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AADE 2009-NTCE-08-02: ADVANCES IN MIXING TECHNOLOGY IMPROVE DRILLING FLUID PREPARATION AND PROPERTIES

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Abstract

Industry has long recognized the importance of providing high-quality fluids for drilling, completion and production operations. With continuous developments of oilfield chemistry, these fluids have become increasingly complex and many of the chemical additives are hard to disperse or emulsify in solution. Traditional mixing techniques, such as circulating the fluid through jet nozzles or impellers, are becoming less satisfactory in achieving the desired properties for polymer-based drilling fluids. The mixing techniques used today are required to better disperse the chemical additives, but be gentle enough to preserve their long polymer chains and chemical structure. The mixing process and apparatus needs to be easily utilized at both onshore fluid mixing plants and at the rig-site. Both process and equipment must be economical, safe and environmentally responsible.

Multifarious chemical processes and mechanical engineering evaluations have allowed the effects of high-shear mixing on water-, oil- and synthetic-based drilling fluid systems to be determined. In addition, laboratory studies have evaluated potential shear degradation of polyacrylic and xanthan polymer systems using several high-shear mixer designs. Through these studies, based on their superior technical performance and cost effectiveness, a multi-stage rotor-stator high-shear mixer was selected as the most appropriate mixing apparatus to prepare drilling fluids. Full-scale testing proved these mixers to be effective and economically acceptable new solutions to drilling fluid preparation by alleviating problems of partially-dispersed or partially-hydrated chemicals or poor emulsification. Because of low operating pressures, these units are considered safer than a high-pressure jet nozzle. The fluids prepared exhibited the required rheological properties through better chemical dispersion and produced stronger emulsions through the application of high shear, while remaining stable over longer periods.

Performance data using single-stage and multi-stage mixers in the preparation of drilling fluids is discussed. Polymer degradation by high shear is confirmed and the data shows that using the proposed mixing devices provides sufficient energy for efficient mixing without polymer degradation. The use of multi-stage rotor-stator high-shear mixers is confirmed as a very powerful and beneficial tool to improve drilling fluid preparation.

Introduction

Today's technological advancements have enabled the industry to drill faster, deeper and safer. The cornerstone of drilling fluid technology is providing cost-effective solutions to the most technically complex drilling and completion applications. The processing technology is developing head-to-head with advances in drilling fluids chemistry. Both of these fields are expected to grow in tandem as the industry is forced to meet new drilling and completion challenges, both onshore and in deepwater offshore.

Be they water, oil or synthetic-based drilling fluids perform a host of critical roles, and many systems are engineered for specific applications and well conditions. Regardless of the type, drilling fluids, or "mud", must be prepared following a specific sequential process. Every step of this process is designed in that chemicals are to be added in the correct order and all chemical additions are performed in a timely manner. The process is controlled by testing the fluid following industry-accepted testing procedures.[2,3] Fluids are built to meet or exceed the specifications and requirements of the individual operator. They may be mixed on the rig, or prepared in a liquid mud plant and delivered to the rig ready to go into the hole. Most mud tanks and pits are equipped with jet nozzles and/or agitators for mixing. Chemicals are added through hoppers that often supply additional mixing capabilities. Furthermore, drilling fluids are subjected to additional blending during pumping and other handling activities.

Land rigs that drill with a simple mix of clay and water are quickly becoming history in favor of more efficient advanced fluid chemical compositions with improved chemical and physical properties and optimized performance.[1] The input of mechanical work, such as: shearing, agitation, and heat, helps the chemistry to perform as designed. These chemical advances required advanced mixing processes and machinery to facilitate innovative technologies for drilling fluid mixing.

Considerations for Drilling Fluid Mixing

Several methods of shearing fluids currently exist.[4] A nozzle and low-pressure pump operated at 50 to 80 psi can achieve shear rates on the order of 3,000 to 5,000 s^{-1}. A nozzle and high-pressure pump, capable of delivering 700 – 800 psi can achieve shear rates of from 30,000 to 50,000 s^{-1}. It is recognized that the highest level of shear is achieved when fluid is passing thought the bit while drilling, where a small orifice, high temperature and high pressure all contribute to create a combined effect. In terms of shear rates, shear through a drill bit nozzle and high-pressure triplex pump can achieve rates 30,000-80,000 s^{-1}. Rotor–stator mixers provide the capability to meet or exceed the highest shear rate levels provided by the drill bit nozzle and triplex pump combination. The lowest shear rates produced by high shear mixers are 10,000 s^{-1}, and the highest are 100,000 s^{-1}.

