AADE-06-DF-HO-01

Rheological Analysis of Oilfield Drilling Fluids

Jason Maxey, Baker Hughes Drilling Fluids

Abstract

Viscometric evaluation of drilling fluids is commonplace within the drilling industry. Increasingly sensitive instruments for the low-shear measurement of viscosity have been introduced and are being used to broaden the field of information upon which downhole predictive models may draw. However, all of these are based solely on rotational viscometric behavior of the fluids and give no serious consideration of the structural behavior underlying the viscous behavior. Techniques are available for the evaluation of the viscoelastic behavior of fluids, and a comparison of rotational viscometry to dynamic rheology of six drilling fluids is presented in the paper. In some cases, the general conclusions reached from examination of the rotational viscosity are supported by dynamic evaluation. However, in other cases, the viscoelastic analysis provides a more complex picture which cannot be fully explained through viscometry alone.

Introduction

A great deal of attention has been given over the years to the design and control of drilling fluid rheology. The impact of rheology on numerous aspects of the drilling and completion process has been reported. Some of the more important aspects include the management of ECD, control of barite Sag, and enhanced hole cleaning. For example, numerous recent papers have examined the use of “flat rheology” invert emulsion fluids that exhibit relatively little change in a few key properties over a broad temperature range as a method for minimizing ECD[1]. Also, recent attention has been given to the effect of changing rheological properties on the occurrence of barite Sag[2,3]. The focus of most of these investigations has been the control and modeling of viscosity as a function of shear rate, with some consideration given to API gel strengths as a measure of structure within the fluid.

More recently, some work has been focused on the dynamic, or oscillatory, behavior of drilling fluids in an effort to come to a more complete understanding of their full rheological behavior. Tehrani, Zamora, and Power have presented work correlating the viscoelastic properties of drilling fluids and viscosity with dynamic Sag as measured by a viscometer Sag test device[4]. In this work, the authors compared the observed dynamic Sag and viscoelastic properties of fluids viscosified by various organophilic clays and polymers. Similar work was performed by Mullen, et al. in comparing the rheological performance of fluids in order to identify a most suitable chemistry for controlling barite Sag and minimizing the impact on downhole pressure losses[5]. To date, however, a complete picture of the rheological behavior of drilling fluids has yet to emerge.

Increased attention has also been given to utilizing better rheological models for prediction of downhole fluid properties. In addition to the commonly used factors of PV and YP from the Bingham Plastic model, the power law, Casson, and Herschel-Bulkley models have been shown to have utility in the description of viscosity profiles of drilling fluids[6]. However, in using these and similar models, the assumption is made that muds are time-independent, purely viscous, non-Newtonian fluids[7], when it is well recognized that drilling fluids demonstrate thixotropic and viscoelastic behavior. Additionally, these models tend to be weighted for greater accuracy at higher strain rates (500 – 1000 s^{-1}) when maximum annular shear rates are not expected to exceed 400 s^{-1} and will tend toward zero in the center of the annular gap[8].

While better methods of predicting downhole behavior of fluids are now more readily available, the predictions are being based predominately on the same set of data that was available 30 to 40 years ago. The goal of this paper is to impart a basic understating of the differences between rotational and dynamic rheological measurements, along with some testing techniques and physical meaning of the measurements. In doing this the basic assumptions common to couette (cup-and-bob) measurements will be discussed in light of the common oilfield practice. Finally, rheological behavior of several water-based and invert emulsion fluids will be discussed.

Comparison of Rotational and Dynamic Testing

The predominant instrument used for viscometry within the oil industry is the FANN® Model 35 VGA or other equivalent viscometer. This system employs a rotating sleeve or rotor about a bob suspended by a torsion spring assembly (couette geometry) which is submersed in a test fluid. The sample in the small gap (1.168 mm) between the rotor and bob is what is tested, with the surrounding fluid contributing only negligibly to results. While other geometries are available for rheological testing, the use of couette geometry has proven to be most robust for common oilfield applications. When discussing more complex measurements, it is necessary to review and understand the basic assumptions which are made in couette-flow measurements.

