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# Improving Drilling Fluid Preparation with High-Shear Mixing in Liquid Mud Plants

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## Abstract

Synthetic-based drilling fluid, or "mud" as it is commonly known, is widely recognized as a cost-effective fluid, especially for deepwater drilling, because of the technical and performance advantages the fluid offers with respect to pressure management, increased drilling rate, enhanced wellbore stability, and resistance to temperature fluctuations and common contaminants. With continuing advancements in oilfield chemistry, drilling fluids and additives are harder to emulsify and disperse sufficiently. Traditional mud plant processing equipment, which consists of impellers, low-pressure jet nozzles, and mechanical agitators, is leaving undeveloped potential in the properties of prepared fluids. The widespread practice to achieve the desired fluid properties is to treat the mud as necessary during mixing, and then condition the mud using the bit to provide shear at the wellsite.

Several operators and mud companies have turned to high-shear mixing devices to improve fluid preparation. The most straightforward method of replicating the shear energy experienced as the fluid travels through the bit is the use of high-pressure pumps at the surface to shear the mud through nozzles. This method, while effective, poses concerns due to complexity, mobility, cost, and safety. An innovative, inherently safe, low-pressure solution, utilizing controlled-cavitation (to produce vigorous conditions of pressure and temperature in overall ambient conditions), was tested and validated as an effective method of improving mud preparation.

Performance data and implications for operational efficiencies are discussed for each stage of the trial. The results show that the selected mixing device: (1) is capable of replicating on a large scale the fluid properties achieved in the lab, and (2) provides sufficient mixing energy to produce relatively stable emulsions.

## Introduction

Advancements in deepwater drilling have enabled the offshore industry to drill faster, deeper, and safer despite the numerous technical challenges. With the growing oil and gas demand, deepwater exploration has continued to expand even deeper into the oceans and into more challenging areas. As technologies evolve and standard practices develop, the relative cost of offshore drilling will continue to decline.

A crucial component of effective drilling is the drilling fluid. Two major advancements in drilling fluid technology are (1) increased customization of drilling fluids specifically tailored to meet or exceed the specifications of the operator for unique downhole conditions and (2) the proliferation of liquid mud plants (LMP) to serve the needs of various drilling locations.[1] Most LMPs have mixing pits and tanks equipped with jet nozzles and/or agitators for mixing. Optimizing the mixing equipment and process is critical to optimizing the LMP efficiency.

## Drilling Fluid Considerations

Synthetic-based mud (SBM), a class of invert emulsion drilling fluids, is an optimal choice for deepwater applications due to their high performance, low risk, and cost-effective nature. In addition to the high temperatures downhole and rapid flow rates through the bit nozzle during drilling operations, the mud will also experience very low temperatures and low shear rates when flowing through the riser during deepwater operations.[2] The wide range of temperatures and shear conditions in deepwater operations makes it both more difficult, as well as more critical, to manage the rheological properties of the mud. The rheology, and other properties of an SBM, are influenced by the specific mixture of oil, water, clays, and other additives which are converted to a stable emulsion or "mud" by intense mechanical energy in the mixing process.

Invert emulsions are a water-in-oil emulsion with a water internal phase and an oil continuous phase. When oil and water phases are mixed, high shear rates are typically required to generate emulsions consisting entirely of small droplets.[3] Emulsion droplets behave as fine solid particles and contribute to the rheology of the mud.[4] Producing a quality emulsion during processing is essential to achieving the target fluid properties and facilitating interactions with other chemical additives.

The typical drilling fluid is a complex multiphase emulsion. Smaller droplet sizes support additional chemical additions which contribute to rheology, emulsion stability, and fluid loss in the emulsion. Organophilic clays are a common rheological modifier which largely influences the low-shear-rate properties responsible for solid suspension. Clay particles must be reduced to their finest constituent parts to expose the maximum surface area to the surrounding liquid to fully yield the potential gel strength.[2] Associative polymers are also increasingly used in deepwater applications as rheological modifiers.[5] Other polymers are ideal for achieving ease of emulsification and stabilization of the emulsion. Polymers, while effective for stabilization, are difficult to emulsify unless high energy is applied to the process.[6]

### *Impact of Fluid Quality on Drilling Operations*

One of the key properties of drilling fluids is rheology, which influences various aspects of drilling operations. Rheology dictates the ability of the fluid to carry drill cuttings and keep solids in suspension when flow stops. Rheology affects the pressure drop during pumping, which contributes to ECD. It affects the degree of turbulence that can be achieved and the exit velocity through the bit nozzles. It can also affect flow across porous media. Rheology has a direct influence on some of the most critical drilling-related challenges, including hole cleaning, barite sag, and lost circulation.