The process of building a drilling fluid involves creating a high quality emulsion and uniformly incorporating all ingredients in this emulsion at the same time. One of the goals is to create relatively stable emulsions capable of performing the required tasks and withstand further handling. Depending on the complexity of the formulation, basic fluids can be viewed as simple two-phase emulsions. However, most drilling fluids are far more complex multi-phase emulsions that may contain clays and solids such as weighting agents or lost circulation materials. Theoretically, a distinction can be made between the relative influences on stability by the rheology of the continuous phase of an emulsion and by the energy barrier between droplets and an emulsion half-life increase.[4,6,8] It has been suggested that increased viscosity would contribute to emulsion stabilization; however, such viscosity must be increased significantly, to the levels found in waxes or molten sulfur.[8] Therefore, the usefulness of assessing viscosity parameters for indications of emulsion stability is a complex issue.

Some drilling fluid additives may contribute to emulsion stability, which also is supported by smaller droplet sizes in the emulsion. Better conditions for additives to reach their full design potential are created by breaking agglomerated particles and dispersing additives on the micro level. Shearing on a rotor-stator device significantly increases the dispersed phase fraction and dampens coalescence. Solid or liquid particles stabilize emulsions when they are involved at the interface. It is important to keep in mind that drilling fluids are designed and formulated to create optimum performance downhole; the target in mixing is to assist a fluid to reach the best possible conditions by applying mechanical tools such as mixers.

High Shear Mixer

A careful evaluation of current mixing processes was undertaken to develop a mechanical solution for the preparation of drilling fluids that would improve the required properties. Reviewing existing practices to find undeveloped potentials with jets, agitators, and some impeller-based mixing devices proved pointless. None of these techniques were deemed sufficient to impart enough energy and meet the solution criteria, which primarily focus on safe, easy, efficient and economic operation. An adequate solution was found outside the oilfield with equipment used in the food and drug processing industries. The rotor-stator high-shear mixer was identified as being capable of providing shear sufficient to enhance fluid properties. These continuous inline high-shear mixers employ a rotor-stator assembly with a precise gap between the rotor and the stator. A number of different designs are available consisting of single, dual or multiple-stage rotors that turn at high speed within a stationary stator. Some units are designed so the high-speed rotation of the rotor creates suction, thus drawing liquids and solids into the rotor-stator assembly. Other units may need to be fed continuously from a secondary pump.

Fundamentally, the mechanism of shearing is different from any other mixing devices.[9] Rotor stator high-shear mixers provide rapid micro-mixing and emulsification. The motion of the rotor creates a centrifugal force on the fluid that pushes it toward the inner wall of the stator. At the interface wall, the fluid is sheared between the rotor and the stator. Furthermore, the fluid is subjected to an additional hydraulic shear as it is forced, at high velocities, through the narrow perforations machined in the stator.

Continuous inline multi-stage high-shear mixers offer a more efficient solution than a similar single-stage apparatus. Mixing fluid using one-pass through a three-stage high shear mixer has produced results comparable to between three and seven passes through a single- stage high shear mixing unit at the same or similar flow rate.

Impact on the Drilling Fluid

Water-Based Drilling Fluid

Water-based drilling fluids (WBM) are sheared to disperse clays, polymers and other additives that cannot be fully dispersed during standard fluid preparation. Adequately dispersed ingredients result in a fluid with optimum properties. In a sheared fluid, all ingredients yield fully and the fluid properties, including viscosity, are corrected per the design requirements; in addition to imparting the optimal drilling properties, the fluid must capable of being pumped, stored, and subjected to handling and transportation. In the case of un-weighted fluid with no clay content, fluid viscosity is changed insignificantly after this type of shearing (Table 1). If clay is added, rheology numbers would be increased. The key reason for shearing WBM is to disperse and hydrate clays.