Assumptions and Errors in Couette Viscometry

A summary of couette flow assumptions was recently presented by Gusler, et al.[9] and is represented here. In the use of couette (cup-and-bob) geometry for the measurement of rheology, several assumptions are first made and must be adhered to if results are to be accurate. These assumptions include[10]:

1. Steady, laminar, isothermal flow
2. $v_\theta = r\Omega$ only and $v_r = v_z = 0$
3. Negligible gravity and end effects, and
4. Symmetry in θ

The implications of these assumptions are enormous, yet these assumptions are often not completely met when working with solids-laden drilling fluids and spring torsion measurement devices. For example, in requiring a steady, laminar flow it is assumed that the motion of solid particles in the gap does not impart impact energy to the torsion bob (which, in practice, is often observed by the "jerky" motion of the torsion dial) and that no secondary flows are occurring in the annular gap. However, secondary flows such as Taylor vortices are known to commonly occur. With the outer sleeve rotating at some speed, inertial forces will cause small axisymmetric cellular secondary flows (Taylor vortices) which dissipate energy and cause an increase in the measured torque (and thus an increase in apparent viscosity). This phenomenon is dependent on fluid density and viscosity as well as rotation rate and the physical dimensions of the cup and bob, with a criterion for stability given by

$$\mathrm{Ta} = \frac{\rho^2 \Omega^2 (R_o - R_i)^3 R_i}{\eta(\dot{\gamma})^2} < 3400 \qquad (1)$$

where Ta is the Taylor number[10]. For high density, high solids content fluids, the possibility for the occurrence of secondary flows is greatly increased. Further, for flow between the rotor and bob to be steady and laminar the gap must be exceedingly small, with the ratio of bob radius to rotor radius being greater than 0.99[10]. However, for a standard R1B1 rotor/bob combination this ratio is 0.936, presenting a small but persistent uncorrected error.

Additionally, beyond the possibility of unsteady and non-laminar flow in the annulus, we find that standard oilfield viscometers do not meet the assumption of fluid flow being a function of radial distance only with no radial velocity or flow in the z-plane. The presence of fluid both inside the annular gap and outside the rotating sleeve results in a circulation of fluid from the outside of the sleeve into the gap, moving from top to bottom. This flow in the z-plane is greatly amplified by the presence of a helix on the outside of the rotor found in HP/HT viscometers. The intention of this is to prevent the settling and accumulation of solids when high temperatures (and thus lower viscosities) are tested. Nonetheless this circulatory flow, like the Taylor vortices, influences the measured torque and thus adds inaccuracy to the measured viscosity of the fluids.

In general, a well maintained oilfield viscometer will adhere to the requirement of symmetry. However, as parts age with use, the rotor is often found to warp into a more oval shape while the bob remains circular. This induces an uneven flow field and distorts measurements. Finally, even the assumption of negligible end effects is not precisely followed as the bob has a conical top-section which is unaccounted for and, in some cases, serves as a collector of solids settling out of the system.

Under most circumstances, these basic couette-flow assumptions are adhered to closely enough that measurements can be made with fair accuracy. However, not understanding when the assumptions break down can result in misleading, inaccurate data.

Rotational and Dynamic Rheology

With few exceptions, oilfield rheological analysis of drilling fluids is performed in a steady, rotational mode where the rotor is continuously in motion. The prime exception to this is the measurement of gel strengths, where the test fluid is allowed to rest for a brief period before restarting the rotor at 3-rpm and measuring the maximum deflection of the bob. This is properly a transient, rotational test where the measured value is not an exact strength of the gel structure but rather its contribution to the low shear rate viscosity as measured at inception of flow. The accuracy and true interpretation of the gel strength measurements has been explored by Jachnik[8] and others; however, this measurement remains a good indicator of structure growth that can be obtained from a rotational viscometer.

The differences between rotational and dynamic testing are illustrated in Figure 1. In steady, rotational testing the rotor moves continuously through a full 360° arc. Any structure that has formed in the fluid will initially stretch and then fracture, with the time frame over which this occurs dependant on shear rate and fluid properties (Figure 1a). In dynamic testing, however, the motion is oscillatory, with the rotor traveling through a very small arc (<< 1°). Because the angle of motion is at a strain within the linear viscoelastic region (LVR), the structure which has formed within the fluid first stretches as the rotor moves in one direction, returns to its initial state as the motion is reversed and then stretches by the same amount in the opposite direction. This oscillatory cycle provides the opportunity to measure fluid properties without breaking its inherent structure, thus measuring the contribution of that structure. An easy way to visualize an example of this type of motion is to picture a bowl of Jell-O™: when gently shaken it can be seen to wiggle but when shaken with greater force it begins to break apart. The strain at which the structure begins to break apart is the boundary of the LVR; thus, when conducting tests below this point the test is nondestructive and the properties of the gel structure can be measured.