The specific rheological properties associated with hole cleaning and barite sag mitigation are low-shear-rate rheology (as measured by the 6- and 3-rpm viscometer readings), yield point, and gel strength.[7] It is slightly ironic that it takes high-shear mixing to achieve a quality emulsion with low-shear-rate rheology.

Large-scale standard fluid preparation techniques have proven less satisfactory in achieving these desired properties with SBMs. The key concerns this poses to drilling and fluid handling operations are barite sage and lack of fluid stability. SBM prepared with conventional processing frequently possess insufficient low-shear rheology, which requires additional treatment in order to mitigate barite sag during transport. The drawback of additional additive treatment is that when the fluid chemistry fully yields, after shearing through the bit, the rheology changes, resulting in further treatment and maintenance. Relatively poor fluid stability, caused by insufficient emulsification of the base fluids, results in oil and water separation during extended periods of storage.

One of the trials presented demonstrates the beneficial impact that high-shear mixing has on low-shear-rate rheology and emulsion stability during fluid preparation. As drilling fluid chemistry advances and becomes more complex, adequate processing equipment and techniques need to develop concurrently. In this study, an innovative high-shear mixer, by which cavitation energy is harnessed to accelerate chemical reactions, is implemented to improve drilling fluids preparation.

### *Liquid Mud Plant Processing*

The bulk of the responsibilities for managing fluids, including chemical storage and fluid preparation, are handled by LMPs. These permanent facilities are strategically located in close geographic proximity to the serviced drilling areas to optimize logistics. The industry is trending toward greater numbers of smaller, more agile LMP's located close to active drilling, and away from large centralized facilities.

Drilling fluid preparation and processing utilize specific chemicals, fit-for-purpose equipment, and require adequate facilities to produce a fluid with specific properties as designed in the laboratory. Fluid processing relies on mechanical equipment to provide the high-shear mixing conditions and temperature which initiate both the chemical and physical reactions required to form a stable emulsion and achieve the performance potential of the designed fluid. Regarding processing parameters, fluid preparation is based on several major influences: mixing energy inputs, mixing time, and conditions of pressure and temperature.[8] A systematic review of standard mixing equipment concluded that jets and agitators fail to achieve the full potential of chemical reactions and emulsification resulting in difficulty meeting the design specifications of the drilling fluids.

The industry widely accepts that the best mixing occurs downhole during drilling, whereby the combination of high shearing conditions created by the drilling fluid passing through the nozzles of the drill bit in the presence of in-situ temperature and pressure facilitates the chemical reactions and emulsification of the drilling fluid. When the drilling fluid is accelerated through a drill bit nozzle, it can experience shear or elongation rates on the order of 100,000 $s^{-1}$.[9]

### High-Shear Mixing Equipment Evaluation

While numerous high-shear mixing solutions are available in the current market, the industry lacks a standard practice with regards to shear. High-pressure shearing was rejected due to concerns with:

- relatively high cost of high-pressure pumping equipment, including pumps, prime-movers, and thick-walled flow lines
- complexity of equipment setup, which requires the additional risk-mitigation measures such as the installation of protective barriers and flow line restraints, and a relatively lengthy pressure test procedure prior to each operation
- higher rate of wear and erosion, especially on nozzles, which changes the performance with repeated usage
- higher frequency and cost of inspection requirements to maintain safe operation of high-pressure equipment.
- higher cost of maintenance on prime-movers
- restrictive installation options with regard to designated high-pressure operating areas

A head-to-head comparison of various available low-pressure solutions was conducted at an LMP. Key points of evaluation for equipment packaging were:

- low-pressure operation
- easy to operate with minimal operator intervention
- easy and cost-effective to maintain
- durable enough to process large volumes of high-solid-content fluids
- easy to transport
- in-line configuration for ease and flexibility of installation

To simulate the shear rate experienced during drilling, without reproducing the extreme downhole conditions, a low-pressure, high-shear controlled-cavitation (HSCC) mixer was tested and implemented in an LMP (Figure 1).

