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Future Challenges of Drilling Fluids and Their Rheological Measurements

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Abstract

The ever-increasing global demand for energy, coupled with declining production from some key areas of the world, is expected to uphold the growing interest to discover unconventional plays that have the potential of driving oilfield operations into new technology frontiers. These could arise from changes in the operational depth, length of horizontal departure in extended reach wells, complexity of drilling operations, and the strict environmental regulations enacted by different governing bodies. Nevertheless, in order to meet the challenges of the future, the oil and gas industry is going to need more than just discovering untapped reserves in every corner of the earth. It is going to need a means to develop these unconventional plays and other hydrocarbon resources, which are not recoverable with current technologies. Achieving these objectives can only be facilitated through the development and application of novel technologies. Adequate understanding of the impact of drilling fluid rheology, so as to selectively design fluids that could address the wide range of difficulties encountered in oilfield drilling operations, is one key portfolio that has garnered considerable attention, and the inherent concern on how they could be substantially modified for success becomes very critical to justifying project economics.

This paper presents a critical review of fluid systems and technologies that the authors believe have come to stay, due to their profound effect on the industry. Next, the authors present a comprehensive review of the significant challenges of the future to which the industry must respond. Finally, the authors discuss their vision on the future of rheology and its applications to the exploration and production sector, namely, smart fluids, fluid blends, nano-rheology, viscoelasticity measurements and applications. Though, most of these are still undergoing developments, while some are just dreams, noteworthy steps that have been taken to achieve them will be discussed in detail.

Introduction

As the demand for oil and gas increases, so does the need for more economic ways to tap these resources. Drilling process comprises of eighty percent of the total well cost. Drilling has evolved from vertical, inclined, horizontal to sub-sea and deep-sea drilling. These specialized drilling processes require specialized drilling fluids to fulfill the objectives. Since reservoir type and the drilling process adopted to harness the reservoir fluid is unique, the drilling fluid has to be customized to suit the drilling process and reservoir conditions.

Conventional drilling fluid systems

A drilling mud is a complex fluid which comprises of multitude of additives. The type and amount of additives is based on the drilling method employed and the type of reservoir to be drilled. The drilling mud can be broadly classified as water based mud (WBM), oil based mud (OBM), synthetic based mud (SBM), emulsions, invert emulsions, air, foam fluids, etc.

Water based muds (WBM)

These consist of water/brine as the base fluid. As they are environment friendly, the drill cuttings can be disposed of easily. A conventional WBM uses a polymer as a viscosifying agent. The polymers used can be linear polymers, crosslinked polymers, synthetic polymers, or bio-polymers. A viscoelastic surfactant (VES) drilling mud is a WBM which uses a surfactant having both viscous and elastic characteristics and thus can reheal itself and restore the rheological properties. Although the VES based drilling mud is expensive compared to conventional WBM, the former does not require frequent mud conditioning and thus saves a significant amount of rig time.

Further advancements/research in WBM would be to combine the advantages of both the VES and bio-polymers to obtain a suitable blend which can outweigh the disadvantages of both VES and bio-polymers [Ogugbue et al, 2010].

Oil based muds (OBM)

They comprise of oil as the base fluid. The fluid formulation is complex compared to WBM and is expensive. Their advantages include excellent fluid loss control, no shale swelling, adequate lubrication to drill bits, good cutting carrying ability etc. Their disadvantages include poor bonding between the cement and formation due to oil wet surfaces; poor filter cake clean up and possible environmental hazards, like seepage into aquifers and causing pollution etc.

The recent advancement in OBM is using crude or refined palm oil instead of diesel to make it more environmentally friendly. This would make it compatible with most of the additives as it would have low aromatic content which is less toxic to marine and freshwater organisms.

Synthetic based muds (SBM)

They are similar to OBM in composition except that the base fluid comprises of a synthetic material instead of oil. The aromatic content is low compared to OBM and hence it is less toxic and more environmentally friendly. The first generation SBM was made using polypha-olefins, esters or ethers. It had a high kinematic viscosity which made it pumping cumbersome. The second generation SBM is an improvised version which is made up of linear alpha olefins, linear paraffins and isomerized olefins [Friedheim, 1997]. It has low kinematic viscosity and can be operated at a low pump pressure. They are more environmentally friendly than first generation SBM and cost-effective in production.

Emulsion drilling muds

It consists of water/brine as the external phase and oil as the internal phase. Synthetic hydrocarbons are now replacing oil as an internal phase. A surfactant is used to make the two phases miscible. These fluids are relatively expensive compared to WBM and cheaper than OBM. It includes all the advantages of WBM. It is environmental friendly and can be safely disposed of after undergoing the Environmental Protection Agency (EPA) tests.

Invert emulsion muds (IEM)

It consists of oil/synthetic hydrocarbon as the external phase and water/brine as the internal phase and the fluid stability is achieved by adding a surfactant. Their advantages include generation of a thin filter cake, increased hole stability, increased rate of penetration, insensitiveness towards shales etc. They are not biodegradable and drilling mud becomes unstable at high temperature and pressure.

The latest development in invert emulsion drilling mud is the negative alkalinity invert emulsion drilling mud [Patel, 1999]. It comprises of synthetic esters as external phase and water/brine as the internal phase. They have low intrinsic viscosity and rapid bio-degradability. They are resistant to contamination by sea water cement slurry and are highly stable under high temperature and pressure. They are made from readily available fatty acid esters and hence they are relatively inexpensive and environmentally friendly.

Air drilling fluids

Air drilling fluids are generally used in underbalanced drilling and where there is no contact with reservoir hydrocarbons or water. The advantages of air drilling process include high rate of penetration, no solid contamination, no formation damage, no lost circulation etc. This results in less number of trips in and out of the wellbore and makes the process economical.

Future challenges would include a thorough understanding of the physics involved in the wellbore hydraulics and to increase the safety factor for the successful execution of this process.

Foam fluids

Foam fluids are used in underbalanced and deepwater and ultra-deep water drilling where the operating pressure window is very narrow. A slight increase in mud density will cause micro/macro fractures and a slight decrease in mud density will cause fluid influx into the wellbore due to high pore pressure. Thus, a better control over the equivalent circulating density (ECD) is needed. Foam fluids generally comprise of 5-25% liquid phase and 75-95% gaseous phase. The liquid phase could be fresh water or brines. The gaseous phase is usually an inert gas. A surfactant is used as a stabilizer and it comprises about 5% of the fluid system. The fluid system can be weighted up using heavy brines or barites. It has superior cuttings carrying ability compared to air drilling fluids. There are two types of foam drilling fluids: (a) a stable foam which is a regular foam fluid system with water or brines as a continuous phase and gas as a dispersing phase, and (b) a stiff foam consisting of viscosified water or brine as a continuous phase and gas as a dispersed phase.

Future studies in foam fluids would include dynamic ECD and viscosity control to meet the stringent conditions of deep water and ultra-deep water drilling process.

Customized drilling fluid systems

Customized drilling fluids have shown great promise of facilitating the drilling process and increasing the producibility of oil and gas wells with significant economic benefits. These are fit for purpose designed drilling mud systems to minimize economic waste due to the prevailing conditions of the formation being drilled and, they are discussed in the following sessions.

Reversible invert emulsion drilling mud

Drilling mud which exhibit the characteristics of both emulsion and invert emulsion drilling mud are called reversible invert emulsion drilling muds [Patel, 1998]. They can be converted from W/O emulsion to O/W emulsion without undergoing a major change in rheological characteristics of the drilling fluid by using a chemical switch. W/O emulsions are preferred during drilling process and O/W emulsions are preferred during completion process. This technology combines the advantages of both the W/O and O/W emulsions. **Fig 1a** shows the reversible characteristics of invert emulsion drilling fluid. **Fig 1b** shows the process of reversing the characteristics of invert emulsion mud. The surfactants used in the emulsion can be protonated to get O/W emulsion and can be deprotonated to get a W/O invert emulsion. This process can be achieved without destroying the structure of the surfactant molecules. The oil wet surfaces of the drill cuttings can thus be converted to water-wet surfaces and is more environmentally friendly. The cement bonding is now improved as the formation is water wet than oil-wet. Filter cake clean up becomes easy compared to W/O inverted emulsions.

High membrane efficiency water based drilling mud

Shale swelling is a common occurrence while drilling with WBM. It leads to increased pore pressure at the wellbore and compromises the wellbore stability. OBM can be used as an alternative but they pose environmental and disposal concerns. SBM eliminate all the problems faced by OBM but they are expensive to produce. This calls for a water based mud which is insensitive to shale. High membrane efficiency water based mud are thus developed which have the capacity to sustain the osmotic pressure between the wellbore and the shale formation [Tan and Drummond, 2002]. The increase in pore pressure caused due to shale swelling can be minimized by reducing the activity of the drilling fluid and by increasing the membrane efficiency. If the activity of the drilling fluid is less than that of the shale, there will be an osmotic outflow of pore fluid from the shale into the wellbore. In overbalanced drilling there is an influx of drilling fluid into the shale formation due to mud pressure penetration. But, if the osmotic outflow from the shale is more than the drilling fluid influx into the shale, pore pressure of the wellbore surface will be considerably reduced. The membrane efficiency can be increased by chemical reaction between drilling fluid and shale, electrical restriction and ion exclusion, hydrogen bonding and clay modification.

