterion of 1% variability in shear stress values was used to determine the steady-state value. The temperature was controlled using the rheometer's Peltier system in conjunction with a thermal bath, maintaining the sample at 25°C. To ensure high reproducibility, the fluid was pre-sheared at a rate of 300 s⁻¹ for 100 seconds, creating a state independent of the sample's shear history and standardizing the fluid. The tests were conducted in triplicate with the aim of verifying the repeatability, homogeneity, and consistency of the measurements.

All the tests were conducted to investigate the rheological behavior of the drilling fluids during flow start-up. The rotational rheometers were used to measure the shear stress response of the fluids under controlled shear rates and rest times (Bonn et al., 2015; Divoux et al., 2011; Nguyen and Boger, 1992). Shear rate-controlled experiments were conducted to replicate conditions of the drilling fluid flow start-up. Various shear rate values were imposed using a linear function, incrementing from zero to a final shear rate (0.003, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 5, 10, and 50 s⁻¹). During the

experiment, the sample was pre-sheared and then allowed to rest for specific durations (10, 60, 600, 1800, and 3600 sec.), following the American Petroleum Institute (2005) guidelines, to assess the gel strength of the drilling fluid.

Table 1. Different drilling fluids used in rheological measurements, specifying the rheometer and geometry used, as well as process specifications prior to rheological measurements.

Fluids	Rheometer and Geometry	Specifications
Bentonite suspension	Anton Paar MCR 702TD rotational rheometer with grooved parallel plate geometry.	The bentonite suspension was prepared by mixing distilled water and bentonite powder in a small bottle using a manual mixer. The mixture was stored for one week before testing to allow for particle hydration and swelling (NORISH, 1954). After one week, the fluid was gently homogenized for one minute and the suspension was then inserted into the rheometer using a spatula.
The olefin-based drilling fluid	Anton Paar MCR 702TD rotational stress-controlled with sandblasted coaxial cylinders.	The olefin-based drilling fluid was a composition of olefin with a sodium chloride brine. Prior to testing, the fluid was homogenized for 10 minutes using a Hamilton Beach shaker. The sample was then inserted and tested in the rheometer.
The water-based drilling fluid	TA-DHR 3 rotational stress-controlled rheometer with Couette roughened surfaces geometry coaxial cylinder geometry.	The water-based drilling fluid was mixed with 0.25wt.% xanthan gum. The fluid is composed of xanthan gum, NaCl brine, high-performant starch, and other components. Before each experiment, the drilling fluid was homogenized for 20 min at 1000 rpm with a low-capacity industrial mixer (Hamilton Beach HMD200).
The olefin-based drilling fluid with a 60/40 oil/water ratio	Haake Mars III rheometer, utilizing grooved parallel plates as the geometry.	The olefin-based drilling fluid with a 60/40 oil/water ratio underwent the same procedures with the addition of Barytine in the rheometer. Barytine was added in three different quantities: 11.5 ppg (pounds per gallon).

The rheometric data obtained from the tests were then analyzed to investigate stress overshoot (gel strength) phenomena and the impact of aging time on the fluids' behavior. The stress overshoot measured in a constant shear-rate experiment leads to similar estimates of characteristic stresses associated to the static yield stress obtained in other experiments. The fitted models, such as the Herschel-Bulkley equation multiplied by the chosen time of rest function, were used to describe the rheological behavior of the drilling fluids and establish correlations between stress overshoot, rest time, and shear rate. These findings have potential implications in optimizing drilling operations in the oil and gas industry, especially in offshore fields, by providing valuable insights into the flow characteristics and stability of various drilling fluids.

3. RESULTS AND DISCUSSION

The present study focuses on investigating the impact of stress overshoot on different drilling fluids. The analysis is carried out using rheometric data obtained from start-up flow tests. Furthermore, the study employs well-fitted mathematical models to establish correlations between stress overshoot and aging time. Through meticulous analysis and interpretation of the rheometric data, this research aims to provide valuable insights into the correlation between aging

time and stress overshoot. The anticipated outcomes suggest that aging time significantly impacts not only the magnitude of stress overshoot but also the shear rate required to break up the gelled structure of a material.