**Figure 1 – High-shear, controlled-cavitation (HSCC) mixer.**

***High-Shear Mixing Utilizing Hydrodynamic Cavitation***

Cavitation is the formation, growth, and subsequent collapse of microbubbles or cavities. Intense pressure and temperature can be generated locally over millisecond intervals due to the energy release from the cavity collapse.[10] The resultant effects can be either destructive or spectacular. When properly harnessed, a hydrodynamic cavitation device can generate millions of such cavities which function as a series of micro shockwave reactors under overall ambient conditions. The harnessed energy is beneficial to mixing as it facilitates both chemical and physical transformations.

A cavitation rotor is a solid cylinder with precisely machined blind bores along the circumference. When the rotor spins, fluid inside the bores is thrown out at great velocity by centrifugal force. The high-velocity fluid exiting the bore leaves a negative pressure zone or a "cavity" at the base of the bore. As the cavities implode, mechanical energy and heat are released into the fluid. When the negative pressure can overcome the centrifugal force on the fluid, the flow is reversed, fresh fluid is drawn into the bore, and the process repeated. In theory, each of these cavitation events functions as a microreactor, capable of subjecting the processed fluid to elevated pressure and temperature while operating in ambient conditions.

The chemical effect of cavitation can be felt in three distinct steps:

1. Extreme conditions of temperature and pressure exist in the interior of the cavity. The contents of the cavity suffer breakages of chemical bonds to generate free radicals.
2. The extreme temperature at the cavity/liquid interface induces chemical reaction.
3. The generated free radicals are released into the bulk fluid and are free to undergo further reactions.[11]

The physical impact of cavitation is particularly beneficial in multi-phase heterogeneous systems. The collapsing cavity results in the formation of a microjet at the interface (Figure 2), a turbulent interface, and generation of shock waves. In a liquid/liquid system such as the oil and brine in an SBM, the microjet breaks down droplets. The resultant, finer droplets (Figure 3) form in relatively stable emulsion and have a larger overall interfacial area for reaction with emulsifiers and stabilizers.

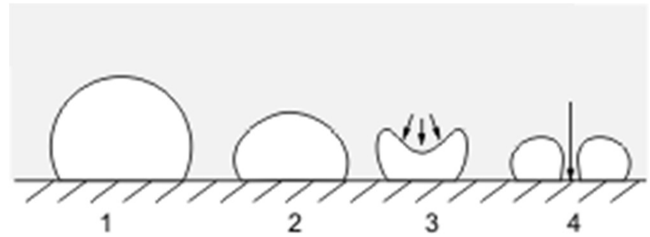


**Figure 2 – Formation of microjet.**

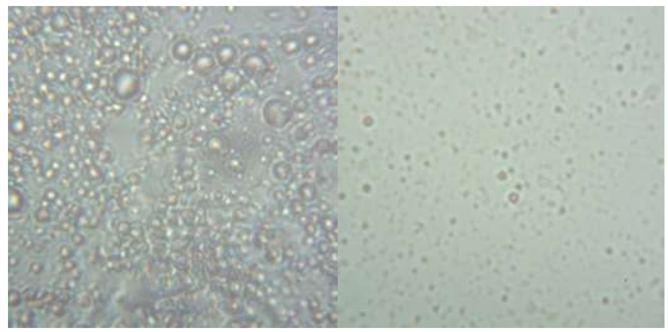

**Figure 3 –Standard mixing (left) and HSCC mixing (right) of a 70/30 oil/water emulsion at 1000X magnification.**

Smaller droplet size benefits the stability of emulsions made from immiscible fluids, as is the case with invert-emulsion "muds", with respect to kinetic stability and relative solubility. Oilfield emulsions are considered macro-emulsions, which are thermodynamically unstable and will separate as a function of time. The relative stability of macro-emulsions is governed by kinetic stability. The settling rate of a dispersed droplet, the primary kinetic parameter, is a function of the density difference between the internal and continuous phase, the gravitational force, the dynamic viscosity of the continuous phase and the droplet size.[12] In drilling fluid processing, the only variable that can change is the droplet size. Larger droplets travel faster through the continuous phase, or conversely, finer droplets move slower, allowing the emulsion to remain relatively stable for a longer period of time. Ostwald ripening results from the limited mutual solubility of the liquid phases. Over time, small droplets diffuse into the continuous phase and become deposited on larger droplets, increasing the mean droplet size. During initial emulsification of the liquid phases, smaller droplets have greater solubility than larger ones, hence the crucial importance of generating the smallest droplet size possible during processing.[6]

In a solid/liquid system, the high-velocity microjet disturbs the boundary layer at the solid surface. Breaking down the thin-layer liquid film facilitates mass transfer, which is the likely explanation for the observed improved hydration of clays and polymers.

