

Emulsion Stability in Nonaqueous Drilling Fluids

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Abstract

Relevant key performance indicators (KPIs) of high-performance drilling fluids are important to avoid misleading directions during a well's development phase. Measurement of emulsion and electrical stability (ES), a useful tool to track changes in the field, can provide misleading results in a laboratory setting when used to compare nonaqueous drilling fluids (NADF) fluids.

Design of experiments (DOE) was used to create a data-rich model to evaluate how the interaction of fluid components affects typical NADF properties, including ES. To establish reliable trends and to correlate ES with other KPIs, 100+ experiments were completed, providing the ability to correlate ES to emulsion stability and other drilling fluid properties across a broad range of fluid formulations.

A model based on multiple input variables was created for each KPI of a drilling fluid. However, consecutive data analysis showed that ES has limited value as a KPI in the laboratory because ES does not correlate well to fluid loss or water in the filtrate. Some correlation of ES to fluid viscosity was observed.

Innovations in drilling fluids design are necessary to increase performance, reduce cost, reduce CO₂ footprint, and improve the sustainability profile of nonaqueous drilling fluids. To achieve these goals, focus should be placed on KPIs with improved correlation to performance. Extensive constructive testing demonstrated ES is not a pertinent KPI in the evaluation of NADF in the laboratory.

Introduction

Laboratory testing of drilling fluids is an early and indispensable phase in the development of new products and formulations within the energy industry. Most of the existing tests could be categorized into two types: basic screening tests and advanced tests. In the industry, there is a prevalent practice of prioritizing basic screening tests due to their cost and time efficiency, lower technical demands, and their capacity to offer preliminary insights into fluid performance. As engineering teams' worldwide endeavor to develop new aqueous, oil, and synthetic-based drilling fluids to meet escalating technical challenges and concurrently enhance the sustainability of drilling operations, this paper emphasizes that it is imperative to periodically reassess and enhance the testing protocols for the fluids. In 2023, a comprehensive study was presented assessing common laboratory tests performed on water-based

drilling fluids. Key performance indicators (KPIs) of interest were evaluated, and the efficiency and suitability of each test on these KPIs were extensively discussed (Khramov et al., 2023). Building upon the insights gained from prior research by the authors of this paper, the current work involves an in-depth analysis focused on interpreting the results from those fundamental screening laboratory tests, with a specific emphasis on nonaqueous drilling fluids (NADF). Among all the common KPIs for NADF, electrical stability (ES) is the focus of this study.

The use of ES in assessing the stability of NADF traces its origins to the 1950s. Crittendon (1958) patented a technology specifically developed for evaluating the stability of water-in-oil drilling fluid. An increasing AC electrical field up to 2,000 V was applied to the emulsion until an arbitrary (61 μ A) current threshold was reached. The recorded voltage difference at 61 μ A, referred to as the ES voltage, was then compared among different drilling fluids. It was hypothesized that the drilling fluid is more stable when the ES voltage is higher. Notwithstanding the distinct breakdown mechanisms induced by electric field, shear, and temperature, this concept has gathered widespread acceptance since its inception. Historically, ES has been routinely measured in the field, serving as an indicator of NADF instability. Further examination and potential mud treatment could be necessary if there is a sudden change in ES (Ali et al., 1987).

Over the years, ES measurement has been introduced into commercial laboratories as one of the standard testing methods to evaluate emulsion stability. Although emphases were made that only the daily trend instead of the absolute value of ES voltage should be considered and evaluated (Growcock et al., 1994; Borges et al., 2022), it is not uncommon in the industry to apply an arbitrary minimum ES value during the product evaluation process. This practice is particularly prevalent during the primary and secondary emulsifier evaluation given that emulsifiers constitute the backbone of any nonaqueous-based drilling fluid and play a direct role in providing emulsion stability. While several studies show that ES voltage correlates well with other KPIs for NADF stability such as high-pressure high-temperature (HP/HT) fluid loss and the amount of water in the filtrate (Growcock et al., 1994; Huang et al., 2018), a substantial part of research contradicts these findings. (Bakar et al. 2020; Murtaza et al., 2021). Additionally, the majority of these studies drew their conclusions based on a restricted

number of experiments.