Very different, yet complimentary, sets of data are obtained from rotational and dynamic testing. In rotational testing, such as with the FANN® 35A viscometer, flow in the annular gap between the rotor and bob results in a torque on the bob, read as a deflection in degrees. This torque is converted to a shear stress (for a FANN®-type viscometer, the deflection is equal to the stress in pounds per 100 square feet) which, along with the set strain rate, can be used to calculate the apparent viscosity of the fluid. For dynamic tests, which are conducted at constant strains, the same induced torque occurs and a stress can be calculated. However, rather than an apparent viscosity a complex viscosity, η^*, is calculated. If tests are performed within the LVR and no specific interactions between particles occur, then we would expect the complex viscosity at a given frequency, ω, to be identical to the apparent viscosity at a strain rate of the same value[11]. This is known as the Cox-Merz rule and usually does not apply to drilling fluids, with deviation resultant from the development of gel structure and colloidal interactions in the mud system. Because η^* does deviate from η, the two values can be compared and, by observation of the offset, a general conclusion drawn as to the extent of structural contribution to the viscosity. Such a dynamic frequency sweep should be conducted after initially shearing the sample to break down any structure and may include a controlled period of rest where the gel structure is allowed to reform.

In addition to viscosity information, dynamic tests allow for direct measurements of the viscoelastic nature of the sample. Drilling muds are complex fluids which behave neither as a simple Newtonian fluid nor as a Hookean elastic solid. The degree to which viscoelastic fluids behave in each of these manners can be determined from examination of G', the elastic or storage modulus, and G'', the viscous or loss modulus, which are components of the bulk modulus of the fluid. G' is representative of the elastic storage of energy within a sample and indicates the presence of solids and structure. G'' is representative of the viscous dissipation of energy and indicates the liquid-like behavior of a sample. The ratio of G'' to G' is $\tan(\delta)$, the loss tangent, and is an indicator of the structural dominance within a sample. When $\tan(\delta)$ is greater than one, the fluid is seen to be dominantly liquid-like and, conversely, when $\tan(\delta)$ is less than one the fluid is seen to be more solid-like. By examining the complex structure of these fluids, a better understanding of how and why certain physical phenomena (e.g. barite Sag, strong or weak gels, excessive shear thinning) can be reached and the systems better designed to mitigate problems or increase desired behaviors.

Rheology of Sample Drilling Fluids

The rheological behavior of six drilling fluid samples was investigated and is reported. The composition and FANN® 35A data for these different mud systems is detailed in Table 1 (water-based muds) and Table 2 (oil-based muds). Among the water-based muds, Fluid #1 is a typical lignosulfonate mud with bentonite clay as the primary viscosifier. Fluid #2 and Fluid #3 are more novel systems utilizing very small particle size (D90 < 1 μm) metal oxides as weighting agents with viscosification coming from xanthan gum. For the invert muds, Fluid #4 is also weighted with the small particle metal oxide used in Fluids #2 and #3 and additionally contains a polymeric viscosifier as well as organophilic clay. Fluid #5 is a field sample of a diesel-based mud and Fluid #6 is a traditional synthetic-based mud viscosified only by organophilic clay.

Rheological testing was performed on two instruments, a Rheometrics SR5000 stress-controlled rheometer and a Rheometrics RFS-III strain-controlled rheometer. In general, before testing, all samples were brought to a test temperature of 120°F and then presheared for two minutes at 1022 s^{-1} (600-rpm on a FANN® 35A) and the relevant test was immediately run. In the case of dynamic frequency sweeps, a rest period of 10 minutes was allowed after preshearing to allow the formation of a gel structure. The results of rotational rheological tests are presented in Figure 2 and Figure 3 while the dynamic rheological data are presented in Figure 4 and Figure 5.

Time Dependence of Drilling Fluids

The first thing to note in the investigation of drilling fluid rheological properties is the importance of shear history on the test sample. Drilling fluids are, to a small or large extent, time-dependent fluids due to the formation of gel structure, flocculation, emulsions, and other reasons. Time-dependent rheological behavior is generally referred to as thixotropy, a review of which can be found in a paper by Andrei Potanin[12]. A simple test to observe the degree of thixotropy in a sample is to perform a shear test where the shear rate is first increased to a maximum rate (up-sweep curve) and then decreased (down-sweep curve). When the up-sweep curve of a shear stress verses shear rate plot is above the down-sweep curve, the fluid is referred to as positively thixotropic. If the reverse is true, with the down-sweep curve above the up-sweep curve, the fluid can either be negatively-thixotropic or rheopectic, depending on other characteristics of the test sample.