3.1 Rheological characterization of drilling fluids

Steady-state flow curves were performed at 25 °C and atmospheric pressure for the four drilling fluids analyzed. Figure 1 displays the shear stress as a function of shear rate, as well as the Herschel-Bulkley fitting model for each fluid. As can be observed in Figure 1, that all four fluids exhibit shear-thinning or pseudoplastic behavior, where apparent viscosity decreases with increasing shear rate.

For the bentonite suspension and the olefin-based drilling fluid with NaCl, this behavior is more predominant, and it is possible to observe a possible high value of dynamic yield stress or yield strength. In the case of water-based drilling fluids with xanthan gum and the olefine-based drilling fluid with a 60/40 oil/water ratio, the yield stress is lower. The drilling fluids exhibited different rheological characteristics regarding dynamic yield stress and viscosity, allowing for a wider range of rheological fluid behavior. These ranged from simpler viscoelastic fluids with minimal yield stress to viscoplastic fluids exhibiting both low and significant yield stress, and even extended to elastoviscoplastic fluids characterized by yield stress and thixotropic behavior, as seen in the case of bentonite suspension.

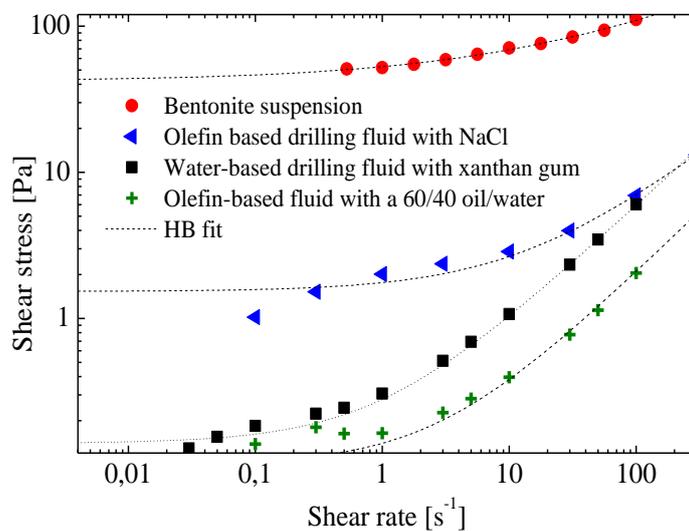


Figure 1. Steady-state flow curves for the various analyzed drilling fluids. The measurements were carried out in triplicate and fitted to the Herschel-Bulkley model, as indicated by the dashed line.

The Steady-state flow curves were fitted to the Herschel-Bulkley model, as presented in Figure 1, enabling an analysis of the different behavior conditions that drilling fluids exhibit with changes in shear rate. The fitting parameters for the four flow curves are detailed in Table 1, providing information on the yield stress, consistency coefficient, behavior index, and the correlation coefficient, all of which gauge the alignment of the curves with the experimental data.

Table.1 Fitting parameters for the Herschel-Bulkley model for each analyzed drilling fluid. Yield stress (τ_0), consistency coefficient (K), flow behavior index (n) and corresponding correlation coefficients (R^2).

	Bentonite suspension	Olefin based suspension	Water-based suspension	Olefin-based suspension 60/40 of 11.5 ppg Baretine
τ_0 [Pa]	42.1	1.53	0.14	0.10
K [Pa.s ⁿ]	10.7	0.23	0.14	0.04
n [-]	0.40	0.69	0.81	0.85
R^2	0.998	0.9938	0.9998	0.9973

In Table 1, a comprehensive overview of the drilling fluids' rheological properties is presented. Notably, the bentonite suspension prominently exhibited a yield stress of approximately 42 [Pa], accompanied by a behavior index of 0.40. These values collectively signify a substantial degree of shear-thinning behavior within this particular fluid. This behavior implies that as shear rate increases, the fluid's viscosity decreases, a critical characteristic in drilling operations where efficient circulation and suspension of cuttings are paramount.