In this work, a series of laboratory experiments were conducted to evaluate the effect of drilling fluid formulation on essential KPIs for a drilling fluid, and most importantly, the correlation between those KPIs. A novel design of experiment (DOE) algorithms was employed in selecting experimental parameters to maximize the number of variables (6) and levels while conducting an optimal number (48) of experiments. A broad yet judicious range of parameters was chosen, enabling the creation of drilling fluids spanning from poor to exceptional stability, as evident by the results of the advanced tests (HP/HT fluid loss and the amount of water in the filtrate).

In addition, reduced two-factor interaction (2FI) models with good accuracy were developed to predict KPIs, including rheology, fluid loss, and ES voltage, based on the selected experimental parameters. Using the advanced statistical algorithms and the correlations between KPIs, a comprehensive analysis was undertaken to evaluate the impact of drilling fluid formulation on its stability, examine the correlations among various industrial KPIs, and ascertain whether ES actually serves as a reliable indicator of a drilling fluid's emulsion stability.

Problem Statement

The foundation of successful innovations in drilling fluids chemistry and formulation resides in the continual advancement and improvement of performance evaluation methods. If certain tests are deemed to be of limited or no relevance, it is advisable to de-emphasize their use, because these methods can impede innovation and decelerate the development process.

Methodology

In 2020, the authors of this paper presented how they used DOE methodology to evaluate various additives in a complicated drilling fluid system (Khramov et al., 2020a). In our consecutive publications, the authors further showcased the power of this DOE approach by successfully addressing an intricate challenge associated with a deepwater drilling fluid, which entails multiple yet often conflicting requirements. (Khramov et al., 2020b). Two years later, these authors once again applied the DOE approach with success, driving the optimization of an amidoamine emulsifier synthesis process to achieve unprecedented levels of performance (Khramov et al., 2022). In summary, DOE has proven to be a powerful technique for analyzing the performance of drilling fluids, allowing for effectively separating the signal from the noise, analyzing the error bars associated with measurement, and developing reliable trends across a broad range of conditions. The same methodology was deployed by the authors for ES analysis in this work. A comprehensive array of experimental conditions was evaluated to ensure meaningful conclusions were derived.

Design-Expert software (Stat-Ease®) was employed to conduct the DOE and data analysis in this study. Figure 1 shows a typical DOE workflow comprised of design setup (digital), implementation (hands-on laboratory testing), and data analysis (digital). This systematic approach resulted in a property-composition response surface, essentially a digital and

predictive model for evaluating the drilling fluid's performance. The model was generated based on least-squares fit and statistical analysis methods and is accompanied by model-quality metrics (fit statistics). Note that each mud property of interest; i.e., KPIs, requires its own model generated from experimental data.

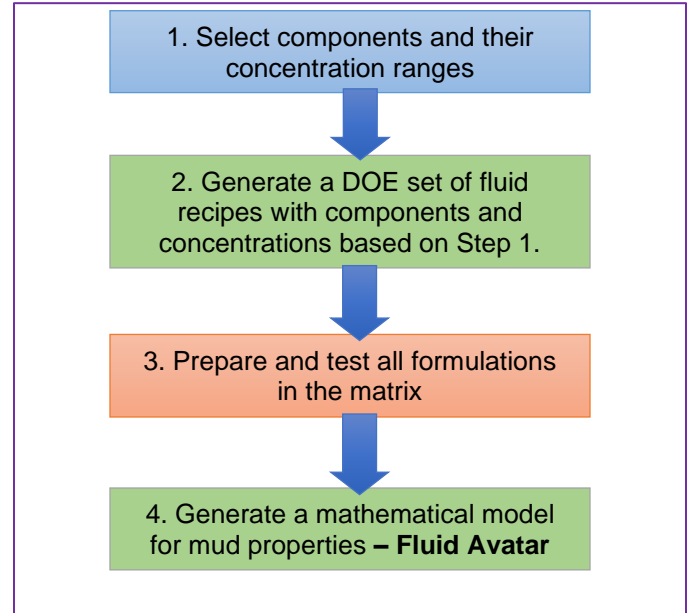


Figure 1—A typical workflow for building a response surface model of a drilling fluid system.

For this investigation, the authors of this paper focused on a 13-lbm/gal invert emulsion drilling fluid with 75/25 oil/water ratio. The formulation of drilling fluid is detailed in Table 1, while the selected variables and their respective ranges are shown in Table 2. To draw meaningful conclusions from this study, it is important to select fluid formulations and testing conditions that are applicable in field operations, as shown in Figure 2 (typical NADF properties). That is, in designing a system, we carefully balanced between the number of experiments that needed to be completed, the variables to evaluate, and the targeted fluid properties. An exercise in correlating ES value with other mud properties may be performed using a substantial amount of field data that had been collected. However, due to the use of seed mud, it is difficult to precisely ascertain the composition of a fluid. Furthermore, the focus of this paper is to determine the benefit of ES as a tool for new product development. Therefore, the focus was on evaluating freshly made laboratory fluids in the authors' attempts to establish what benefit ES voltage provides to a laboratory engineer.