The results of two such thixotropic loop tests for Fluid #1 are presented in Figure 2, with one test performed first on a sample immediately after preshearing and one test preformed after preshearing and a ten minute gel period. The shear rate was swept from 0 – 1200 s^{-1} over a ten minute period and then swept back to 0 s^{-1} over a second ten minute period. The curves for both the no gel and ten minute gel tests are similar in form, and in both cases the up-sweep curves lie below the down-sweep curves. This would indicate that Fluid #1 is either negatively-thixotropic or rheopectic. Further examination of the curves reveals that in the up-sweep curve of both tests there is initially a sharp peak in shear stress (which is more pronounced in the gelled test) after which the stress decreases significantly. This is indicative of the breakdown of structure that was formed within the fluid and would suggest that the sample is negatively-thixotropic, as a rheopectic sample would not exhibit this reduction in stress after mild shearing. It is of interest to note that the break in shear stress for the up-sweep curve exhibited in the gelled test is of significantly greater magnitude and results in a lower stress / rate curve than that of the sample when no gel time was allowed. This would indicate that the gel test was initially more structured than the test with no gel time, which would be expected, and that the induced structure was more completely broken after allowing this gelation time, a result that is not entirely expected.

In general, most drilling fluids exhibit a similar negatively-thixotropic behavior as does Fluid #1. The time-dependent behavior is less pronounced in fluids viscosified solely by polymeric additives, without the use of clays, but is still observed to be present in some small degree. In application, this is a very important consideration in conducting rheological tests. Differences in how a mud sample is prepared for testing on a lab or field viscometer, such as preshearing the sample before heating, shearing the sample in the heat cup while it comes to testing temperature, and the shear rate used and length of time over which the sample is sheared while coming to test temperature, can have a significant effect on the resultant viscosity curve. Such differences in measurement technique, which occur from operator to operator, lead to variability of reported properties and to an uncertainty of the true rheological behavior of a sample.

Rotational Rheometry

Rotational viscometry is the method by which all field rheological data of drilling fluids is obtained. For this reason, because all predictive models used in the drilling fluids industry are based on rotational rheological tests, it is important that the rotational rheometry of fluids be well characterized. It is also vital to understand the applicability and limitations of models based solely on rotational data, without the consideration of structural data obtained from dynamic oscillatory tests.

To this end, the rotational viscosity curves for the three water-based sample muds are presented in Figure 3a and the curves for the three oil-based sample muds presented in Figure 3b. Rotational viscosity curves were obtained after a two-minute preshear at 1022 s^{-1} and the strain rate was then swept downward from 1200 s^{-1} to 0.001 s^{-1}. There were a total of 25 data points obtained per decade of strain rate, with an equilibration time of 5 seconds and sampling time of 5 seconds allowed for each data point. For comparison, the complex viscosity curves obtained from dynamic frequency sweeps are presented on the same graphs. This procedure demonstrates the previously mentioned deviation from the Cox-Merz rule and the effect of structure growth on the viscosities of the fluids. Also seen on the graphs are two short solid black lines forming a window between 0.17 and 1.7 s^{-1}. This is the Dynamic Sag Window previously report by Dye, Mullen, and Gusler[13], which was empirically derived from flow loop tests of oil-based muds to represent a minimum viscosity level at which the probability of dynamic Sag occurring is acceptably low.

The first observation that can be made about the test fluids is that all of the fluids are shear thinning, with Fluids #1, #4, #5, and #6 having similar degrees of shear thinning while Fluids #2 and #3 are relatively less shear thinning. Additionally, the four fluids with greater shear thinning characteristics all pass through the Dynamic Sag Window. It should be noted that the three oil-based fluids (Fluids #4, #5, and #6) all exhibit a significant change in the viscosity curve in the region of 0.1 s^{-1} – 1 s^{-1}, resulting in a discontinuity in the curve. This discontinuity is due to the influences of wall slip, resulting from the highly lubricious nature common to invert emulsion fluids. Although this wall slip effect causes the apparent viscosity to drop outside of the Dynamic Sag Window, a corrected viscosity curve would not exhibit such a step change. Thus, from the correlation represented by the Dynamic Sag Window, these four fluids should exhibit a low probability of the occurrence of Sag.