In contrast, the remaining drilling fluids displayed significantly lower yield stresses of 1.53, 0.14, and 0.10 [Pa], respectively. These values are notably lower, almost negligible, especially when considering the last two, which were water-based drilling fluids with xanthan gum, and the oleophilic drilling fluid with a 60/40 oil-to-water ratio. Such low yield stresses are indicative of their relative ease in responding to applied stresses and flowing, making them suitable choices for specific drilling conditions.

Moreover, the behavior indices, a measure of fluid consistency and flow behavior, were found to be greater than 0.6 for the majority of the fluids studied. This indicates a behavior that tends towards Newtonian fluids, which exhibit consistent viscosity regardless of shear rate. Understanding these rheological characteristics is pivotal in the oil industry, as it informs the selection of drilling fluids best suited for various operational scenarios and wellbore conditions.

Understanding the behavior of different fluids in this stable state provides us with a clearer insight into selecting the shear rates to be explored during transient states, as well as the parameters that can influence the restart of flow for these fluids.

3.2 Experimental Analysis and Fitting of Stress Overshoots

The evolution of shear stress over time provides intriguing insights into material behavior. Initially, as shear stress increases, this ascent can be primarily attributed to the material's inherent elasticity, as observed in prior studies (Divoux et al., 2011; Nguyen and Boger, 1992). This initial phase showcases how the material reacts to applied forces, with elasticity assuming a dominant role. However, as time progresses, a notable phenomenon emerges—the stress overshoot. This overshoot serves as a distinct marker of the transition from a gel-like consistency to a more liquid state (Fernandes et al., 2016). This transition is a complex process influenced by various factors, including the material's thixotropic nature, indicating that its viscosity changes over time (Mujumdar et al., 2002), and its viscoelastic properties.

In essence, the evolution of shear stress over time serves as a valuable indicator of material behavior, offering insights into both its elasticity and its intriguing shift from a gel-like to a more liquid state, driven by thixotropy and viscoelasticity. This understanding holds significance for various applications where material flow and deformation characteristics are crucial. To analyze the transition from solid-like to liquid-like behavior, we examine its behavior in the liquid-like regime. Here, the material is allowed to rest for a specified time interval. After the rest period, a constant shear rate is applied and maintained until a steady-state regime is achieved. Upon analyzing the shear stress, we observe that, in some cases, the material undergoes initial deformation, followed by a sharp drop, resulting in decreased shear stress. This highest point of shear stress is referred to as the stress overshoot, a critical indicator in the transition from elastic to viscous behavior (see Fig. 2).

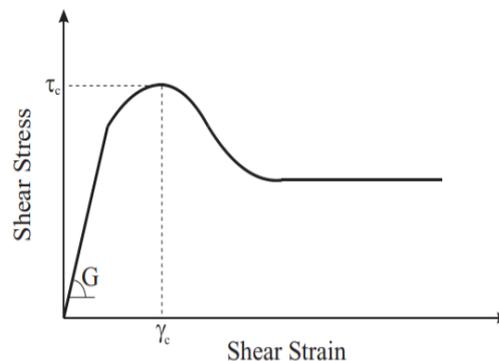


Figure 2. Typical results of the start-up test in viscoelastic-thixotropic fluids, displaying shear stress as a function of shear strain or shear rate.

The flow startup test was conducted for all four drilling fluids, utilizing various shear rates and resting times. Experimental data from stress-strain curves obtained through rheological tests were processed to determine the maximum stress values (Stress Overshoots). These values were then plotted as a function of shear rate, as depicted in Figure 3, for each drilling fluid. In Figure 3(a), we present the experimental data for the olefin-based drilling fluid with NaCl. Figure 3(b) displays the olefin-based drilling fluid with a 60/40 oil-to-water ratio and barytine. In Figure 3(c), the data represents the bentonite suspension, and finally, Figure 3(d) illustrates the water-based drilling fluid with xanthan gum.