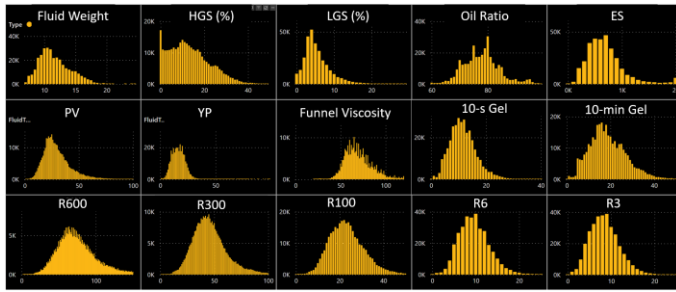


Figure 2—Typical properties and operational conditions of NADF.

Variables that were considered included two types of primary emulsifiers because emulsifiers have a strong influence on emulsion stability. Four types of base oils were selected to make the conclusions universally applicable across many different situations. Considering the substantial differences in the viscosity of the base oils, different amounts of organoclay were chosen and added to each base oil to ensure similar rheology responses. The authors aimed to apply the results of this study across various drilling scenarios and reservoir conditions; therefore, a typical hot roll time (16 hours) was maintained, while various hot roll temperatures (250, 280, and 325°F) were selected as a variable. Rheology measurements after hot roll were performed at a typical temperature (150°F) for synthetic-based mud (SBM). The selected KPIs shown in Table 3 could be categorized into two main groups: rheology and stability. Rheology KPIs were standard for laboratory drilling fluids measurement, which include basic 6-speed viscosity as well as 10-sec and 10-min gels measured by an automated rheometer (Grace Instrument). Stability KPIs include ES voltage (measured at 150°F) and HP/HT test results (total filtrate volume and, separately, the amount of water in the filtrate). Note that the HP/HT test was conducted at the same temperature as the hot roll process. Detailed experimental and fluid characterization procedures can be found in previous papers (Khramov et al., 2020a, 2020b, 2022).

Table 1—Formulation of the Drilling Fluids

Chemical	Concentration (lbm/bbl)
Base oil	140 to 170
Emulsifier (two types)	4 to 12
Rheology control additive	5
Wetting agent	0 to 3
Organoclay	2.6 to 6.5
Lime	5
25% CaCl ₂ brine	85 to 90
Suspension additive	6
Fluid loss additive	1.5
Rheology modifier	1 to 2.5
Micronized barite	260 to 290

Table 2—Selected Variables and the Ranges

Variables	Unit	Type	SubType	Min	Max
Emulsifier concentration	lbm/bbl	Numeric	Continuous	4.00	12.00
Wetting agent concentration	lbm/bbl	Numeric	Continuous	0.00	3.00
Rheology modifier concentration	lbm/bbl	Numeric	Continuous	1.0	2.50
Hot roll and HT/HP temperature	°F	Numeric	Discrete	250	325
Emulsifier type	-	Categoric	Nominal	A	B
Base oil type	-	Categoric	Nominal	IO1618, Saraline 185V, Diesel, Escaid 110	

Table 3—Selected KPIs and the Response Ranges

KPIs	Unit	Group	Min	Max	Mean
R600 at 150°F	°VG	Rheology	43.2	105.2	63.6
R6 at 150°F	°VG	Rheology	3.0	24.5	7.9
10-min gel at 150°F	lb/100ft ²	Rheology	2.5	58.3	15.3
ES voltage at 150°F	V	Stability	141	656	380
HP/HT fluid loss (30 min on paper)	mL	Stability	0.3	19.8	5.4
Water in the filtrate (30 min on paper)	mL	Stability	0	4.0	0.5

Each KPI was evaluated independently with different variables contributing to the models. The signal-to-noise ratio, significance, and accuracy of the models were assessed using advanced statistical algorithms. Based on the selected variables, a comprehensive experimental dataset was generated from 48 distinct experiments.