Another observation which may be made is that the complex viscosity of each fluid is greater than the rotational viscosity. In the instances of the two metal oxide-weighted water-based muds (Fluids #2 and #3), this difference is small and might be an expected result for fluids which contain relatively little clay. However, in the case of water-based Fluid #1, the complex viscosity is nearly an order of magnitude greater and for the oil-base muds it is more than an order of magnitude greater. This difference between rotational and complex viscosity is indicative of the contribution of gel structure which is measured by the dynamic test. It is therefore reasonable to say that fluid viscosities at low strain rates may range between the rotational curve (where all structure is broken and does not contribute) to the complex viscosity (where structural contributions are included in the measured viscosity). Indeed, since the complex viscosity was measured after only a ten minute gel period, the true viscosity of the fluid that is experienced may be greater, depending on the progressiveness and strength of the gel.

While the low strain rate viscosity curves for Fluids #1, #4, #5, and #6 all fall within the Dynamic Sag Window and, from correlation with invert emulsion systems, would be expected not to exhibit Sag we see, both observationally and from dynamic investigation, that Fluids #1 and #5 do indeed have barite settling. Additionally, while Fluids #2 and #3 have a viscosity curve that is very much lower than the window, neither exhibits settling of weight material. (It should be noted that the Dynamic Sag Window was originally developed by correlation with a selection of invert emulsion fluids, and is not strictly applicable to water-based fluids, or even to all oil-based fluids.) The reasons for this will be more fully explained when addressing the dynamic testing of these fluids; however, it may be concluded that building fluid viscosity does not directly equate to prevention of the settling of weight material. This issue has been previously addressed with the general conclusion that clay viscosifiers, which better produce structure, are more effective at managing barite Sag in oil muds than are polymeric viscosifiers[4,5].

Dynamic (Oscillatory) Rheometry

To add to the understanding of the behavior and effects of gel structure formation on drilling fluids, it is necessary to conduct dynamic, or oscillatory, tests on the sample fluids. For reasons previously stated, tests were conducted within the linear viscoelastic region of each fluid. Results for dynamic frequency sweeps of the sample fluids are presented in Figure 4, where tests were conducted after a two minute preshear at 1022 s^{-1} and a ten minute gel period. Presented in each graph are the complex viscosity (the same as previously presented in Figure 3), G' (the storage modulus), G'' (the loss modulus), and tan(δ). For purposes of evaluating drilling fluids it is of interest to observe the complex viscosity in relation to the rotational viscosity and changes in the separation of G' and G'' with frequency. This separation of G' and G'' is of greater importance at lower frequencies where dynamic Sag is more likely to occur. Preferably, it is desirable to have G' remain dominant over G'' (or tan(δ) remain less than one) even at very low frequencies. The storage modulus may be elevated for two basic reasons in a drilling fluid: either there are increased solids in the fluid or there is increased structure in the fluid. Depending on the solids loading of a mud, the dominance of G' may indicate either a strong structural network which would effectively suspend solids or simply indicate the presence of solids dispersed in the mud.

It can be seen in Figure 4 that three fluids (Fluids #1, #5, and #6) exhibit strong dominance of G' over G'' while the three fluids weighted with the small particle metal oxide (Fluids #2, #3, and #4) exhibit little or no dominance of G' over the entire frequency range. The low dominance of G' in the metal oxide fluids is likely a result of the very small particle size of the weight material and because of little clay in the fluid to build a structured network. Fluid #4 exhibits the greatest dominance of G' of the three metal oxide weighted fluids, due to the use of organophilic clay as a viscosifier and to the effects of the emulsion. Fluid #5 shows excellent dominance of G' over G'' over most of the test region, especially when considering the low density of the fluid (i.e. low solids content); however, it also exhibits a rapid decrease in the G' dominance at very low frequencies indicating that problems with solids suspension may be observed.

From the dynamic frequency sweep we may observe interesting trends in structural behavior at various frequencies. When performing a dynamic time sweep, it is possible to observe the development and maintenance of gel structure over time. Dynamic time sweeps of the sample fluids are presented in Figure 5, where the fluids were first presheared at 1022 s^{-1} for two minutes and then a small strain (within the LVR) applied at a low frequency (below 1 rad/sec) for two hours. Although this test does not directly measure the gel strength in the fluid, by observing η*, G', G'', and tan(δ) over time it is possible to infer what changes are occurring in structural development and solids suspension. Typically, during gel growth for drilling fluids, the tan(δ) value will initially decrease sharply over the first few minutes, indicating the growth of structural dominance in the fluid, and then continue to decrease over the first 10 – 30 minutes before leveling out. The degree to which tan(δ) continues to decrease after the initial drop translates to what is normally referred to as the flatness or progressiveness of the gel. Once the initial gel structure is built, it is desirable to see that it is maintained over the duration of the test. Any major increases in tan(δ) or G'', or decreases in G' or η*, are notable and indicative of changes in gel structure and/or the settling of solids.