This comprehensive analysis provides valuable insights into the rheological behavior of these drilling fluids under different conditions, shedding light on their performance in real-world drilling operations.

In our analysis, we took the experimental data and subjected it to a comprehensive fitting process. This involved the utilization of a nonlinear fitting model, specifically employing the method of least squares to ensure the best possible fit. To describe the rheological behavior of the materials under study, we incorporated the Herschel-Bulkley model, as

depicted in Equation 1, coupled with a function that accounted for the influence of rest time. The critical task of parameter estimation was executed using the Levenberg-Marquardt method, a robust optimization technique. This meticulous approach allowed us to accurately capture and model the complex rheological properties of the materials, facilitating a deeper understanding of their behavior.

$$\tau_{Overshoot} = (\tau_0 + k\dot{\gamma}_p^n)f(t_r); \rightarrow f(t_r = 0) = 1 \quad (1)$$

Where τ_0 represents the yield stress, K stands for the consistency coefficient, n denotes the behavior index, $\dot{\gamma}_p$ signifies the peak shear rate, and $f(t_r)$ is a function that accounts for the variation in sample resting time and t_r represent aging time. Therefore, when this function equals zero, its value becomes 1, signifying that the fluid's behavior adheres to the Herschel-Bulkley model in a proportional manner.

$$f(t_r) = \frac{A + t_r}{A + Bt_r} + Ct_r \quad (2)$$

In this equation, A, B, and C are fitting coefficients that allow for a precise modeling of how the time a fluid spends at rest impacts its response to subsequent stresses or shearing. The term $(A + t_r)$ in the numerator represents a gradual increase in the property or behavior of the fluid as the resting time increases, while the denominator $(A + Bt_r)$ modulates this influence. Additionally, the additional term Ct_r adds a linear contribution to the value of $f(t_r)$. In summary, this equation is useful for characterizing and predicting how a fluid behaves after different resting periods, which is crucial in applications involving the manipulation of viscous or rheologically complex fluids.

In Figure 3, the stress overshoot responses of the drilling fluids with different aging times and shear rates are presented. These responses were obtained using a rheometer and were fitted using the correlations in Equations (1) and (2) (dotted lines). It is evident that the stress overshoot increases in varying proportions with aging time, depending on the material's microstructure and the concentration of its primary components. In Figure 3(a), the olefin-based drilling fluid with NaCl exhibited nearly proportional increases of approximately 10 [Pa]. However, the drilling fluid with a 60/40 oil-to-water ratio, as shown in Figure 3(b), displayed an insignificant increase when left to rest for 600 seconds. Even with an extended aging time of 1800 seconds, only a slight increase occurred, differing from the NaCl-based drilling fluid.

A similar trend is observed for the water-based fluids in Figures 3(c) and (d). In the case of the bentonite suspension, a substantial increase in stress overshoot is evident with an extended aging time. Conversely, for the drilling fluid with Xanthan gum, the increase in aging time had a nearly negligible impact. It can be observed that the concentration of the viscosifying components significantly influences the increase in stress overshoot.

The distinct stress overshoots are illustrated across various aging times. As depicted in Figure 3, it becomes evident that there exists a correlation between the escalation of stress overshoot and both rest time and shear rate. For the olefin-based drilling fluid with a 60/40 oil-to-water ratio [can see Figure 3(b)], a trend of enhanced stability is noticeable with prolonged rest times. This trend is accompanied by an increase in stress overshoot, observed for both low and high shear rates. In contrast, the Bentonite suspension [Figure 3(c)] exhibits higher values of yield stress and viscosity and does not display sedimentation. Consequently, there is a pronounced rise in stress overshoot as the resting time extends.