Results and Discussion

P-value and adequate precision of the models indicated that for all of the KPIs, the signal-to-noise ratios are desirable, and the models demonstrate statistical significance. However, as shown in Table 4, the model for ES voltage has undesirably low R² values and a high coefficient of variation (c.v.%). In contrast, the R² values for all other KPIs are all greater than 0.750. According to the fit statistics, it is observed that ES voltage exhibits a notable variation, and it is independent of our formulation efforts. In contrast, rheological and other stability models demonstrate a high degree of reliability. These findings closely align with our previously published DOE works (Khramov et al., 2020a, 2020b, 2022), suggesting that reliable models can be readily obtained for typical mud KPIs, except for those that exhibit excessive variation or lack correlation with the input variables in the model.

Table 4—Fit Statistics for ES Voltage

Std. Dev.	90.99	R ²	0.3225
Mean	380.20	Adjusted R ²	0.2713
C.V. %	23.93	Predicted R ²	0.1466
		Adeq Precision	8.5585

Upon closer examination of the KPIs, it becomes apparent that a broad range of drilling fluids was generated in this DOE, including those with very high and very low rheological properties, as well as varying levels of emulsion stability (ranging from high to poor) as shown in Table 3. These fluid properties center around the conventional ranges for NADF (Figure 2). This result serves as evidence of the success of our DOE implementation, as depicted in Figure 3. The figure shows a correlation plot between HP/HT fluid loss (x-axis), water in the filtrate (represented by color with a scale on the plot), and ES voltage (y-axis). It can be observed that HP/HT fluid loss ranges from 0.1 to 20 mL, water in the filtrate spans from 0 to 4 mL, and ES voltage varies from 150 to 700 V. Similar observations and statements can be made regarding the rheological KPIs that drilling fluids with a broad range of responses were created in this study.

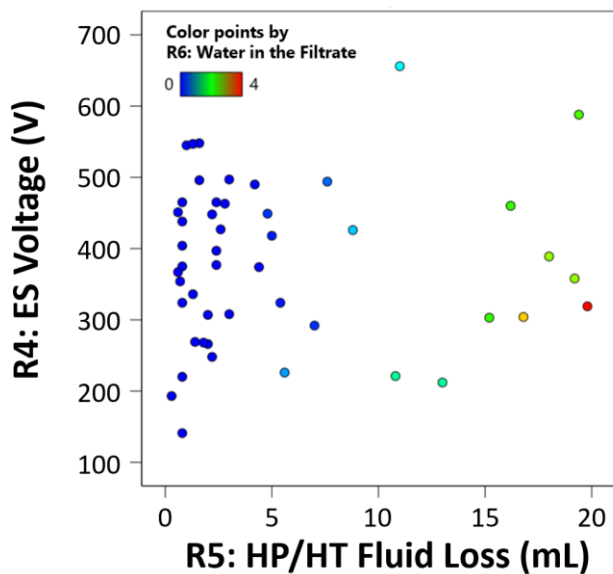


Figure 3—Correlation between stability KPIs.

Among all of the stability KPIs, particular emphasis was placed on HP/HT and water in the filtrate. These KPIs were generated through a more advanced, time- and labor-consuming test, which enhances the simulation of actual drilling operations. Moreover, the presence of water in the filtrate in a stable invert emulsion is a robust indicator of demulsification, or destabilization of the emulsion (Tirmizi et al. 1996). There is a strong correlation between HP/HT fluid loss and water in the filtrate, with an R² value of 0.950 derived from the fitting statistics. On the contrary, Figure 3 shows that a minimal correlation was observed between the HP/HT fluid loss and ES

voltage, as reflected in the R² value of 0.042. Advanced data visualization further confirms that ES voltage is not a reliable tool for evaluating emulsion stability. A correlation plot consists of all the inputs (variables) and outputs (KPIs) as shown in Figure 4. In this plot, the red zone signifies a positive correlation, the blue zone indicates a negative correlation, and the intensity of the color represents the strength of the correlation (i.e., the darker the zone color, the stronger the correlation). It can be seen that hot roll and HP/HT temperature exhibit robust positive correlations with both HP/HT fluid loss and water in the filtrate. Similarly, R600, R6, and gel properties correlate with each other as expected. In contrast, hot roll temperature only demonstrates a weak correlation with ES voltage. The R² of ES voltage vs HP/HT correlation was determined to be only 0.141. Numerous studies and field results have shown that the emulsion stability of NADF is highly influenced by downhole temperature (Fjelde 2009, Lee et al. 2012). If ES voltage could genuinely reflect the stability of the emulsion, one would anticipate a strong, negative correlation with hot roll and HP/HT temperature, meaning, as temperature increases, ES voltage should decrease owing to the common understanding that higher temperatures destabilize emulsions (which is also confirmed in the study presented in this paper). Upon further examination of Figure 4, it could be observed that ES voltage only exhibits a moderate correlation to the rheology KPIs (R²= 0.431 for R600, R²= 0.488 for R6, and R²= 0.448 for 10-min gel).