In addition to contributing relatively high physical mixing energy, cavitation also generates heat. Heat generation is the primary differentiator between mixing with hydrodynamic cavitation compared to other forms of low-pressure high-shear mixing. During drilling fluid processing, the HSCC mixture has generated temperature increases of 20-25°F, above the incoming fluid temperature. Studies have shown that when a water and oil emulsion is heated during mixing, the resultant droplets decrease in size with increasing temperature, up to the phase inversion temperature (PIT) of the fluid,[6,13] During the trials presented in this paper, the HSCC mixer was operated with the objective of meeting the target processing rate. Reducing the processing rate through the device increases the temperature change achieved. Further investigation needs to be performed on the impact of different temperature increases on the resultant fluid properties.

## High-Shear Mixing Equipment Validation

After initial selection of the HSCC mixer, further performance trials were performed at an LMP servicing the Gulf of Mexico. All trials were performed with the fluid system prepared with LMP standard mixing procedures. Mud checks were performed to compare resultant fluid properties when processed with standard equipment versus the HSCC mixer.

The HSCC was connected in a side stream off the recirculation loop of the mixing pit. The whole fluid system was pumped through the HSCC in a single pass and discharged into an empty pit. The test setup was specifically designed to allow a side-by-side comparison of the fluid properties between standard mixing equipment and the HSCC device.

### *Liquid Mud Plant Trial*

A trial was performed with a recycled 9.0-lb/gal SBM (further referred to as Fluid 1). A 200-bbl batch of Fluid 1 was agitated in the mixing pit using standard LMP equipment. Without chemical treatment, the fluid was processed through the HSCC and the properties compared. Following mixing in a standard mud pit and shear through the HSCC, rheology, electrical stability (ES), and fluid loss readings were obtained in accordance with API 13B-2 test procedures at 120°F (Table ***1***).

**Table 1 – Comparison of Fluid 1 Properties with LMP Agitation and HSCC Shear**

| | LMP Agitation | HSCC Shear |
|---|---|---|
| Vol Mixed, bbl | 200 | |
| Density, lb/gal | 9.0 | |
| Temp, °F | 120 | |
| 600-rpm Reading | 60 | 92 |
| 300-rpm Reading | 36 | 60 |
| 200-rpm Reading | 27 | 48 |
| 100-rpm Reading | 16 | 33 |
| 6-rpm Reading | 3 | 16 |
| 3-rpm Reading | 2 | 15 |
| Plastic Viscosity, cP | 24 | 32 |
| Yield Point, lb/100 ft$^2$ | 12 | 28 |
| 10-sec gel, lb/100 ft$^2$ | 5 | 23 |
| 10-min gel, lb/100 ft$^2$ | 9 | 25 |
| Electrical Stability, v | 65 | 220 |
| API Fluid Loss, mL | 4.6 | 1.8 |

Electrical stability (ES) is an indicator of the relative stability of an invert emulsion. The better the dispersion of the electroconductive internal brine phase in the nonconductive external oil phase and solid load, the higher the ES readings. It is a best practice to monitor and maintain relatively high ES throughout the operating lifecycle of an SBM. Trends in ES are also consistent in most cases with other field indicators of emulsion stability. Anomalies in ES trends are explained in terms of a physicochemical model for electrical breakdown of the emulsion.[14] Therefore, the ES property was selected as a measure to evaluate the performance (i.e., emulsion stability) of the HSCC on SBM preparation.

The comparison results of Fluid 1 show that high-shear mixing has marked impact on emulsion stability, low-shear rheology, and fluid loss values. The electrical stability (ES) of Fluid 1, increased from 65 to 220 with the HSCC mixer. It would be appropriate to conclude that the increase in ES was a result of emulsion droplet size reduction as result of high shear.