Drilling fluids for depleted mature reservoirs

Depleted mature reservoirs are low pressure reservoirs with a very low value of fracture gradient. They are highly prone to common drilling problems like differential pipe sticking, excessive mud losses, wellbore collapse etc. An inter-bedded shale or cap rock if present would require a higher density drilling mud compared to the depleted reservoir. Hence, conventional WBM cannot be used for such type of reservoirs. Engineered solutions require the use of OBM consisting of sized particulates of graded ground marble ($CaCO_3$) and resilient graphite material (RGM) [Calder et al, 2009], or specially designed WBM with optimally sized acid-soluble bridging particles [Al-Mehailani et al, 2009; Ezell and Harrison, 2008]. These particulates would aid in blocking and stopping the micro/macro fractures. The particle type, shape and amount of these materials are based on the expected fracture width. The fracture width depends upon rock mechanics, hydraulic data and pressure regime. This technology will be able to plug micro fracture widths up to 1200 microns. The disadvantage of this technique is the density increase in the mud if the amount of granular particles is very high compared to optimum amount.

Drilling fluids with pipe freeing agents

Differential pipe sticking is one of the major problems encountered in overbalanced drilling where the drillstring gets embedded into the mud filter cake. A drilling mud mixed with a spotting fluid is generally used to free the stuck pipe. A recent technology uses a spotting fluid compounded with premium grade high melting point asphalt in diesel oil [Baker Hughes]. Once it is spotted to the required location, the drilling mud circulation is stopped and it begins removing the filter cake through wetting and flocculation. After the removal of the filter cake, it begins to form a thin and tough filter cake which reduces the differential pressure. It also lubricates the stuck part of the drillstring and reduces the drag and torque on the drillstring so that it can be released by jarring or rotating.

Coalbed Methane (CBM) drilling fluids

As the frontiers of CBM wells are pushed into the horizontal drilling realm, the importance of the drilling fluid becomes economically essential. The fluid needs to stabilize the wellbore during the drilling phase and also minimize any production shortfalls caused by damage. Baltoiu et al [Baltoiu et al, 2008] presented two versions (cased or openhole application) of newly developed drilling fluid by innovatively creating a series of intimate, very low-permeability surface bridges, or mats, across the intersected fractures, face cleats, and tectonic fractures. The fluid achieves this by exploiting the strong surface electrical charge of the coal. The filtercake building materials in the drilling fluid are attached to the face of the coal by electrical charge attraction, rather than depending solely on a pressure differential between the circulating fluid and coal formation pressure.

Drilling fluids for HTHP applications

The need for fluids with service temperatures above 300^oF has increased beyond the capabilities of conventional bio-polymers to create rheologically stable fluids. The drilling fluids used in high temperature, high pressure application (HTHP) tends to exhibit sagging behavior. It can also exhibit syneresis where the liquid is expelled from the gel structure. This calls for the need of a HTHP drilling mud which has a high value of low shear rate viscosity (LSRV) and high anti-sagging abilities [Knut et al, 2004]. A specially formulated organophilic clay is used that is composed of clay material and quarternary amines. It gives the drilling mud a unique capability of withstanding sagging of particles due to reduced viscosity. They are added at 0.5-5 lb/bbl concentration to enhance the suspension ability of the drilling fluid. Another industry accepted approach is the use of high-density thermally-stable polymeric solutions [Ezell and Harrison, 2008].

Drilling fluids with shale inhibitors

The WBM tend to react with shale causing shale swelling and increase in pore pressure. A drilling fluid with polyalkylene glycols (PAG) can counter this problem and are most prevalent in drilling through shale [MI SWACO]. The PAG exhibits a cloud point behavior which causes the polyglycol to become insoluble or precipitate out of the solution at a certain temperature. They form a barrier by plugging the shale pores and prevent the equalization of hydrostatic pressure which helps in preventing the water migration into the shale. The cloud point of the PAG depends upon the polyglycol concentration and water phase salinity. The process by which the PAG stabilizes shale is chemical adsorption. As the clouding out of the PAG increases, the surface adsorption increases. Apart from shale stabilization they also help in improving HTHP fluid loss control, enhance filter cake quality, provide lubrication to the drill bits, reduce skin factor and bit balling.

Formate drilling fluids

Formate drilling fluids are used in deep, slim-hole operations in deep and ultra deep sea drilling where gas hydrate formation is rampant. Formate based drilling fluids have high density and low frictional pressure loss. The addition of weighting materials increases the density of the drilling fluid and also results in increasing the frictional pressure loss. As formate based drilling fluids has high density by itself, the addition of weighting materials like bentonite would increase the drilling mud density to a very high value where it could cause formation damage. Formate based drilling muds are compatible with polymeric viscosifiers up to a very high temperature.

They are prepared by addition of formate salts like sodium formate (HCOONa), potassium formate (HCOOK) or anhydrous caesium formate ($HCOOCs.H_2O$) to fresh water [Howard, 1995]. They exhibit excellent shale stabilization due to high filtrate viscosity and low water activity of the brine systems. This leads to high formation strength and wellbore stability. They are also environmentally acceptable as they are bio-degradable.

Drilling through a salt formation is generally cumbersome as the drill cuttings mix with the drilling fluid and change the fluid rheology. This can cause severe problems during drilling and completion. It can be successfully overcome by preheating and using concentrated brine for the drilling fluid preparation. This makes the additional salt dissolving in the drilling fluid as low as possible, thus keeping the drilling fluid rheology constant.

Gas hydrates is another common problem that has to be reckoned with during deep and ultra-deep sea drilling. It generally occurs due to high pressure and low temperature. Ning [Ning et al, 2009] suggested that a formate based drilling fluid with gas hydrate inhibitors like NaCl and KCl can be used to reduce the formation of gas hydrates in the drill pipe which could otherwise lead to considerable reduction in production and cause safety issues.

Nano-Technology

Nanotechnology is becoming a widely popular in every aspect of science and technology. It involves using particles which are of 1–100 nm in size. It can play a major role in solving some of the most common problems encountered while drilling.

Amanullah and Al-Tahini [Amanullah and Al-Tahini, 2009] classified the nano-fluids as simple or advanced nano-fluids based on the nano-particles concentration in the drilling fluid. Nano-particles can be customized for achieving single or multiple functionalities. The nano-particles have a very high surface area to volume ratio which increases the reactivity of the nano-particles. Due to this fact, the amount of nano-particles required for any application is much less which reduces the cost to a great extent.

One of the major factors which contribute to creation of micro and macro fractures during overbalanced drilling is the presence of weighted solid content in the drilling mud. The use of nano-particles reduces the solid content and the density of the drilling mud which increases the ROP. It also eliminates the dispersion and sagging of solid content in the drilling mud.

The smart fluid containing multifunctional nano-particles can be customized to form a thin layer of non-erodible and impermeable nano-particle membrane around the wellbore which prevents some of the most common problems like shale swelling, spurt loss and mud loss due to lost circulation. This simple process eliminates the addition of fluid loss additives, shale inhibitors, rheology modifiers, formation strengthening materials etc. These nano-particle membranes are very useful during drilling application and can be removed easily during clean-up before the completion process. This is very helpful in deviated, horizontal and extended reach wells.

Recently, Sensoy et al [Sensoy et al, 2009] presented data showing the benefit of adding nano-particles to water-based drilling muds. Their results showed that nano-particles reduce the permeability of the Atoka shale by a factor of 5 to 50. Water penetration into Atoka shale was reduced by 98% as compared to sea water.

The smart fluids can be used in reducing the torque and drag in the drilling process. The nano-particles form a continuous thin film around the drill-pipe. This provides lubrication and thus reduces the torque and drag problems. The same concept can be used to reduce the differential pipe sticking problem. Specialized nano-particles can also be used to tackle drilling problems encountered while drilling through gumbo shale, gas hydrate and acid-gas environments.

Nano-Technology in shallow waters

Shallow water flow is a common problem in most of the onshore and deep water drilling process. It usually calls for an additional casing installation which thereby increases the well cost. Shallow water sands are highly porous and highly permeable. Engineered nano-particles which have gluing, sealing, filling and cementation properties can be used in such regions which increase the inter-granular strength and reduces the porosity and permeability of the formation. This process reduces the shallow water flow problem to a great extent. This technology can be applied to unconsolidated formation mainly deep sea beds in which the increased overburden results in the formation having a weak bonding and inter-particle cohesion. It can also be applied in formation which requires sand control.

Drilling fluid systems for deep water and ultra-deep water wells

Deep water and ultra-deep water drilling pose many challenges in design of a drilling mud as we deal with high pressures and low temperatures. A drilling mud which is highly environment friendly is recommended for such drilling process. The use of WBM should be avoided as the window between the pore pressure gradient and fracture gradient is very narrow. The use of OBM and SBM is not feasible as a large quantity of drilling mud is required for this process, which makes the entire process uneconomical. IEM with brine as internal phase would be an ideal drilling fluid for such process as it is comparatively economical and would aid in encountering the problems faced during deepwater and ultra-deep water drilling [Camero, 2000].

The other common problems encountered during such drilling process include shallow water flows, low temperature effects, excessive lost circulation, equivalent circulation density management, gas hydrate formation, wellbore breathing (ballooning), shale reactivity, unconsolidated formation etc. The above problems can be encountered to a large extent by customizing the IEM and adding suitable drilling mud additives.