In the scenario of the water-based drilling fluid with xanthan gum [Figure3(d)], a noteworthy observation was made: the stress overshoot diminished as the resting time increased, particularly at lower shear rates. However, this effect was not replicated at higher shear rates. This phenomenon could potentially be linked to the decreasing stability of the fluid over prolonged periods. It's worth noting that the fitting process yielded effective results for both the Bentonite suspension and the olefin-based drilling fluids. Nevertheless, the outcomes for the water-based drilling with xanthan gum fluid did not exhibit a straightforwardly proportional relationship with resting time.

For all fluids, the simple model adapted well to their behavior, particularly regarding the increase in stress overshoot. All fits were statistically significant, as indicated by their p-values (< 0.001), thus ensuring the combined expanded uncertainty of the stress overshoot and shear rate measurements at the 95% confidence level. All the fits were adequately representative, with a correlation coefficient exceeding 0.98. The exception was the water-based drilling fluid with Xanthan gum, which displayed a coefficient of 0.876. This may be attributed to sedimentation, as observed in Quitian et al., (2022), when the fluid is left to rest for 600 seconds.

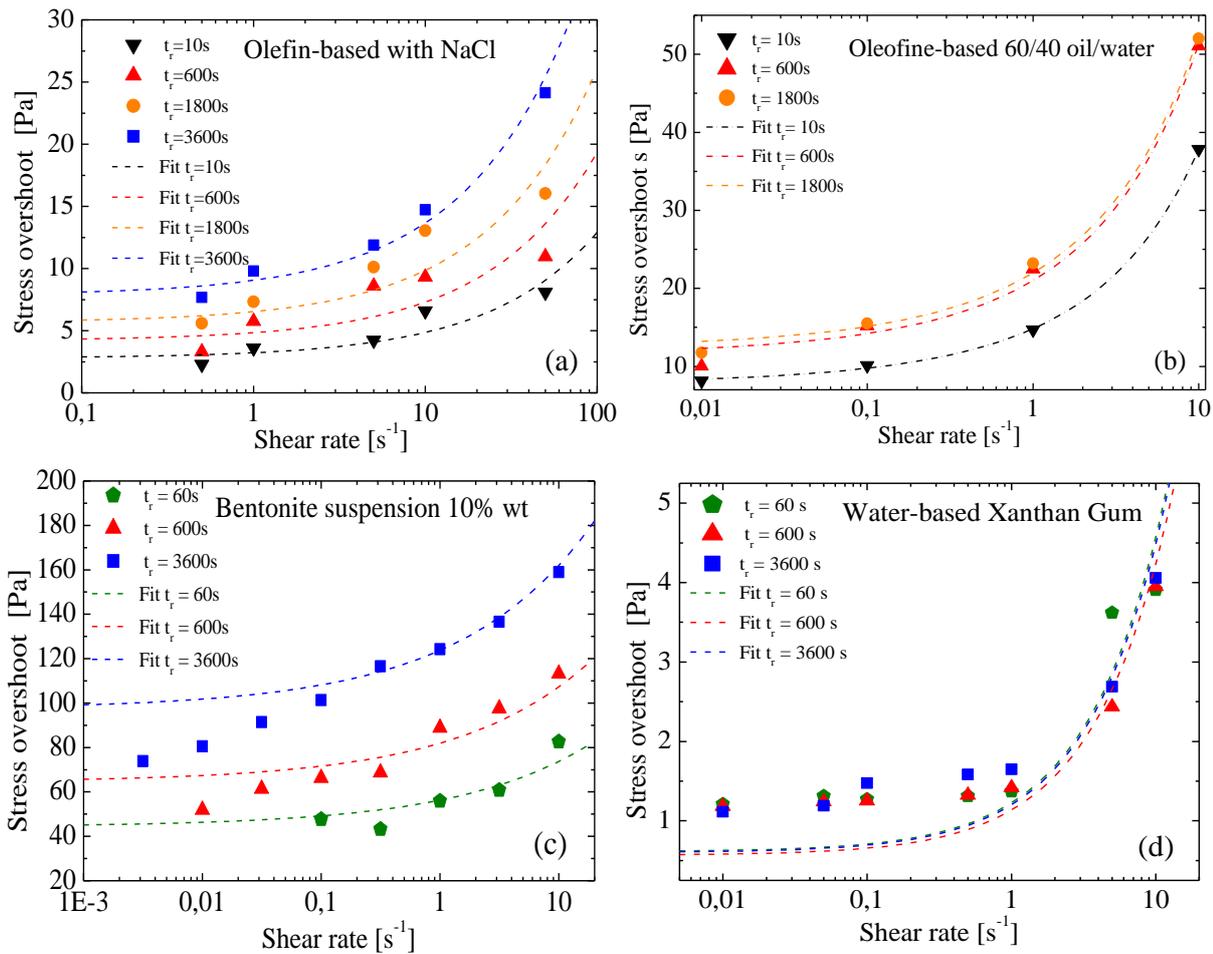


Figure 3. Comparison between the experimental results and the fits for: (a) Olefin-based with NaCl, (b) Olefin-based 60/40 oil/water, (c) Bentonite, and (d) Water-based with xanthan gum.

The practical implications of these discoveries extend significantly, as they contribute to improving the efficiency, safety, and cost-effectiveness of drilling operations within the oil and gas sector. In summary, this scientific article delves deep into the complex rheological characteristics of drilling fluids, shedding light on the influence of stress overshoot and aging time on the disruption of the gelled structure. The knowledge acquired from this research holds substantial promise for driving progress in drilling fluid technology and streamlining drilling activities, especially in offshore environments.

The successful fitting of the models to experimental data, along with the established correlations, establishes a robust foundation for further exploration and application of these findings in practical drilling operations.

4. CONCLUSIONS