As previously mentioned, Fluids #1 and #5 exhibit settling of solids, despite both having high viscosities and strong gel structures. The answer as to why can be found in the dynamic time sweep results for these fluids. We see that for Fluid #1 (Figure 5a) there is initially a significant buildup of structure, as tan(δ) drops and G' increases significantly over the first ten minutes of testing. However, after approximately 80 minutes we see tan(δ) begin to increase due to an increasing G''. This would seem to indicate that, although a significant gel structure has formed and G' remains largely dominant over G'', the gel structure is beginning to break down. The continued dominance of G' is due more to the volume of solids in the system and less to any gel structure. In the case of Fluid #5 (Figure 5e) we observe that after 30 minutes, there is a rapid and significant decrease in G' and in η* that would seem to indicate the settling of solids (barite) in the system. Also, we observe that there was initially relatively little growth in G', indicating that little structure was built. Therefore, due to an insufficient gel structure, barite Sag was evident. In contrast to these two examples of Sag, Fluid #6 (Figure 5f) is a good example of a fluid which does not Sag. We see that within the first ten minutes there is an order of magnitude increase in G' and a very significant decrease in tan(δ). The gel structure which develops is well maintained over a long period of time, indicating stability without excessive, progressive gels.

When examining the dynamic time sweeps of the two water-based, metal oxide weighted fluids (Fluids #2 and #3) we can understand why these do not exhibit settling of weight material, despite the very low viscosity profiles of the fluids. In both cases, but more pronounced in the higher density Fluid #3, we observe that G' grows significantly over time while G'' quickly levels off after an initial increase. This is indicative of the growth of a structured network within the fluids, though not a gel network. In these fluids, the observed structure is more likely the result of colloidal interactions between the <1-µm metal oxide particles; thus the reason the higher density fluid exhibits the more pronounced growth of G' is due to the greater concentration of metal oxide particles. The third metal oxide weighted fluid (Fluid #4), which is an oil-based fluid, behaves significantly differently than the other five examples. In this instance, the fluid exhibits an initial increase in tan(δ) and decrease in G' which is then followed by a more normal structure growth period where tan(δ) decreases and G' increases. A full explanation for this phenomenon is not available; however, it may be theorized that a complex relationship exists between the metal oxide colloidal complex, the emulsion, and the polymeric viscosifier present in the fluid.

Conclusions

- Drilling fluids are time dependent, viscoelastic materials which are heavily influenced by their shear history.
- Rotational viscometry data is and will continue to be vital to the industry, but provides only limited information as to what occurs rheologically within a fluid.
- Dynamic evaluation of drilling fluids is increasingly important for understanding the structural behavior of fluids.
- Correlations for evaluation of phenomenon such as Sag are very useful but are limited in applicability to the scope of the original data set used in formulating the correlation. However, the use of dynamic testing and the evaluation of the viscoelastic structure is broadly applicable for any fluid system and gives a more clear picture of when and why phenomenon such as Sag occur.
- Modeling of the downhole performance of drilling fluids could be greatly enhanced by the inclusion of structural information, but would require the use of more complex constitutive equations in place of current viscosity models.

Nomenclature

ECD	=	*equivalent circulating density*
v_i	=	*velocity component in the* i^{th} *coordinate plane*
r	=	*density, g/cm*^{3}
W	=	*angular velocity, rad/sec*
R_o	=	*radius of the couette cup*
R_i	=	*radius of the couette bob*
g	=	*strain (deformation), %*
$\dot{g}$	=	*strain (or shear) rate, s*$^{-1}$ *or Hz*
w	=	*frequency, rad/sec*
t	=	*shear stress, dyne/cm*^{2} *or lb/100 ft*^{2}
h	=	*viscosity, Poise or cP*
LVR	=	*linear viscoelastic region*
*h**	=	*complex viscosity, Poise*
G'	=	*storage modulus, dyne/cm*^{2}
G''	=	*loss modulus, dyne/cm*^{2}
tan(d)	=	*loss tangent*