Researchers at Houston’s Rice University have developed a nano-particle honeycomb structure graphene which is a single sheet of graphite and it is around one carbon atom thick [Tour, 2009]. Formation plugging can be prevented by adding a combination of oil soluble and water soluble graphene oxides at small dosages. These particles form a thin filter cake on the wellbore due to fluid pressure and thus prevents pore clogging which is caused by mud invasion into the formation. Once the drilling process is completed and the drill bit is drawn out, the formation pressure would be higher than the hole and this would facilitate the removal of the filter cake and would allow the reservoir fluid to flow into the wellbore without any obstruction.

Drilling fluid systems for CT drilling

Coiled Tubing (CT) drilling is becoming more popular in our industry. Due to the coiled nature of the tubing, it is easy to introduce it into the wellbore and retrieve it which saves a considerable amount of rig time. The CT is used in deviated, horizontal and extended reach wells to a large extent. The drilling fluid in CT undergoes a higher level of degradation due to a reduced area of cross-section and curvature effects of coil. This calls for a drilling fluid with higher viscosity which makes the fluid formulation for drilling process involving CT different than conventional process. The use of crosslinked fluid and VES are thus becoming popular in CT drilling application. The crosslinked fluids have a high viscosity compared to linear polymers/bio-polymers which prevent the fluid degradation to a large extent. The VES, on the other hand, is a self-healing fluid which regains its original rheological and viscoelastic properties once the shear stress is released.

Drilling fluid rheology

Rheology measuring equipment

The drilling fluids are constantly checked for their rheology and fluid consistency in the field. Drilling mud viscosity is generally measured in the field by Model 35 Fann viscometer. It is a constant shear rate viscometer and can provide measurements at atmospheric pressure and temperatures from ambient up to 200^{o}F. The viscosity of the fluid is proportional to the shear stress experienced by the fluid. The dynamic oscillatory tests for determining drilling fluids viscoelastic characteristics are generally conducted using rheometers such as Bohlin CS-50 Rheometer (now obsolete). It is a constant shear stress rheometer that can take measurements at ambient conditions as well as elevated temperature up to 400^{o}F and pressures up to 600 psi. The fluid can be tested in various configurations such as cup and cone, parallel plate and concentric cylinder arrangement.

As the payzone depth increases, the drilling mud rheology changes drastically due to high pressure, temperature, contamination and shear degradation. The WBM have inorganic bentonite clay dissolved in it or acquired while drilling through clay formation. This causes thermal instability which results in clay complex decomposition. The OBM have organic clay complex that dissolves and swells in diesel and mineral oils. They are thermally stable up to 350^{o}F and beyond that they start to decompose gradually. At low temperatures, they have a tendency to form gels. The equipment used to measure the rheology of such fluid functions only in a limited range of viscosity, pressure and temperature. Thus, there is a need to develop new rheology measuring instruments which can accurately predict the behavior of the drilling fluids at extremely high temperatures and pressures.

The VES fluids used as drilling muds have both viscous and elastic properties. During on-site operations, the rheological and viscoelastic measurements are very time consuming using conventional rheometers. This limitation can be overcome by designing a rheometer which would help analyze the fluid behavior on-site in a reasonable time. The various rheometers used in the laboratory/industry and their features are listed in **Table 1**.

The rheological behavior of foam fluids is somewhat complex. Foam fluids are compressible non-Newtonian fluids and are thermodynamically unstable. The viscometers that are used to measure the rheologies of foam fluids are of two types: Rotational viscometer and Pipe viscometer [Chen et al, 2005]. Rotational viscometers include Couette-type, parallel disk and cone and plate viscometers. In Couette-type instrument, the fluid rheology can be measured by keeping either the shear rate or the shear stress constant. In a pipe viscometer, the test fluid is pumped through a pipe of standard dimension at constant temperature and the flow parameters such as friction pressure and volumetric flow rate are measured in laminar flow region. Viscometric analysis that correlates the wall shear stress to nominal or Newtonian wall shear rate can be used to derive the foam rheology.

Future challenges would be to manufacture inline viscometers and rheometers which could be coupled to the flow loop directly to get real-time measurements at ambient conditions as well as high temperature and pressure and eliminate the need to test fluid samples for rheology at regular intervals. It should also withstand severe conditions of pressure and temperature when installed on the sea/ocean floor.

Rheology and Viscoelastic measurements

Gel strength

Gel strength is the ability of the drilling mud to suspend drill cuttings and other solid additives. It can also be defined as the shear stress of the drilling mud measured at a very low value of shear rate after it has set for ten minutes. This feature of the drilling mud helps in suspending the drill cuttings along the length of the drillpipe/borehole annulus when the drilling mud circulation is stopped during tripping or any other secondary operation.

In deep, ultra-deep and slim-hole wells, the drilling mud encounters shear degradation due to increased depths and high pipe shear. As a result, the viscosity of the drilling mud reduces considerably. Hence, the drilling mud should be formulated such that it will have excellent cutting transport capabilities even at low viscosity values.

Steady-shear viscosity and Oscillatory measurements

Steady shear rate tests can be used to analyze the rheological behavior of the drilling fluids. For this test, apparent viscosity is plotted against shear rate and the data trend shows the viscosity behavior as a function of shear rate. This experiment is repeated at various elevated temperatures to study the fluid degradation.

Steady shear rate test does not, however, provide information regarding the fluid structure. Thus, dynamic oscillatory test can be used to analyze the viscoelastic behavior of the fluids.

The rotor of the rheometer in steady shear measurements makes a full 360^o. The fluid structure tends to stretch and finally breaks down. According to Maxey [Maxey, 2006] the strain at which the fluid structure begins to stretch and break apart is the linear viscoelastic range (LVR) boundary. In dynamic oscillatory tests, the rotor makes an arc of a very small angle ($<< 1^o$) and reverses the direction. This test is conducted within the LVR to maintain the integrity of the fluid structure. The fluid undergoes stretching in one direction to a small extent and then stretches in the reverse direction to the same extent when the direction of the rotor reverses and restores the initial structure. **Figs. 2a** and **2b** show the difference between the steady shear rate and dynamic oscillatory rheometers.

At the Well Construction Technology Center (WCTC), the University of Oklahoma (OU), steady shear rate and dynamic oscillatory tests for different types of fluid systems have been conducted. The fluid systems tested include: 1.70 lb/bbl Xanthan in fresh water, 4% Aromox APA-T (VES) in fresh water, 2.25 lb/bbl Welan gum in fresh water, etc.

Fig. 3 shows the apparent viscosity versus shear rate plot for 1.70 lb/bbl Xanthan fluid at ambient temperature and pressure. It can be seen that it exhibits the upper Newtonian plateau, a shear thinning region and a lower Newtonian plateau (not well defined, however). The viscoelastic characteristics of the same Xanthan fluid are depicted in **Fig. 4**. From this figure, it can be observed that for Xanthan fluid, the elastic modulus is significantly higher and also dominates throughout the range of frequency. The G' values are approximately 32 to 186% higher than the G" values over the frequency range reported. Thus, the Xanthan fluid possesses excellent drill-cuttings suspension properties.

The apparent viscosity versus shear rate data for 4% Aromox APA-T (VES) in fresh water at ambient temperature and pressure are presented in **Fig. 5**. It can be observed that the VES fluid has a lower value of apparent viscosity and is more shear thinning compared to Xanthan fluid at low shear rates, but as the shear rate increases we see a reversal in the fluid behavior trend. The viscoelastic characteristics data for the VES fluid are shown in **Fig. 6**. At low frequency it exhibits more fluid-like behavior but at higher frequency the elastic modulus dominates, i.e. it behaves more solid-like. The elastic modulus crosses the viscous modulus at a frequency of 2.5 rad/sec. The deviation of G" from G' ranges from a minimum of 9% to a maximum of 616%, before the cross-over. After the cross-over point is reached, the deviation of G' from G" ranges from a minimum of 10% to a maximum of 614%.

Fig. 7 shows the apparent viscosity versus shear rate data for 2.25 lb/bbl Welan gum in fresh water at ambient temperature and pressure. The Welan gum fluid shows considerable low shear viscosity and shear thinning characteristics compared to Xanthan. The viscoelastic characteristics of 2.25 lb/bbl Welan gum in fresh water at ambient conditions are depicted in **Fig. 8**. It can observed that the elastic component dominates the viscous component over the entire frequency range of 0.1–100 rad/sec and there is no crossover between G' and G" plots. Both G' and G" values are significantly higher and less frequency dependent unlike Xanthan or VES fluids. The G' values are approximately 107 to 266% higher than G".

In addition to the above mentioned fluid systems, tests are also conducted for Welan gum-VES fluid blends [Ogugbue et al, 2010]. Welan gum is a bio-polymer and has good stability at high temperature, has limited filtrate loss due to its wall building ability, has good flocculation prevention and shale stabilization characteristics. However, it leaves a residue behind while clean up which can block pore spaces causing formation damage. VES, on the other hand, is a surfactant and is not stable at high temperatures and has high filtrate loss. However, it does not cause any significant formation damage as it does not leave residue.