In conclusion, the results of this study indicate that the fitted models, based on the Herschel-Bulkley equation multiplied by the chosen time of rest function, demonstrate a good fit to the experimental data obtained from flow start-up tests on different drilling fluids. The correlations established between stress overshoot, rest time, and deformation rate provide valuable insights into the rheological behavior of these fluids during critical operational stages. The success of the fitted models in accurately describing the stress response of the drilling fluids opens up possibilities for their potential application in flow start-up tests of other fluids. However, it is important to acknowledge that the effectiveness of these models in predicting the behavior of other fluids needs to be confirmed through future testing. Conducting flow start-up tests with a variety of drilling fluids and comparing the results with the predicted values from the fitted models can further validate their reliability and generalizability.

One notable observation is that the water-based drilling fluid showed some discrepancies in its behavior, which may be attributed to the delay of the rheometer in imposing the defined shear rate. This delay could have influenced the stress overshoot values and led to differences between the predicted and actual behaviors of the fluid. Therefore, when dealing with fluids that exhibit rapid changes in their rheological properties, careful consideration should be given to the experimental setup and measurement devices to ensure accurate data acquisition. Furthermore, it is essential to recognize

that the obtained results and correlations may be specific to the tested fluids or other fluids with similar rheological characteristics. The diverse composition and properties of drilling fluids may lead to variations in their rheological responses, thus limiting the generalizability of the findings to a broader range of fluids. Therefore, when applying the fitted models to different fluids, it is crucial to consider the specific nature and composition of each fluid to ensure the accuracy of the predictions. Despite these limitations, the insights gained from this study hold significant promise for enhancing the planning and simulation of drilling operations in offshore fields. The ability to predict stress overshoot and understand the impact of aging time on the disruption of the gelled structure of drilling fluids can contribute to improving the efficiency, safety, and cost-effectiveness of drilling processes in the oil and gas industry.