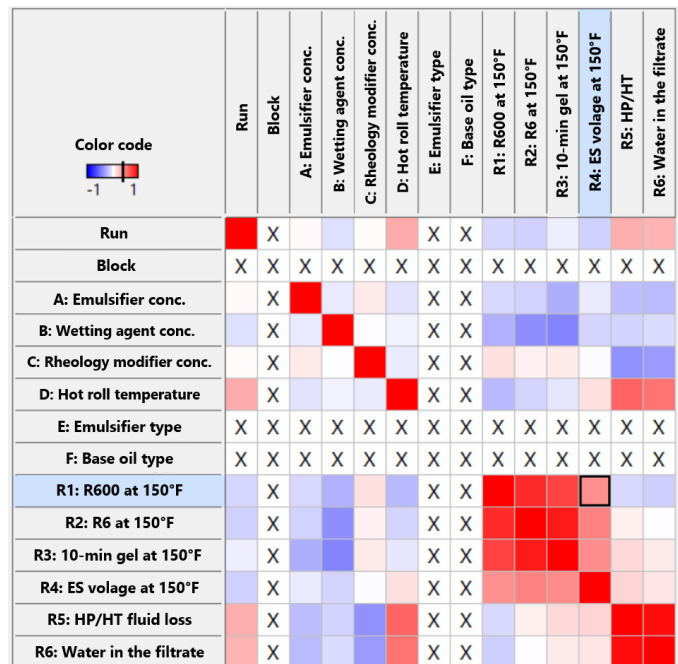


Figure 4—Visualization of the correlation between selected variables and KPIs (does not support categorical variables).

An additional data-mining exercise was performed, which combined over 100 measurements of NADF from a Gulf of Mexico (GoM) product development project, where all muds

were hot rolled at 280°F. This additional dataset strengthens the assertion of the lack of correlation between HP/HT fluid loss and ES voltage. As shown in Figure 5 there is scarcely any correlation between HP/HT fluid loss and ES voltage even across a wide range of measured values, further validating our statement that ES voltage is not a suitable KPI during product development process for NADF. It is important to note that this dataset was collected as part of unique DOE projects, where the fluids were deliberately designed to perform from inferior to outstanding.

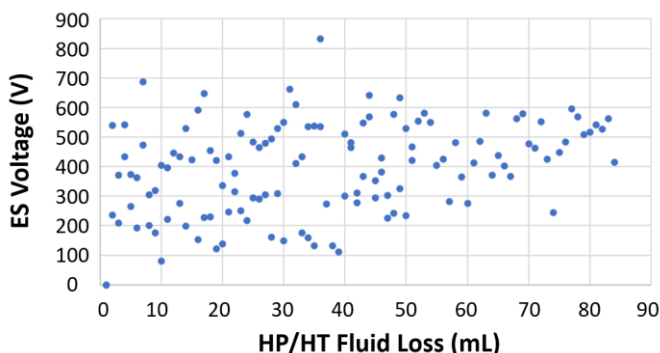


Figure 5—Correlation between HP/HT fluid loss and ES voltage from three previous DOE studies.

Conclusion

ES measurements, or specifically the trends in electrical voltage measured for the same section during drilling, can serve as a useful monitoring tool during the drilling operations to evaluate if there is a sudden change in the properties of NADF in a field setting. However, it is essential to recognize that ES voltage should not be considered as a reliable tool to evaluate the stability of NADF in the laboratory. Extensive formulation efforts and advanced statistical algorithms in the work presented in this paper indicate a minimal correlation between ES voltage and other KPIs that more accurately represent the stability of the emulsion. Therefore, the authors of this paper recommend de-emphasizing ES value when discussing and comparing different laboratory fluids.

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Nomenclature

KPI = Key performance indicators
ES = Electrical stability
NADF = Nonaqueous drilling fluids
DOE = Design of experiments
HP/HT = High-pressure high-temperature
2 FI = Two-factor interaction
SBM = Synthetic-based mud

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