Fig. 9 depicts the apparent viscosity versus shear rate data for the fluid blend containing 75% vol. of 2.25 lb/bbl Welan gum and 25% vol. of 4% VES at 75 and 175^oF. Welan gum is stable at higher temperatures, while VES is not. However, the fluid blend in **Fig. 9** shows similar temperature stability as Welan gum. **Fig. 10** shows the viscoelastic data for this fluid blend. The elastic modulus dominates over the entire frequency range. The G' values are approximately 12 to 240% higher than G" at ambient temperature while they are 7 to 300% higher at 175°F.

Fig. 11 shows the comparison of elastic modulus versus frequency range for various fluids at ambient temperature which is an indication of rehealing ability that plays a major role in cuttings transport. It can be clearly noticed that the Welan gum has the highest elastic modulus followed by Welan gum-VES fluid blend, Xanthan, and VES fluids. **Fig. 12** shows a similar comparison for viscous modulus versus frequency for various fluids. It can be concluded that the Welan gum has the highest value of viscous modulus followed by Welan gum-VES fluid blend, Xanthan, and VES fluids.

From viscoelastic data, it can be concluded that the order of fluid systems that is best suited for cuttings transport application would be Welan gum fluid, Welan gum-VES fluid blend, Xanthan fluid, and VES fluid respectively. It can be seen that by using 75% of 2.25 lb/bbl Welan gum with 25% VES system, the values of both G' and G" have increased significantly.

In future, as fluids become more exotic, their rheological characterization will become even more complex. Drilling fluids will have to be characterized more for their viscoelastic and time-dependent properties.

Foam fluids rheology

Foam fluids are widely used in underbalanced drilling, low pressure formations, deep water drilling etc. where the drilling pressure window is very narrow. The primary concern in such operations is ECD control. Foam fluids have low density and high viscosity and thus possess good cuttings carrying ability and ECD control. Thus, the rheological properties of the foam have to be studied to successfully design a foam fluid system with the desired characteristics. Experimental studies conducted by Bonilla and Shah [Bonilla and Shah, 2000] showed that aqueous and guar foam fluids rheology can be characterized with Herschel-Bulkley model and as the foam quality increases, shear stress and apparent viscosity increase. **Fig. 13** depicts the shear stress versus shear rate plot for aqueous foam fluids at various qualities measured at ambient conditions using smooth cup-rotor assembly [Chen, et.al, 2005]. The foam comprised of air, water and 1% surfactant by volume. **Fig. 14** shows similar shear stress versus shear rate data for the same foam fluids at various qualities but measured using rough cup-rotor assembly. From **Fig. 13**, it can be inferred that the foam fluids exhibit shear thinning behavior. Furthermore, the apparent viscosity of the foam fluids decreases as the shear rate increases and increases as the foam quality increases. However, the data in **Fig. 14** from a rough cup-rotor assembly reveal that these foam fluids do exhibit yield-stress and the behavior is more of a yield-pseudoplastic fluid. Also, the shear stress values are considerably higher than those obtained with a smooth cup-rotor arrangement. During the measurements using a smooth cup-rotor assembly, foam fluids experience slippage at the wall and thus, not providing the true rheological behavior of fluids. During drilling process, when drilling fluid enters the annulus with drill cuttings, it experiences rough surfaces of both the outer surface of the drillpipe and the formation wall.

Recently, Ahmed et al [Ahmed et al, 2009] successfully made viscometric measurements of foam-cement slurries employing a flow through assembly with Haake RS-300 rheometer. They characterized these fluids as yield-pseudoplastic and reported rheological data of various quality foam fluids.

Rheology models for drilling fluids

Drilling fluids used in the oil and gas industry usually comprise of either non-Newtonian pseudoplastic or yield-pseudoplastic fluids. There is no single rheological model which can exactly fit the shear stress-shear rate data of all fluids over the range of shear rates investigated. The simplest and hence most popular non-Newtonian pseudoplastic fluid model available is Ostwald-de-Waele or Power law model and is given by,

$$\tau = k\dot{\gamma}^{n} \quad\text{.............................}\ (1)$$

The power law model has two-parameters, n and k. To fit the rheological data over a wider range of shear rate, three-parameter and even up to five and six parameter-models are available in the literature. However, these models present a more complex mathematical analysis while solving the flow problems of engineering interest. The commonly used three-parameter model is the Ellis model and is given by,

Ellis Model $\tau = [\mu_o/\{1+(\tau/\tau_{1/2})^{\alpha-1}\}]\ \dot{\gamma}$ ....….....……….. (2)

where, $\tau_{1/2}$ is the value at which $\mu_a = \mu_o/2$. A (α-1) is the slope of line obtained when $[(\mu_o/\mu_a)-1]$ is plotted against $\tau/\tau_{1/2}$ on a log-log scale.

Four-parameter fluid models are Cross and Carreau models and are listed below.

Cross Model $$\frac{\mu_a-\mu_\infty}{\mu_o-\mu_\infty}=\frac{1}{1+\left(\dot{\gamma}t\right)^{p}} \quad\text{......................}\ (3)$$

Carreau Model $$\frac{\mu_a-\mu_\infty}{\mu_o-\mu_\infty}=\left[1+\left(\lambda\dot{\gamma}\right)^{2}\right]^{\frac{-n}{2}} \quad\text{.....................}\ (4)$$

The challenge with more than two parameter models is the determination of model parameters accurately.

As the power law and other pseudoplastic models do not incorporate the yield stress of drilling fluids, several other models are developed to incorporate yield stress. Hence the two-parameter models like Bingham plastic and Casson and the three-parameter models like Herschel-Bulkley and Robertson-Stiff were developed. These models are listed below.

Bingham-Plastic $\tau = \tau_o + \mu_p(\dot{\gamma})$ ………………. (5)

Casson Model $\tau^{\frac{1}{2}} = \tau_o^{\frac{1}{2}} + (\mu_o \dot{\gamma})^{\frac{1}{2}}$ …..………… (6)

Herschel-Bulkley $\tau = \tau_o + k(\dot{\gamma})^n$………………… (7)

Robertson-Stiff Model $\tau = k\left(\dot{\gamma} + \gamma_o\right)^n$ ……..…………… (8)

Davison et al [Davison et al, 1999], showed that Bingham plastic and Herschel-Bulkley models fit the data of low toxicity OBM. Bingham plastic model, however, tends to deviate from the data at high temperatures. Herschel-Bulkley and Casson models accurately fit the OBM/synthetic base muds over a wide range of temperature, pressure and shear rates. The Casson model can be extrapolated to get the fluid behavior at high temperature, high pressure conditions. **Fig. 15** shows the comparison of Herschel-Bulkley and Casson model with 80:20 OBM data at ambient conditions. Both models fit the rheological data of this mud very well. In **Fig. 16** it can be seen that Herschel-Bulkley model fits the weighted and salt/polymer based WBM very well. It can also be concluded from the figure that the Casson model holds good for weighted WBM.

It is possible that the models discussed here may still not fit certain fluids rheological data accurately.

Time-dependent Fluids

In reality the fluids used in the oil and gas industry for drilling are thixotropic in nature. They possess time-dependent properties. The fluid structure continually breaks down with time upon applying shear stress but upon rest the fluid structure is rebuilt. This is a very desirable property. Shear-thinning properties help lower the friction pressure loss in the drillpipe but in the drillpipe/wellbore annulus where shear rate is significantly lower, the fluid rebuilds its structure and exhibits yield stress. The presence of yield stress will keep the drill cuttings suspended if for some unforeseen reason the drilling process is stopped. There are models available to capture the fluids thixotropic properties. Most of these models are based on chemical kinetic rate equations and incorporate fluids molecular structure, in terms of entanglement/disentanglement. These models, however, are not very convenient to use and therefore, most of the time our industry has shied away from their usage.

Hydraulics of Drilling Fluids

Linear polymers are most widely used in the oil and gas industry for rheology modification in drilling mud. A 1.7 lb/bbl Guar and 1.7 lb/bbl Xanthan fluids are commonly used linear polymers in the industry. The rheology of the drilling fluid can be further improved by using small amount of crosslinker as additive. These fluids are pumped through straight pipe such as drillpipe in conventional drilling or straight and coiled tubing as in CT drilling. Regardless of the drilling process, it is imperative to characterize these fluids accurately for their hydraulic properties. The hydraulics of drilling fluids, however, is strongly dependent upon the fluids rheological properties.

The Fanning friction factor versus generalized Reynolds number plot for 1.7 lb/bbl Xanthan in water flowing through a 1 ½ in. straight and coiled tubing is shown in **Fig. 17.** The ST and CT data are compared with their respective Drew [Drew et al, 1932] and Srinivasan correlations [Srinivasan et al, 1970] for Newtonian base fluid respectively. These correlations are given below:

Drew Correlation:

$f = 0.0014 + 0.125(N_{\mathrm{Re}})^{-0.32}$ ……..……..……..……… (9)

Eq. 9 is valid for the Reynolds number range of $2{,}100 < N_{\mathrm{Re}} < 3\mathrm{x}10^6$.

Srinivasan Correlation:

$f = \dfrac{0.084}{N_{\mathrm{Re}}^{0.2}}\left(\dfrac{r}{R}\right)^{0.1}$ ……...…..……………………………… (10)

where, r/R is the curvature ratio of the CT reel.