Future research endeavors should prioritize validating the predictions of the fitted models across a broader spectrum of fluids and refining experimental procedures to address potential limitations. The ongoing investigation into the behavior of drilling fluids during flow initiation will undoubtedly advance our comprehension of their rheological properties and enhance the optimization of drilling processes within the oil and gas industry.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

- American Petroleum Institute, 2005. API RP 13B-2 - Recommended practice for Field-testing Oil-based Drilling Fluids.
- Balhoff, M.T., Lake, L.W., Bommer, P.M., Lewis, R.E., Weber, M.J., Calderin, J.M., 2011. Rheological and yield stress measurements of non-Newtonian fluids using a Marsh Funnel. *J. Pet. Sci. Eng.* 77, 393–402. <http://dx.doi.org/10.1016/j.petrol.2011.04.008>.
- Bonn, D., Denn, M.M., Berthier, L., Divoux, T., Manneville, S., 2015. Yield Stress Materials in Soft Condensed Matter. arXiv 1502.05281, [cond-ssoft]. <https://doi.org/10.1103/RevModPhys.89.035005>.
- Bourgoyne, A.T., Millhelm, K.K., Chenevert, M.E., Young, F.S., Bourgoyne Jr., A.T., Millheim, K.K., Chenevert, M.E., Young Jr., F., 1991. Applied Drilling Engineering. In: SPE TEXTBOOK SERIES, second ed. Society of Petroleum Engineers, Richardson.
- Calcada, L.A., Martins, L.A.A., Scheid, C.M., Magalhães, S.C., Martins, A.L., 2015. Mathematical model of dissolution of particles of NaCl in well drilling: de-termination of mass transfer convective coefficient. *J. Pet. Sci. Eng.* 126, 97–104. <http://dx.doi.org/10.1016/j.petrol.2014.12.011>.
- Divoux, T., Barentin, C., Manneville, S., 2011. Stress overshoot in a simple yield stress fluid: an extensive study combining rheology and velocimetry. *Soft Matter* 7, 9335–9349. <https://doi.org/10.1039/c1sm05740e>.
- Dullaert, K., Mewis, J., 2006. A structural kinetics model for thixotropy. *J. Non-newtonian Fluid Mech.* 139, 21–30. <http://dx.doi.org/10.1016/j.jnnfm.2006.06.002>.
- Gautam, S., Guria, C., Rajak, V.K., 2022. A state of the art review on the performance of high-pressure and high-temperature drilling fluids: Towards understanding the structure-property relationship of drilling fluid additives. *J Pet Sci Eng.* <https://doi.org/10.1016/j.petrol.2022.110318>
- Livescu, S., 2012. Mathematical modeling of thixotropic drilling mud and crude oil flow in wells and pipelines-A review. *J. Pet. Sci. Eng.* 98–99, 174–184. <https://doi.org/10.1016/j.petrol.2012.04.026>.
- Mujumdar, A., Beris, A.N., Metzner, A.B., 2002. Transient phenomena in thixotropic systems. *J. Nonnewton. Fluid Mech.* 102, 157–178. [http://dx.doi.org/10.1016/S0377-0257\(01\)00176-8](http://dx.doi.org/10.1016/S0377-0257(01)00176-8).
- Negrão, C.O.R., Franco, A.T., Rocha, L.L.V., 2011. A weakly compressible flow model for the restart of thixotropic drilling fluids. *J. Nonnewton Fluid Mech.* 166, 1369–1381. <http://dx.doi.org/10.1016/j.jnnfm.2011.09.001>.
- Nguyen, Q.D., Boger, D.V., 1992. Measuring the Flow Properties of Yield Stress Fluids. *Annu. Rev. Fluid Mech.* 24, 47–88. <https://doi.org/10.1146/annurev.fl.24.010192>.
- Quitian, L.H., Andrade, D.E. V., Franco, A.T., 2022. Bentonite-free water-based drilling fluids at HP/HT condition: a rheometric analysis. *Rheol Acta.* <https://doi.org/10.1007/s00397-022-01356-x>
- Ragouilliaux, A., Herzhaft, B., Bertrand, F., Coussot, P., 2006. Flow instability and shear localization in a drilling mud. *Rheol. Acta* 46, 261–271. <http://dx.doi.org/10.1007/s00397-006-0114-2>
- Tanner, R.I., 2018. Review Article: Aspects of non-colloidal suspension rheology. *Phys. Fluids* 30. <https://doi.org/10.1063/1.5047535>

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