Once formed, "fish eyes", or lumps of undissolved polymer or other chemicals, generally are difficult to disperse with standard jets, agitators and low-pressure pumps. However, fish eyes in water-based fluids can be reduced significantly or eliminated altogether after shearing on multi-stage high-shear mixers (Fig. 1 and Fig. 2). During the initial addition of viscosifiers, the increased viscosity decreases the mixing efficiency, thereby creating ideal conditions for the formation of fish eyes. The use of shakers and other rig solids control equipment to eliminate or remove fish eyes from the fluid is both undesirable and costly. If fish eyes remain in the fluid, additional chemicals may be required to compensate for the loss of ingredients. However, pumping and handling, increased temperature, or other influences downstream will help break the clumps of chemicals initially lost in fish eyes. These chemicals become dispersed in the fluid, causing a sudden and undesirable viscosity increase, and negatively impacting not only the drilling fluid, but the entire drilling operation. Other complications from fish eyes can be significant, such as causing filtration issues and affects on the filter cake.

Polymers

A major concern with shearing polymers, either man-made partially hydrolyzed polyacrylamide (PHPA) polymers or more complex biopolymers, is they are likely to be shear sensitive.[5] The mechanical degradation of polymer solutions occurs when fluid stresses developed during deformation, or flow, become large enough to break the polymer molecular chains. High shear mixers are capable of introducing the higher level of shearing that could accelerate shear degradation.

Prior to testing, it had not been established if high-shear mixers were able to generate sufficient shear stress to promote polymer degradation. Theoretically, PHPA polymer and biopolymers are both expected to be degraded to different extents if affected by excessive shear.[5] However, the three-dimensional molecular structure and molecular weight distribution of the biopolymer in the presence of salts may form a polymer structure that allows shearing the polymer without little or any shear degradation. The polymer degradation was not observed either during field mixing trials or in the laboratory, except when the test was designed for this level of shearing.

Several series of tests were conducted during these laboratory trials. The first set of tests were carried out on an open-loop, pump-fed shearing device. It was designed to study how geometry of the stator would affect water-based fluid rheological properties during the shearing process. Moreover, it was used to determine how the number of passes through a shearing unit with the same stator geometry affects rheological properties. For the next set of tests a pump was added to form a closed-loop system that allowed a significant increase in the flow rate. This test was used to determine the possibility of partial or complete shear degradation as well as shear stability. The final tests were performed to evaluate the viscosity gain or loss for water-based polymer drilling fluids in a high-shear mixing device.

All tested drilling fluids, WBM, OBM and SBM, were highly engineered and established systems with well developed correlation between rheological data and product data. Thus, the rheological data could be used to predict performance and behavior. It was decided to base the judgment of the fluid properties on numbers produced by a viscometer that was typical and commonly accepted in the industry. Tests were designed to comply with API 13 Standards and ANSI/API/ISO Recommended Practices for testing water-based drilling fluids.[2,3] Rheological properties of the polymer solutions were determined on a viscometer at each available speed, 600 through 3 rpm at constant preset temperature . Every mud sample was checked for fish eyes on an 80-mesh screen before and after shearing.

It was shown that continuous shearing degraded the fluid. However, the amount of shear in terms of time and energy input required for degrading the fluid was approximately 30 times higher than is practical for the normal oilfield applications. After the expected optimum rheology numbers for the particular fluid were achieved, the fluid started losing the "viscosity hump" followed by a relatively stable rheology phase (Fig. 3 and 4).

Laboratory studies were conducted prior to scale up and validated that shearing on rotor-stator mixing devices is beneficial for drilling fluid preparation as the properties improved and achieved model design characteristics faster. Different designs of larger rotor-stator mixers were tried during scale-up studies that confirmed the overall positive effects of shearing on rotor-stator devices. Scale-up studies found superior devices that were later used during full-scale studies.

Oil-Based and Synthetic-Based Drilling

Fluids Shearing is considered more important for oil-based and synthetic-based drilling fluids (OBM and SBM, respectively) as it creates smaller droplets of an emulsion in addition to dispersing clays and generating viscosity. The stability of the drilling fluid is often related to strength of the emulsion which is measured by electrical stability (ES). Experience in the North Sea determined the minimum acceptable ES for a sheared oil-based fluid is 500 volts; however, other regions have used 300 volts as the minimum acceptable value. This level indicates the fluid is sufficiently sheared and water dispersed effectively throughout the fluid with sufficient viscosifier to support the barite and cuttings in the fluid.