Eq. 10 is valid between critical Dean number, $(N_{DN})_{\mathrm{critical}}$, and $N_{DN} = 14{,}000$ and curvature ratio from 0.0097 to 0.135.

The Dean number is defined as,

$N_{DN} = N_{\mathrm{Re}}\left(\dfrac{r}{R}\right)^{0.5}$ …………………………………… (11)

Critical Dean number is given by,

$\left(N_{DN}\right)_{critical} = 2100\left[1 + 12\left(\dfrac{\mathrm{r}}{\mathrm{R}}\right)^{0.5}\right]$……………….. (12)

It can be seen in **Fig. 17** that the friction factors of Xanthan fluid in both ST and CT are lower than their respective base fluids. It means that Xanthan fluid exhibits a significant drag or friction reduction in both ST and CT. However, the drag reduction is somewhat less in CT compared to ST because of the curvature effects associated with CT. The maximum drag reduction observed in ST and CT is 86% and 72% respectively.

Linear gels are not stable and degrade at high temperature and with shear. Thus, linear gel fluid systems are replaced by VES fluid systems as it is structurally stable. There are various VES fluid systems that are used in the oil and gas industry. At OU's WCTC, we have conducted flow tests and rheological characterization of various VES systems such as 4% Aromox APA-T (VES) in fresh water, 5%

Aromox APA-TW (VES) in fresh water and 2% KCl, and 1% Nalco VX 8721 in 4% KCl through ST and CT. **Fig. 18** shows the Fanning friction factor versus generalized Reynolds number plot for the flow of 4% Aromox APA-T (VES) in ST [Kamel and Shah, 2008b] and CT [Kamel and Shah, 2008a]. It can be observed from the figure that the VES fluid also exhibits significant drag reduction both in ST and CT. Again, the drag reduction is more in ST than in CT. The maximum drag reduction observed in ST and CT is 69% and 55% respectively. At higher generalized Reynolds numbers, the VES fluid shows shear degradation and drag reduction decreases. The micelle structure of the VES system is destroyed due to constant application of shear. Once the applied shear is released, the micelles in the system re-structure themselves and the fluid reheals and regains its original rheological properties.

As mentioned earlier, the VES fluid systems are usually unstable at high temperatures. This can be overcome by using biopolymers like Xanthan and Welan gum. Bio-polymers like Welan gum is highly stable at elevated temperatures and is relatively less expensive than surfactant based fluids.

Fig. 19 presents similar Fanning friction factor versus generalized Reynolds data for 2 lb/bbl Welan gum in fresh water through ½-in. ST and CT. The maximum drag reduction observed in ST and CT is 78% and 59% respectively.

CFD Simulations of fluids through ST and CT

At WCTC, we have performed Computational Fluid Dynamics (CFD) simulations for the flow of Newtonian and non-Newtonian fluids for different configurations of ST and CT and for various conditions [Jain et al, 2004]. **Figs. 20a** and **20b** show the velocity contour and corresponding profile obtained from the CFD simulations for the laminar flow of 1.5 lb/bbl Xanthan fluid in 2-3/8 in. ST at a flow rate of 2.8 bbl/min. It can be seen that as expected, the velocity contours and profile of the fluid are symmetrical along the pipe center, showing the maximum velocity in the center of pipe and zero at the wall. **Figs. 21a** and **21b** show similar velocity contours and profile for the laminar flow of 1.5 lb/bbl Xanthan fluid in 2-3/8 in. CT at a flow rate of 2.8 bbl/min. Here, the maximum velocity is closer to the outer pipe wall of CT and zero velocity at the inner wall. This can be attributed to the curvature effect of the CT which causes to generate centrifugal forces and secondary flows within the flow field.

With increased CT drilling activity, the industry must realize the need for thoroughly characterizing the complex fluid systems, i.e. understanding fluid behavior in coiled tubing and characterizing the complex rheological behavior of various fluid systems.

On-the-fly recipe modification for fluid preparation

On the fly hydration of polymers are widely used in the industry today. The conventional fluid mixing technique was to subject a large amount of fluid to low shear for a longer duration in large agitation tanks. This process consumed a lot of energy. The residence time required for the treated fluid for complete hydration was around four to seven minutes. The disadvantage of this system was that the unused fluid left in the mixing tank had to be disposed, large and heavy blenders were required and their transportation was cumbersome, etc. The latest technique is to treat a small amount of gelled fluid by imparting a large amount of shear for a short duration of time [Gupta and Pierce, 1998]. The gelled fluid flows through centrifugal pump and water is sucked into the pump from a water tank. The gelled fluid is then subjected to a shear rate of 25,000 sec^{-1} to 1,000,000 sec $^{-1}$ in the high shear imparting unit. This results in fragmentation of particles into smaller pieces which increases the surface area of the particles of the fluid for faster and complete hydration which results in higher viscosities. The residence time is thus reduced to 20 seconds.

Conclusions

- Overall the industry has kept up with the growing demand of drilling fluids for numerous unique applications. The conventional drilling fluid systems have proven to be effective and are here to stay due to their profound effect on the industry. As new technology frontiers of deep and ultra-deep water drilling are explored, there will be a demand for more exotic and more temperature stable drilling fluids. Some polymer/surfactant blends have shown promising results and should be explored further. With the advent of nano-technology, it is anticipated that more smart or customized fluids for preventing shale swelling, spurt loss and mud loss due to lost circulation will be introduced.
- The instruments to characterize today's drilling fluids are somewhat adequate. However, there is a need for instruments that can characterize drilling fluids better (a) at extremely low shear rate for their yield stress values, (b) for steady shear viscosity measurements at elevated temperature and pressure, (c) for viscoelastic measurements at elevated temperature and pressure, (d) for measuring foam fluids rheology, and (e) inline rheometers for the real-time rheological measurements of drilling fluids.
- Numerous rheological models or constitutive equations are available to characterize drilling fluids. Traditionally, most of these models have been simple and they do not capture the fluids rheological behavior accurately. With the introduction of more complex drilling fluids in the future for deep and ultra-deep water drilling, there will be a need for understanding the behavior of these fluids at molecular level. The constitutive equations involving chemical kinetics should be re-examined for fluids time-dependent properties.
- In recent years, CT and slim-hole drilling has become popular. Drilling fluids with added shear resistant characteristics should be developed. Furthermore, in CT drilling, fluid is subjected to the

curvature effects of the coil (centrifugal forces and secondary flows). As a result, the fluid degrades and reduces its drag reduction property quicker. Therefore, the fluids rheological as well as hydraulic properties need to be modeled properly for the accurate hydraulic calculations.

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Nomenclature

f = *Fanning friction factor, dimensionless*
G' = *Elastic modulus,* lb_f/ft^2
G'' = *Viscous modulus,* lb_f/ft^2
k = *Fluid consistency index,* $lb_f.sec^n/ft^2$
n = *Fluid behavior index, dimensionless*
N_{DN} = *Dean number, dimensionless*
$(N_{DN})_{critical}$ = *Critical Dean number, dimensionless*
N_{Re} = *Reynolds number, dimensionless*
N_{Req} = *Generalized Reynolds number, dimensionless*
P = *Model constant, dimensionless*
r = *Radius of the coiled tubing, in.*
R = *Radius of the coiled tubing reel, in.*
t = *Characteristic time constant, sec*

Greek Symbols

γ_o = *Shear rate at zero shear stress,* sec^{-1}
$\dot{\gamma}$ = *Shear rate,* sec^{-1}
τ = *Shear stress,* lb_f/ft^2
τ_o = *Yield shear stress,* lb_f/ft^2
$\tau_{1/2}$ = *Shear stress at which* $\mu_a = \mu_0/2$, lb_f/ft^2
μ_a = *Apparent viscosity, cP*
μ_p = *Plastic viscosity, cP*
μ_o = *Zero shear rate viscosity, cP*
μ_∞ = *Infinite shear rate viscosity, cP*

Abbreviations

CBM = *Coal Bed Methane*
CFD = *Computational Fluid Dynamics*
CMC = *Critical Micelle Concentration*
CT = *Coiled Tubing*
ECD = *Equivalent Circulating Density*
EPA = *Environment Protection Agency*
HTHP = *High Temperature and High Pressure*
IEM = *Invert Emulsion Mud*
LSRV = *Low Shear Rate Viscosity*
LVR = *Linear Viscoelastic Range*
OBM = *Oil Based Mud*
O/W = *Oil in Water*
PAG = *Polyalkylene Glycols*
RGM = *Resilient Graphite Material*
ROP = *Rate of Penetration*
SBM = *Synthetic Based Mud*
ST = *Straight Tubing*
VES = *Visco Elastic Surfactant*
WBM = *Water Based Mud*
WCTC = *Well Construction Technology Center*
W/O = *Water in Oil*

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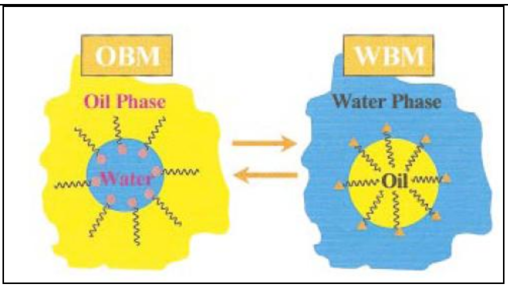
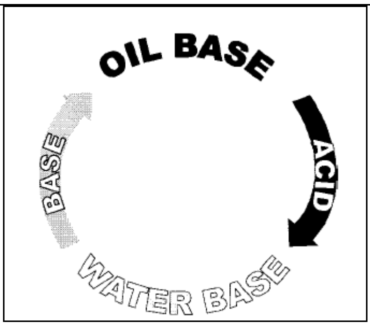
Table. 1 Commercially available rheometers and their features