References

1. Lee, J., Friendheim, J., Toups, B. and van Oort, E.: "A New Approach to Deepwater Drilling Using SBM with Flat Rheology" AADE-04-DF-HO-37, American Association of Drilling Engineers Conference, Houston, April 6-7, 2004.
2. Dye, W. and Mullen, G.: "New Technology to Manage Barite Sag" AADE-02-DFWM-HO-12, American Association of Drilling Engineers Conference, Houston, April 2-3, 2002.
3. Aldea, C., Growcock, F.B., Lee, L.J., Friedheim, J.E., and van Oort, E.: "Prevention of Dynamic Sag in Deepwater Invert Emulsion Fluids" AADE-01-NC-HO-51, American Association of Drilling Engineers Conference, Houston, March 27-29, 2001.
4. Ahmadi, T., Zamora, M. and Power, D.: "Role of Rheology in Barite Sag in SBM and OBM" AADE-04-DF-HO-22, American Association of Drilling Engineers Conference, Houston, April 6-7, 2004.
5. Mullen, G., Perez, J., Dye, B. and Gusler, B.: "Coupling of Technologies for Concurrent ECD and Barite Sag

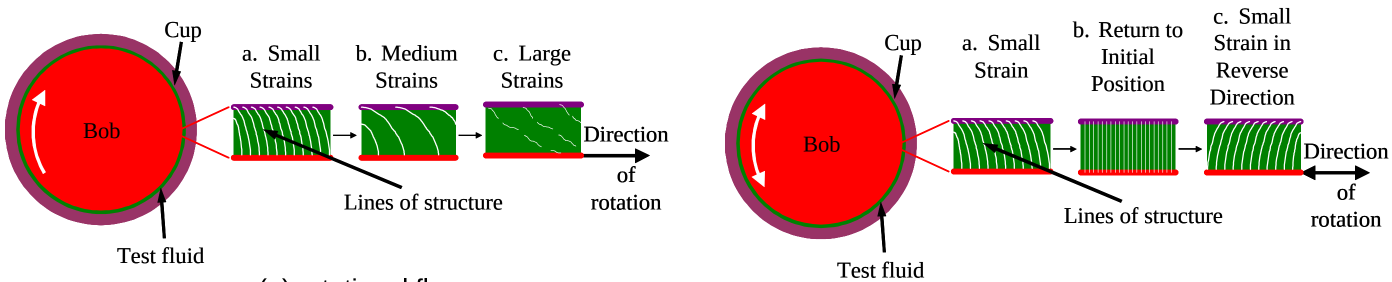
Management" AADE-03-NTCE-29, American Association of Drilling Engineers Conference, Houston, April 1-3, 2003.
6. Davison, J., Clary, S., Saasen, A., Allouche, M., Bodin, D., and Nguyen, V-A.: "Rheology of Various Drilling Fluid Systems Under Deepwater Drilling Conditions and the Importance of Accurate Predictions of Downhole Fluid Hydraulics" SPE 56632, SPE Annual Technical Conference, Houston, Oct. 3-6, 1999.
7. Zamora, M. and Power, D.: "Making a Case for AADE Hydraulics and the Unified Rheological Model" AADE-02-DFWM-HO-13, American Association of Drilling Engineers Conference, Houston, April 2-3, 2002.
8. Jachnik, R.: "Drilling Fluid Thixotropy & Relevance" Annual Transactions of the Nordic Rheology Society v. 13, 2005.
9. Gusler, W., Pless, M., Maxey, J., Grover, P., Perez, J., Moon, J., and Boaz, T.: "A New Extreme HP/HT Viscometer for New Drilling Fluid Challenges" IADC/SPE 99009, IADC/SPE Drilling Conference, Miami, Feb. 21-23, 2006.
10. Macosko, C.: Rheology: Principles, Measurements, and Applications, Wiley-VCH, New York, NY (1994).
11. Cox, W.P. and Merz, E.H.: "Correlation of Dynamic and Steady Flow Viscosities" Journal of Polymer Science v. 28, No. 118 (April 1958) 619-622.
12. Potanin, A.: "Thixotropy and rheopexy of aggregated dispersions with wetting polymer" Journal of Rheology v. 48, No. 6 (November/December 2004) 1279-1293.
13. Dye, W., Mullen, G., and Gusler, W: "Field-proven Technology to Manage Dynamic Barite Sag" IADC/SPE 98167, IADC/SPE Drilling Conference, Miami, Feb. 21-23, 2006.

Table 1 – WBM formulations and FANN® 35A data.