API-standardized high-temperature, high-pressure (HTHP) filtration testing results show that fluid-loss numbers, depending on type of fluid, may increase or decrease for fluid sheared on a shearing device. Excessively low or high fluid-loss numbers may be detrimental for some of the fluids; therefore, a shearing process needs to be designed for a type of fluid and controlled to achieve optimum results.

Equipment Selection and Package

The mixing apparatus was selected from available on the market equipment. The objectives of improving drilling mud preparation were focused on the most challenging of mixing fluids that are used extensively in the field today and anticipation of potential challenges of tomorrow's products were also taken into account. The choice is governed by the technical performance of an apparatus, when tested with drilling fluids, and the economic impacts. From the rotor-stator mixers, two high-shear mixers (one multi-stage and one single-stage) were found to outperform other models in preliminary testing. Both high-shear mixers were subjected to extended trials and both improved the fluid properties in liquid mud plants and on the rig site. The multi-stage high-shear mixer was shown to have the most efficient performance throughout all of the performed trials.

The philosophy behind a package design is based on the intention that equipment should be easy to maintain, easy to operate, have low labor requirements and be well adapted to transportation. Each unit (Fig. 5) should be compact enough to fit on a medium-sized pick-up truck or moved with a forklift. The control panel is important to create an operator friendly and safe means of controlling the unit. If it is possible to provide electrical supply from a rig or liquid mud plant grid, a quick connect type of electrical connection will be used. In case an independent electrical supply is required, a generator can be utilized easily. To connect to mud lines, the unit uses two inlet and outlet piping connections. A strainer is used for capturing and removing any oversized objects from the mud stream and installed at the entrance of the shearing unit to protect both it and all downstream equipment. A flow meter positioned after the strainer allows some level of flow control. Local mud pumps, typically centrifugal pumps, piped into the mixing tanks, supply fluid to the unit.

Results of mixing and shearing are fluid dependant and it was found that one pass through an in-line multi-stage rotor-stator device provided sufficient shear to meet objectives in terms of improved fluid properties. Multiple passes through a single stage rotor-stator device, on the other hand, are needed to achieve similar results. On average, the time consumption for shearing is shown to be equal to the time consumption for using a standard mud pump at a liquid mud plan to pump the same amount of fluid. The unit is enable to supply maximum flow rate with a drilling fluid approximately 500 gal/min depending on fluid properties. The fluid properties should be measured and monitored to determine when optimum conditions/properties are achieved. The multi-stage mixer used in the packaged unit is a powerful machine selected to match with drilling fluid chemistry and provide a cost efficient result with the minimum number of fluid passes through the machine.

Performance Examples

WBM

In the Gulf of Mexico, the shore-based liquid mud plant prepared 6,500 bbl of two different types of 10.2-lb/gal (1.2-SG) water-based polymer drilling fluids. Samples of those fluids were analyzed in the laboratory using newly developed testing techniques to provide quality assurance for end results and determine how much shearing would be needed.

The equipment was rigged up quickly on location. Two high-shear mixing units were used for this operation, one single-stage high-shear mixer, and one multi-stage high-shear mixer. Before the shearing equipment was installed, the plant had built approximately 3, 000 barrels of biopolymer water–based drilling fluid that was put in storage waiting to be sheared. The stored fluid was pumped through the shearing units for a single pass and back to storage easily. The shear mixer hose configuration allowed the use of both the shearing units in parallel operation to maximum throughput.

For the next batch, 1,000 barrels of PHPA water-based fluids were prepared and sheared. Time required to process a single 500-bbl tank was approximately 20 to 30 min. Building this fluid went smoothly as the plant personnel mixed the required formulations and passed the fluid through the shearing units back to storage. The remaining 2,500 bbl were built and processed through the shearing units in a similar manner. The flow rates to the shearing units were stable throughout the process.