Manufacturer	Instrument	Temperature	Pressure	Features
Fann Instrument	Model 50 HTHP Viscometer	Up to 500°F	Up to 700 psi	It is a high temperature high pressure viscometer.
	Model 70 &75 HTHP Viscometer	40 to 500°F	Up to 20,000 psi	It can also be used to make deepwater sub-ambient rheology measurements up to 40°F.
	Extreme HTHP Viscometer	Up to 600°F	Up to 30,000 psi	It can make measurements in hot wells and wells subjected to very high pressure.
Brookfield Engineering	Cap-2000+ Rheometer	40 to 455°F	Ambient Pressure	It is equipped with a peltier plate for rapid temperature control. The sample size required is very small (<1mL). It is rugged in design and can handle harsh production environment.
	PVS Rheometer	-40 °F to 500°F	Up to 1,000 psi	It is a controlled shear rate rheometer. It is designed to operate in severe environment conditions. It can measure rheologies at sub-ambient temperatures. It is also equipped with triple annular geometry for increased sensitivity while measuring low viscosity fluids.
	R/S Plus Rheometer	Ambient Temperature	Ambient Pressure	It can function as both controlled shear rate and shear stress rheometer. It has the capability to measure yield stress, thixotropic and creep properties. It is available in wide variety of spindle configurations. Temperature control can be achieved using peltier plate, circulating temperature bath or electronic heating.
Grace Instrument	M 5600 HPHT Rheometer	Up to 500°F	Up to 1,000 psi	It can measure both rheological and viscoelastic data. This instrument is ideal to test fluids for its cuttings carrying and suspending ability.
	M 7500 Ultra HPHT Rheometer	Up to 600°F	Up to 30,000 psi	It has a cement module to measure the rheology of cement slurry.
Chandler Engineering	Model 7600 HPHT Rheometer	Up to 600°F	Up to 40,000 psi	It is a controlled shear rate rheometer. It is equipped with a stepper motor for accurate shear rate measurements.
Malvern Instruments	Bohlin CVO Rheometer	-40 °F to 400°F	Ambient Pressure	It is a controlled shear rate rheometer. It can be used to test wide range of fluid systems from low viscosity fluids to high viscosity polymer melts. It is equipped with unique air-bearing technology and automatic gap adjustment which facilitates the precise measurement of low viscosity and low shear stress.
Thermo Scientific	Haake RS - 300	up to 220°F	Up to 1,500 psi	Flow through devices for foam rheology measurements.

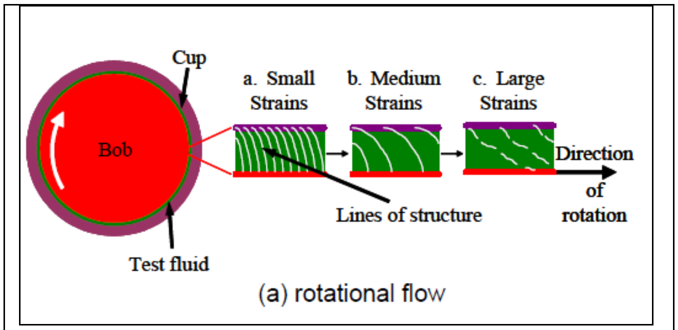


(a) Reversible characteristics of an invert emulsion drilling fluid

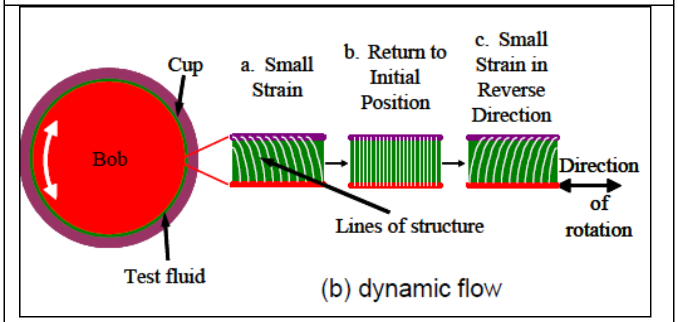


(b) Process of reversing an invert emulsion drilling fluid

Fig.1 Reversible invert emulsion mud [Patel, 1998]



(a) Fluid structure change in rotational rheometer



(b) Fluid structure change in dynamic oscillation rheometer

Fig. 2 Fluid structure change in rheometers [Maxey, 2006]

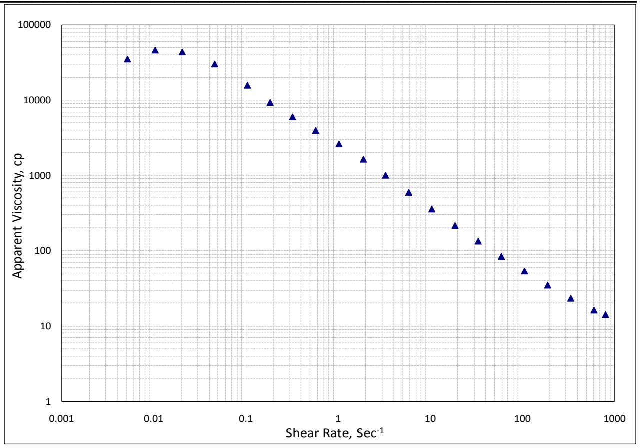


Fig. 3 Apparent viscosity versus shear rate for 1.7 lb/bbl Xanthan fluid at ambient conditions.

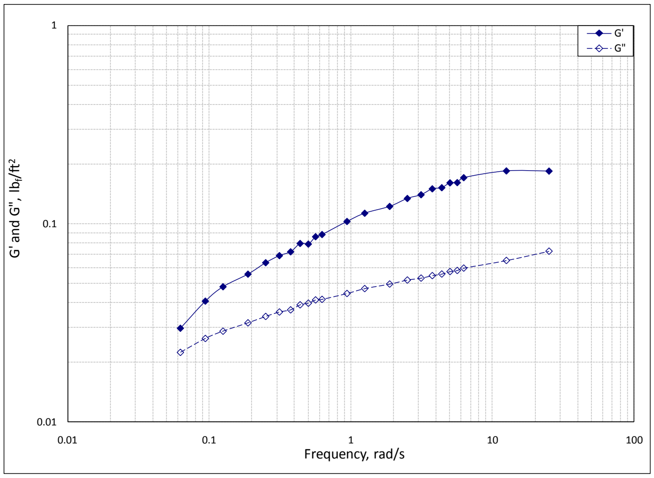


Fig. 4 Viscoelastic data for 1.7 lb/bbl Xanthan fluid at ambient conditions.

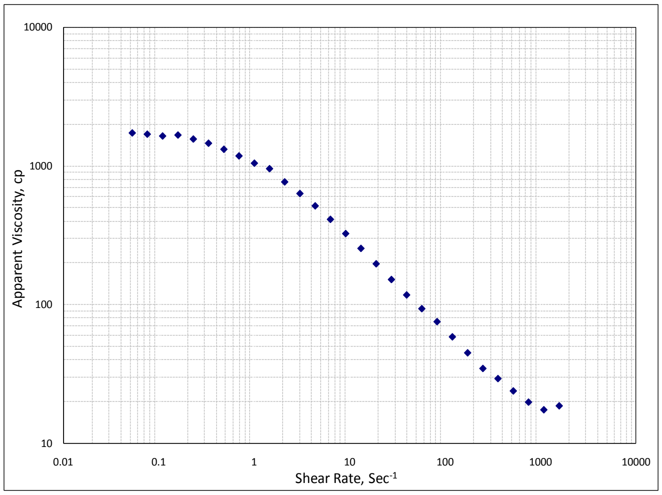


Fig. 5 Apparent viscosity versus shear rate for 4% Aromox APA-T (VES) fluid in fresh water at ambient conditions [Kamel and Shah, 2008b].

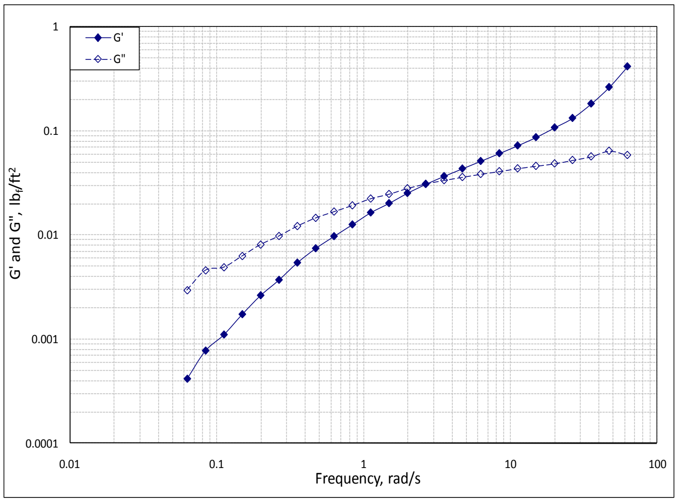


Fig. 6 Viscoelastic data for 4% Aromox APA-T (VES) fluid in fresh water at ambient conditions [Kamel and Shah, 2008b].