Low-shear-rate rheology increases, characterized by the 6- and 3-rpm readings, were also observed after shearing. These increases are an indicator that the fluid is more resilient against dynamic barite sag. The static rheology, characterized by the yield point and gel strengths, was also improved. Finally, high-temperature, high-pressure (HTHP) fluid loss was performed on the samples from the different mixing regimes. Fluid loss is a relative measure of the filtration rate of liquid that can invade a permeable formation through deposited mud solids. Controlling fluid loss is desirable for minimizing filter cake thickness, which can cause drilling problems such as differentially stuck pipe. The results conclusively demonstrated the improved mud performance realized from the additional mixing energy provided by high-shear mixing.

### *Field Trial*

A trial was performed with an invert emulsion fluid prepared for operation in the Gulf of Mexico. For this test, the liquid mud plant processed 1,200 bbl of fresh 14.2-lb/gal mud (further referred to as Fluid 2). When the fluid properties were tested after standard LMP preparation, there were concerns about the electrical stability and low-shear-rate rheology values. Moreover, the mud was not intended to pass through a bit at the rig. In order to verify the potential fluid properties were obtainable, a fluid sample was sheared with a Hamilton Beach blender for 30 minutes in the laboratory. The resultant fluid properties were acceptable, so the decision was made to shear the fluid with the HSCC mixer.

The improvement in ES was consistent with the previous trial. A 60% increase in Fluid 2 ES reading was observed (Figure 4). In fresh mud, as is the case with Fluid 2, the benefit of high-shear is in the production of a more stable emulsion than can be achieved by standard mixing equipment. Further validating the basic assumption that standard mixing equipment at the LMP cannot achieve sufficient high-energy shear to bring the mud to the full potential emulsion as design.

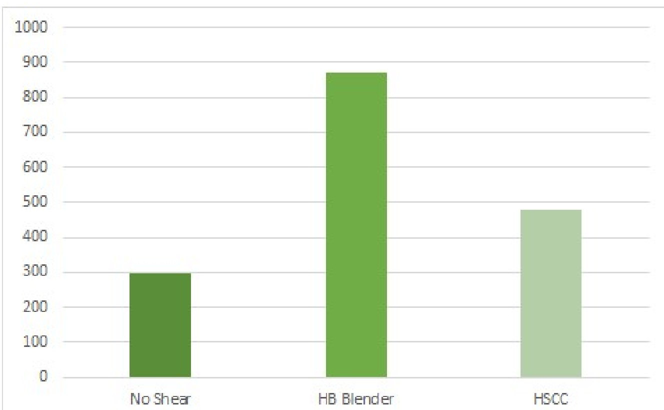


**Figure 4 – Fluid 2 electrical stability, in volts, compared under three different mixing regimes.**

The greatest impact of high-shear for SBM preparation was observed in the low-shear-rate rheology measurements (Figure 5**Error! Reference source not found.**). The HSCC mixer is capable of achieving the mixing energy imparted by the Hamilton Beach blender. One of the critical concerns with Fluid 2 was the possibility of barite sag due to insufficient low-shear-rate rheology. From a logistical perspective, barite sag causes issues with handling, transportation, and storage. If barite sag is not mitigated during mud preparation, it can lead to excessive cleanout costs with transport vessels and require additional treatment on the rig.

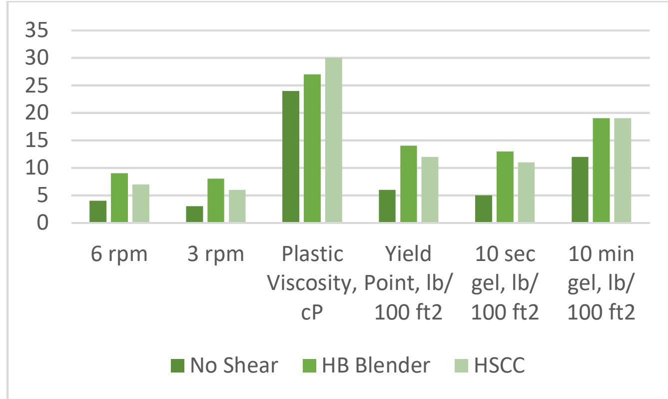


**Figure 5 – Fluid 2 low-shear-rate rheology results comparing the three mixing regimes.**

The longer term impact of high-shear mixing on emulsion stability was evaluated by comparing the fluid properties immediately after LMP processing with those measured after the mud was delivered to the rigsite. The ES decreased from 479 to 396 V over a period of 5 days, indicating some reduction in fluid stability (Figure 6). However, after 5 days of storage and transport, the fluid still maintained a higher ES compared to the 299 V result achieved with standard LMP processing. The low-shear-rate rheology measurements increased over time (Figure 7). It would be appropriate to conclude that due to high-shear processing, Fluid 2 did not require additional treatment to achieve the designed fluid properties. Further analysis is required to assess the potential operational efficiency and cost saving that can be gained from improving the fluid quality during LMP processing.