All fluid was processed to an acceptable level after only one pass through the shearing devices and the shearing operation added no more than 30 min to the processing time. The fluid after shearing was described as more homogeneous, with a visual increase of its plasticity and elasticity. The color change was noticeable for an un-weighted fluid that changed from "grayish" with some noticeable phases to a "milky off-white" homogeneous fluid. The quantity of fish eyes were checked in the mud plant laboratory. It was found that before shearing a large amount of fish eyes were present. And after shearing the fish eyes were minimized or non-existent. Fluid sheared with the single stage high-shear mixer contained some fish eyes in 350 mL samples (Figure 1); fluid sheared with the multi-stage high-shear mixer contained no fish eyes in 350 mL samples (Figure 2).

A better result is achieved when the mud is built and sheared immediately before storage. This preferred processing order will reduce the number of fish eyes as compared to drilling fluid that is stored before shearing. In field operations, it is desirable to achieve optimum fluid properties as fast as possible, preferably in one pass through the shearing device. Single-stage high-shear mixers improved the quality of the fluid in one pass; however the fluid needed to be re-processed on the same machine to achieve optimum yield. Multi-stage high-shear mixers exhibited the best performance delivering a fluid that achieved optimum yield in only one pass.

Because the fluid was built to standards in accordance with liquid mud plant procedures, fluid rheology did not change significantly after shearing. It was found that the mud achieved theoretically optimum rheological properties after shearing without requiring circulation through the drillstring and bit as normally experienced in the field.

The fluid continued to maintain desired properties during transportation, storage and use in the field. The final fluid was pumped to a supply vessel to be delivered to the offshore platform, but owing to rig issues, the mud was not used for a month and subsequently was returned to the plant for storage. After a month, with no further fluid processing necessary, the fluid was returned to the rig for consumption. Mud plant personnel characterized the condition of the fluid as very good and compliant with all specifications for re-use.

OBM and SBM

During trials with oil-based fluids in the Norwegian Sea sector, both single-stage and multi-stage high-shear mixing units were used and the data compared. The plant had a need to process 2,200 bbl of a recycled 11.6-lb/gal (1.4-SG) OBM. This fluid was further weighted up to 13.3 lb/gal (1.6 SG) and sheared on high-shear devices to increase the ability of the fluid to suspend barite. At this time, it was noted the single-stage mixer required approximately seven passes of the fluid to achieve results similar to the multi-stage unit. After the shearing device, the fluid was transported by supply vessel to the rig and consumed.

The multi-stage high-shear mixer also was used to build 200 bbl of un-weighted synthetic-based fluid pre-mix. This fluid possessed all the synthetic oil and chemicals required to support barite in solution, but there was no barite in the premix. Once the fluid was mixed it was passed through a shearing unit and the ES measured. The multi-stage high-shear unit raised the ES rate more than four times faster than a comparable single-stage device.

Conclusions
This paper presented an innovative solution for drilling fluid preparation that delivers drilling fluids with improved rheological properties.

These trials indicate that shearing either water or oil-based drilling fluids with a high-shear mixing device is definitely beneficial and using the multi-stage device provides faster shearing.

The multi-stage high-shear mixing device can achieve excellent fluid rheology with one pass through the unit, whereas a single-stage shear mixer requires four to seven more passes to achieve similar results.

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Nomenclature

API = American Petroleum Institute
Bbl = Barrels
lb/bbl = Pound per Barrel
OBM = Oil-Based Mud
PHPA = Partially Hydrolyzed Polyacrylamide
lb/gal = Pound per Gallon
SBM = Synthetic-Based Mud
WBM = Water-Based Mud
SG = Specific Gravity

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Table 1 – Rheology Data for Freshly Prepared WBM Sheared One Pass From The Mixing Tanks on a Liquid Mud Plant