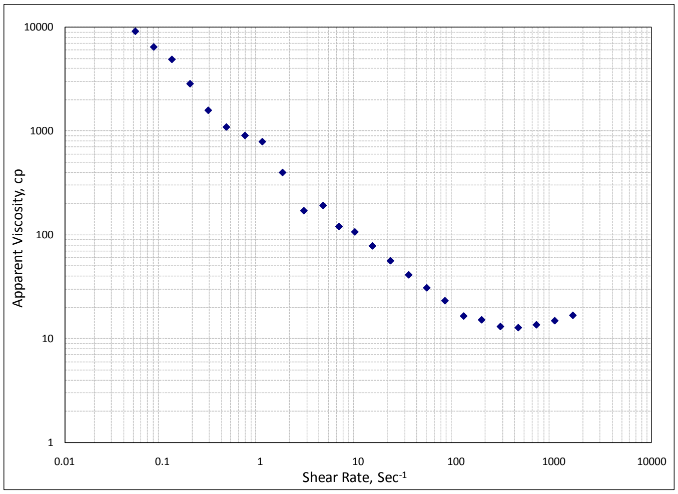


Fig. 7 Apparent viscosity versus shear rate for 2.25 lb/bbl Welan gum at ambient conditions.

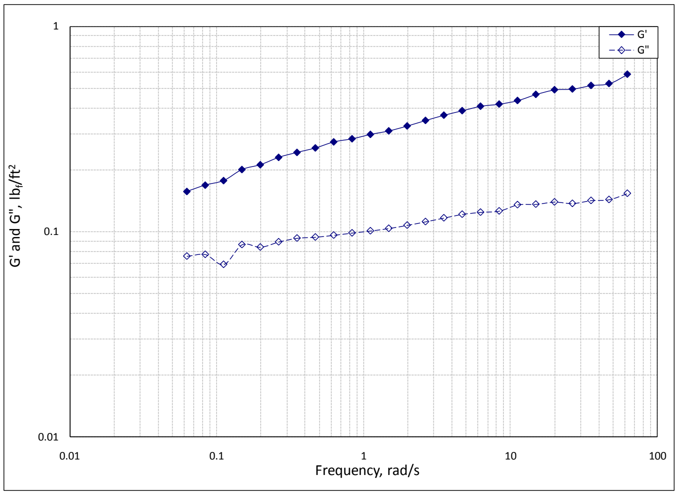


Fig. 8 Viscoelastic data for 2.25 lb/bbl Welan gum at ambient conditions.

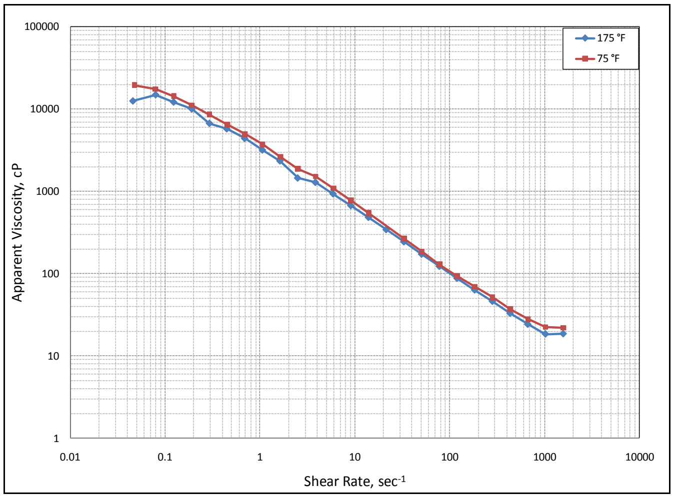


Fig. 9 Apparent viscosity versus shear rate for 75% vol of 2.25 lb/bbl Welan gum and 25% vol of 4% Aromox APA-T (VES) at 75 and 175°F [Ogugbue et al, 2010]

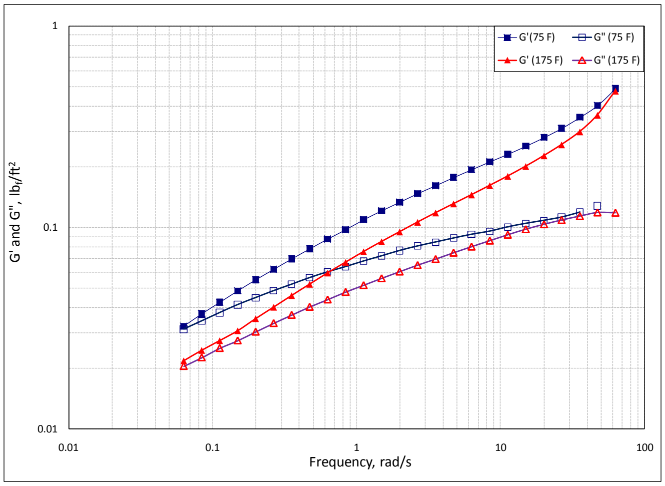


Fig. 10 Viscoelastic data for 75% vol of 2.25 lb/bbl Welan gum and 25% vol of 4% Aromox APA-T (VES) at 75 and 175°F [Ogugbue et al, 2010]

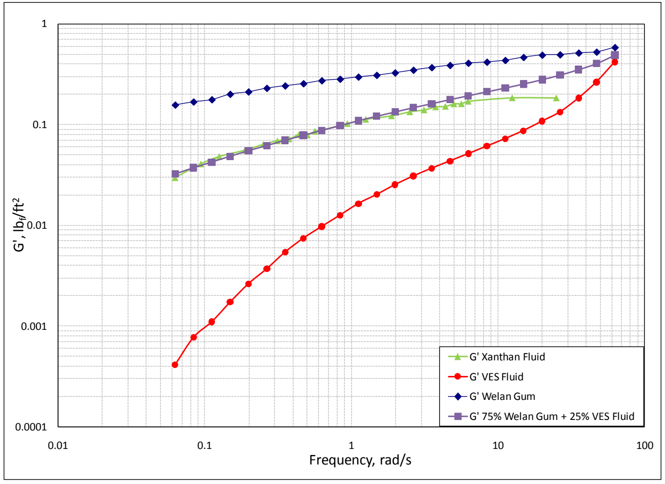


Fig. 11 Elastic modulus data for various fluids at ambient temperature.

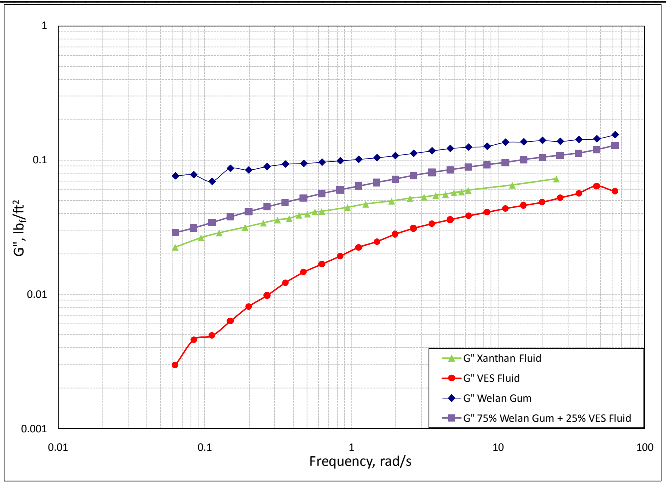


Fig. 12 Viscous modulus data for various fluids at ambient temperature.

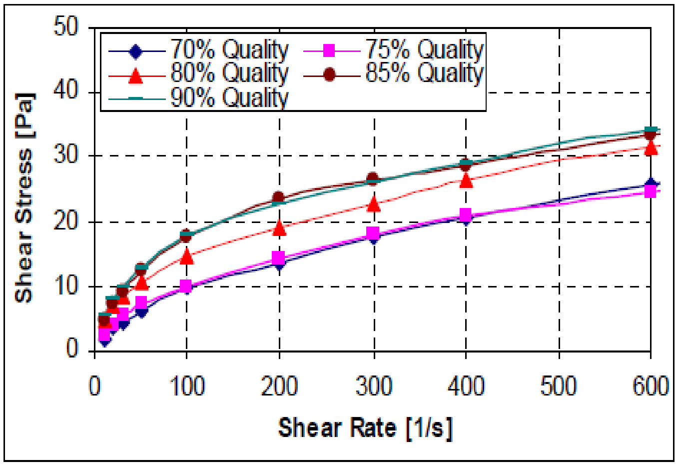


Fig. 13 Shear stress versus shear rate for different foam qualities in smooth cup-rotor assembly [Chen et al, 2005]