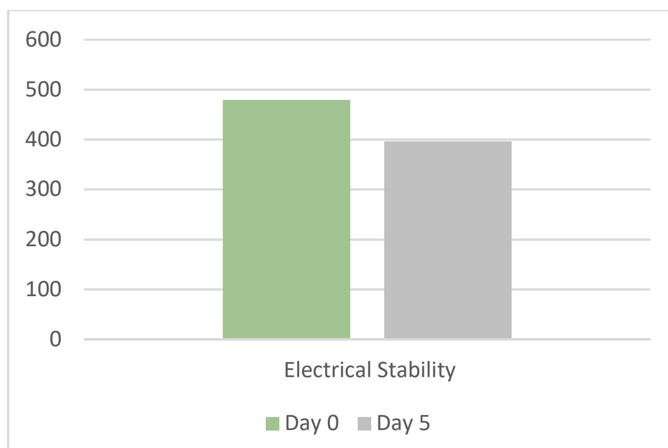


**Figure 6 – Fluid 2 electrical stability, in volts, compared over time.**

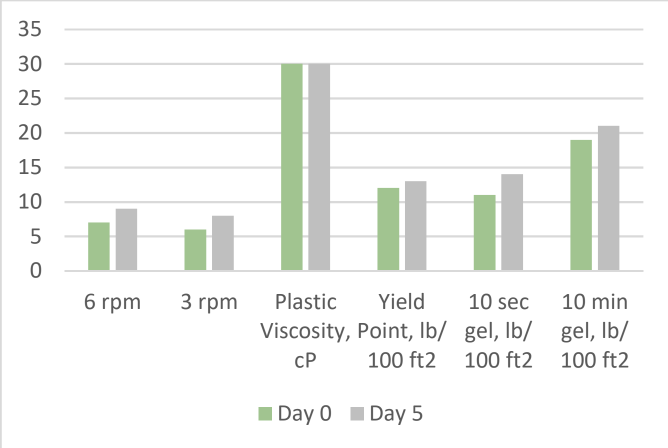


**Figure 7 – Fluid 2 low-shear-rate rheology results compared over time.**

## Conclusions

High-shear mixing with controlled cavitation presents a low-risk, viable solution for improving drilling fluid preparation. The trials and field validation data presented indicate significant benefits to quality control of the fluid during drilling. Some of the key considerations that were validated are summarized as follows:

- High-shear mixing dramatically improves emulsion stability. Better fluid stability is known to mitigate barite sag during transport and reduce additional treatment required at the wellsite.
- The equipment can be used regularly when fluid systems prepared in the mud pit do not meet the designed specifications.
- The equipment package has proven to be effective as well as simple to operate and maintain.

### *Recommendations and Future Investigation*

Future trials would explore and validate the optimization of high-shear mixing and exploit the intrinsic heat generation of controlled cavitation in fluid processing in accordance with the aforementioned operating principals:

- Assess the economic impact that high-shear mixing could have on operating parameters such as efficiency gains and cost savings due to improved quality control during fluid processing. Areas of focus include: reducing cost to the operator via the minimization of drilling fluid maintenance and improvement in fluid storage and handling.
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- Improve functionality through optimization of the fluid preparation procedure by assessing the impact of high-shear mixing at various stages of chemical addition. Depending on the fluid design, certain chemicals will benefit more than others with the addition of shear. Optimizing the addition and processing procedure can minimize chemical treatment and possibly save time.
- Quantify the impact of various heating regimes on fluid properties during processing.

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## Nomenclature

*ECD* = *Equivalent Circulating Density*
*ES* = *Electrical Stability*
*LMP* = *Liquid Mud Plant*
*HSCC* = *High-Shear Controlled Cavitation*
*HTHP* = *High-Temperature, High-Pressure*
*PIT* = *Phase Inversion Temperature*
*SBM* = *Synthetic-Based Mud*

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