	Base	Single-stage Unit	Multi-stage Unit	Base	Single-stage Unit	Multi-stage Unit	Base	Single-stage Unit	Multi-stage Unit
Vol Mixed, bbl	500			500			500		
Wt, lb/gal	9.6			9.6			9.7		
Alkalinity, pH	3.8			4.0			3.8		
API FL, mL	6.6	4.6	6.8	6.0	4.0	6.0	6.0	4.4	6.4
Chlorides, ppm	107K			108K			110K		
Temp °F	120	120	120	120	120	120	120	120	120
600-rpm dial reading	55	57	57	55	57	57	55	57	58
300-rpm dial reading	37	41	42	37	41	42	40	41	42
200-rpm dial reading	31	34	33	31	34	33	33	34	33
100-rpm dial reading	23	25	21	23	25	21	25	22	21
6-rpm dial reading	11	11	11	11	11	11	12	11	11
3-rpm dial reading	10	10	10	10	10	10	11	10	10
Plastic Viscosity, cP	18	16	15	18	16	15	15	16	16
Yield Point, lb/100 ft^2	19	25	27	19	25	27	25	25	26
10-sec gel strength, lb/100 ft^2	9	10	12	9	10	12	8	10	12
10-min gel strength, lb/100 ft^2	12	16	18	12	16	18	13	16	18

Figure 1. Some fish eyes on the 80-mesh screen after shearing by the single-stage unit.

Figure 2. Shows no fish eyes on the 80-mesh screen after shearing by the multi-stage unit.

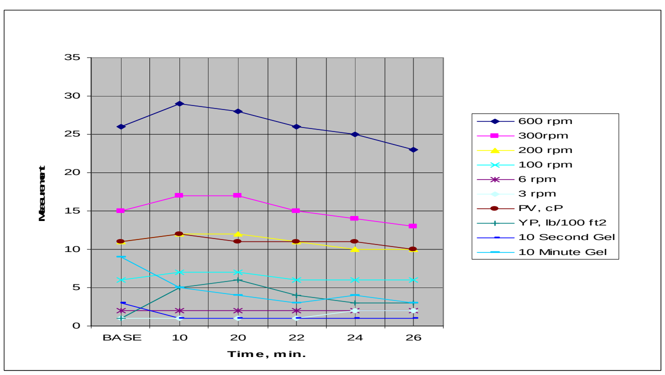

Figure 3. Rheology of extensively heat-aged, unweighted PHPA WBM while shearing.

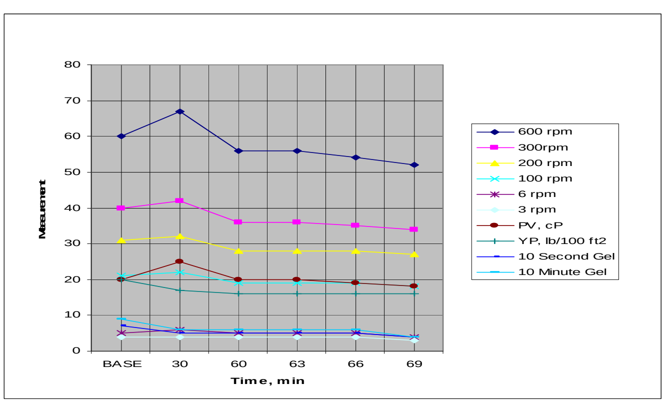

Figure 4. Rheology of extensively heat-aged, unweighted biopolymer WBM while shearing.

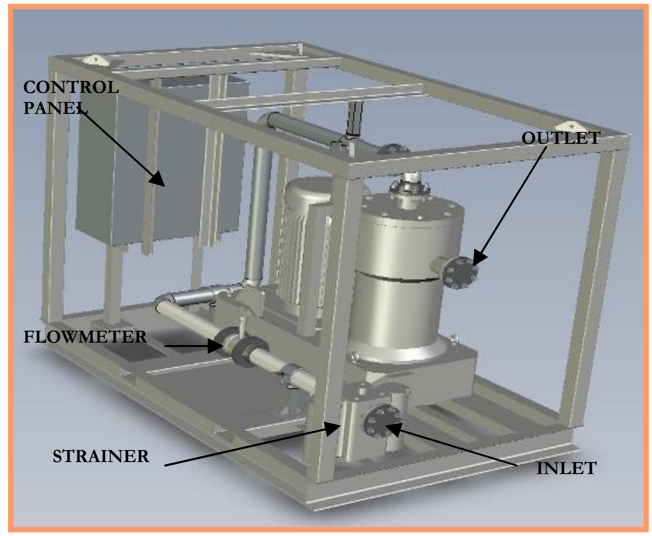

Figure 5: Shearing unit containing multi-stage rotor-stator high-shear mixer.