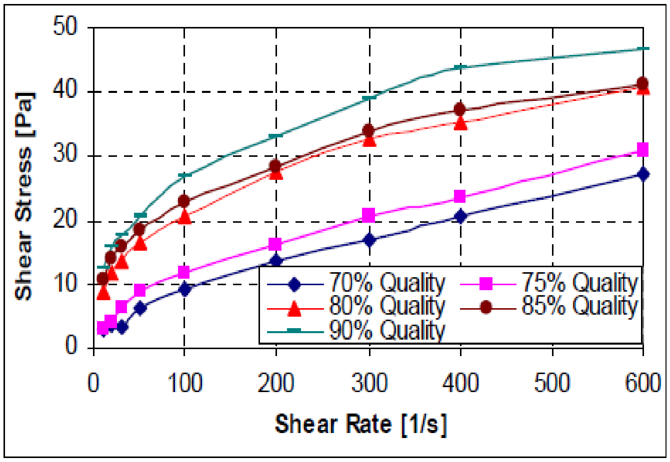


Fig. 14 Shear stress versus shear rate for different foam qualities in rough cup-rotor assembly [Chen et al, 2005]

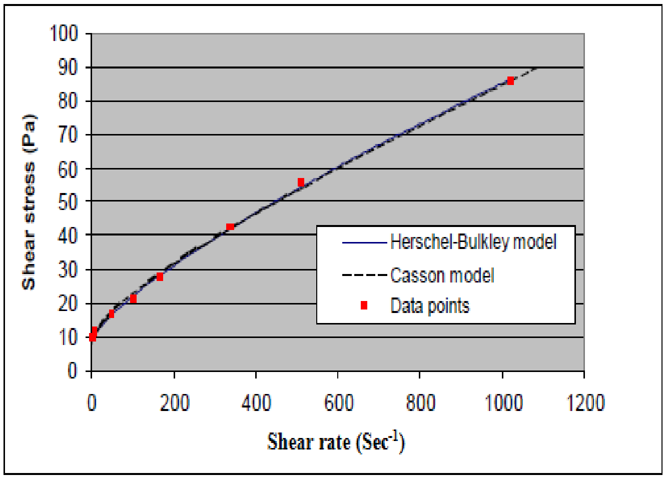


Fig. 15 Comparison of Herschel-Bulkley model and Casson model with 80:20 OBM at ambient conditions [Davison et al, 1999].

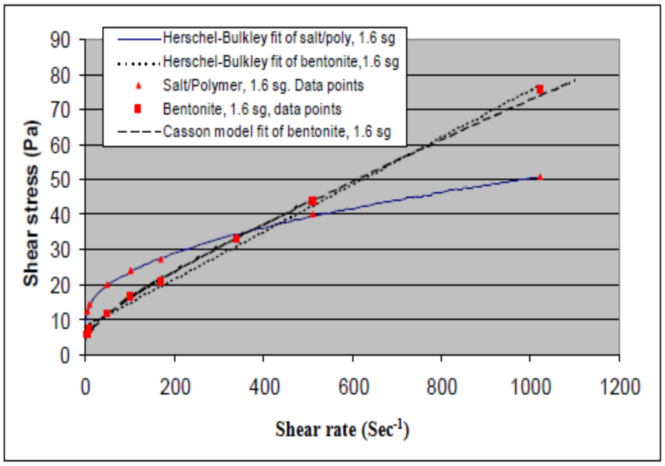


Fig. 16 Comparison of Herschel-Bulkley model and Casson model with salt/polymer and bentonite based WBM at ambient conditions [Davison et al, 1999].

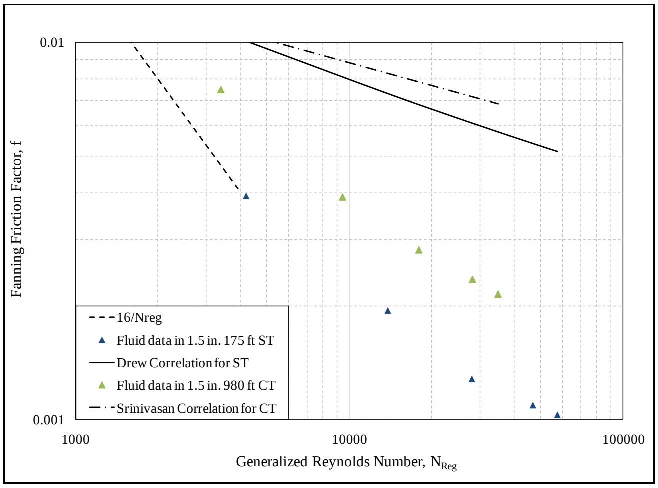


Fig. 17 Fanning friction factor versus generalized Reynolds number for the flow of 1.7 lb/bbl Xanthan in fresh water through ST &CT.

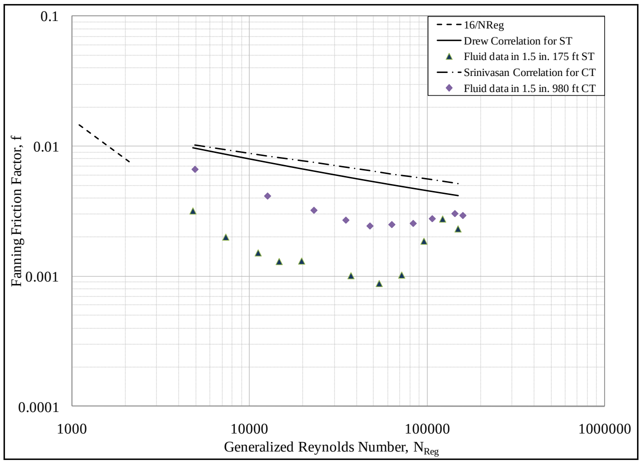


Fig. 18 Fanning friction factor versus generalized Reynolds number for the flow of 4% Aromox APA-T (VES) in fresh water through ST &CT [Kamel and Shah, 2008a,b].

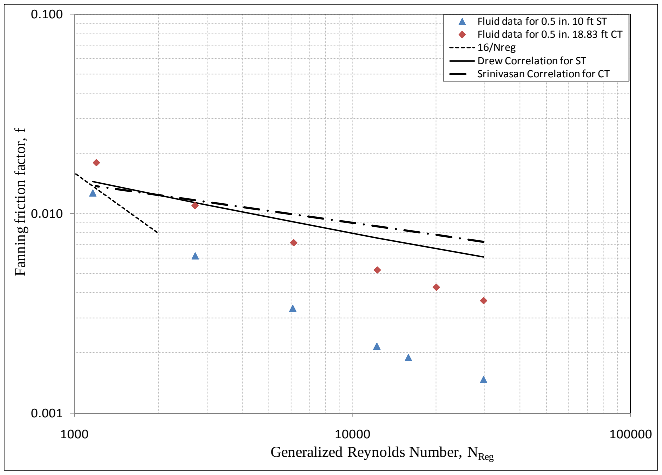
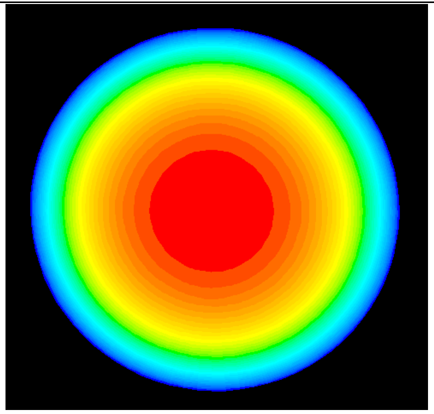
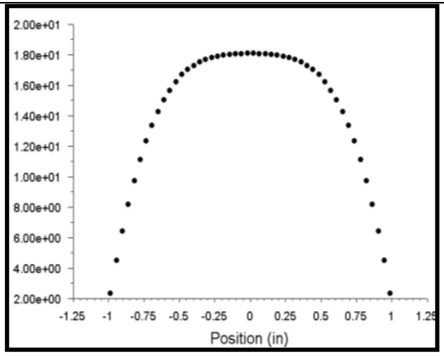


Fig. 19 Fanning friction factor versus generalized Reynolds number for the flow of 2 lb/bbl Welan Gum in fresh water through ST &CT.

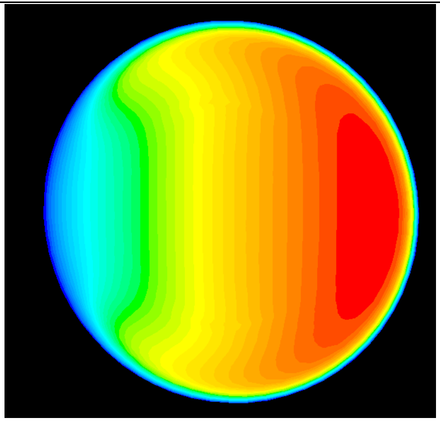


(a) Velocity Contour

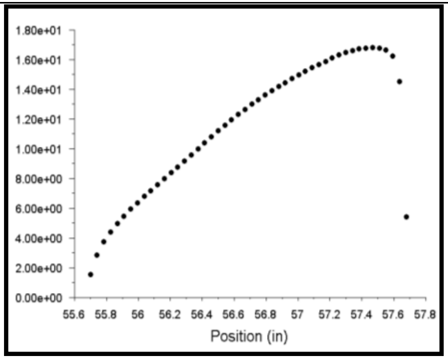


(b) Velocity Profile

Fig. 20 CFD simulation of 1.5 lb/bbl Xanthan fluid flowing at 2.8 bbl/min in 2-3/8 in. ST.



(a)Velocity Contour



(b) Velocity Profile

Fig. 21 CFD simulation of 1.5 lb/bbl Xanthan fluid flowing at 2.8 bbl/min in 2-3/8 in. CT.