	Fluid #1	**Fluid #2**	**Fluid #3**
Sodium Chloride Brine, bbl	0.7814		
Potassium Formate Brine, bbl		0.9685	0.9459
Bentonite, lb/bbl	10		
Xanthan gum, lb/bbl		0.5	0.5
Lignosulfonate, lb/bbl	1		
Lignite, lb/bbl	0.5		
Caustic Soda, lb/bbl	0.5		
Carboxymethyl Cellulose, lb/bbl	1	2	1.5
Starch, lb/bbl		2	1
Calcium Carbonate, lb/bbl		10	10
Barite, lb/bbl	254.3		
Metal Oxide, lb/bbl		20.68	60.87
Drilled Solids, lb/bbl	27	10	10
Dynamic Aging, 16 hrs @:	**150°F**	**200°F**	**200°F**
Mud Weight, lb/gal	14	12.8	13.9
FANN® 35A 600-rpm @ 120°F	47	91	98
FANN® 35A 300-rpm @ 120°F	27	60	62
FANN® 35A 200-rpm @ 120°F	21	47	47
FANN® 35A 100-rpm @ 120°F	14	30	31
FANN® 35A 6-rpm @ 120°F	6	7	6
FANN® 35A 3-rpm @ 120°F	4	4	5
Plastic Viscosity, cP	20	31	36
Yield Point, lb/100 ft^2	7	29	26

Table 2 – OBM formulations and FANN® 35A data.

	Fluid #4	**Fluid #5**	**Fluid #6**
Base Fluid, bbl	0.6257	Field mud, no data available	0.616
Organophilic clay, lb/bbl	3.5		2.5
Polymeric Viscosifier, lb/bbl	2		
Emulsifier, lb	8		10
Potassium Formate Brine, bbl	0.1252		
Calcium Chloride Brine, bbl			0.175
Organophilic Lignite, lb/bbl	2		
Calcium Carbonate, lb/bbl	10		
Metal Oxide, lb/bbl	278.81		
Barite, lb/bbl			214.1
Drilled Solids, lb/bbl	25		27
Dynamic Aging, 16 hrs @:	**200°F**		**150°F**
Mud Weight, lb/gal	12.8	10.9	12
FANN® 35A 600-rpm @ 120°F	48	43	54
FANN® 35A 300-rpm @ 120°F	31	27	32
FANN® 35A 200-rpm @ 120°F	25	20	22
FANN® 35A 100-rpm @ 120°F	18	14	14
FANN® 35A 6-rpm @ 120°F	9	6	5
FANN® 35A 3-rpm @ 120°F	8	6	4
Plastic Viscosity, cP	17	16	22
Yield Point, lb/100 ft^2	14	11	10



(a) rotational flow

(b) dynamic flow

Figure 1 - Illustration of the differences between rotational and dynamic testing of fluids in couette flow.

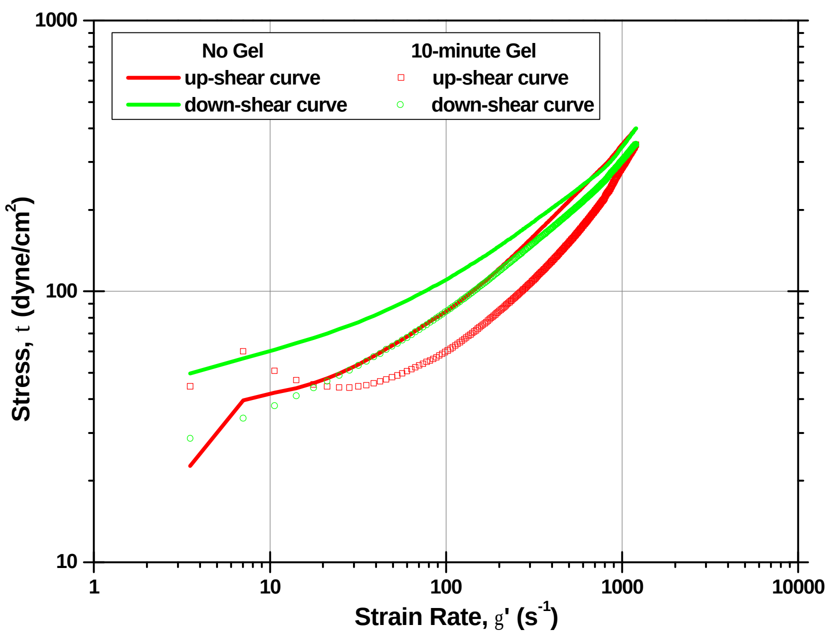
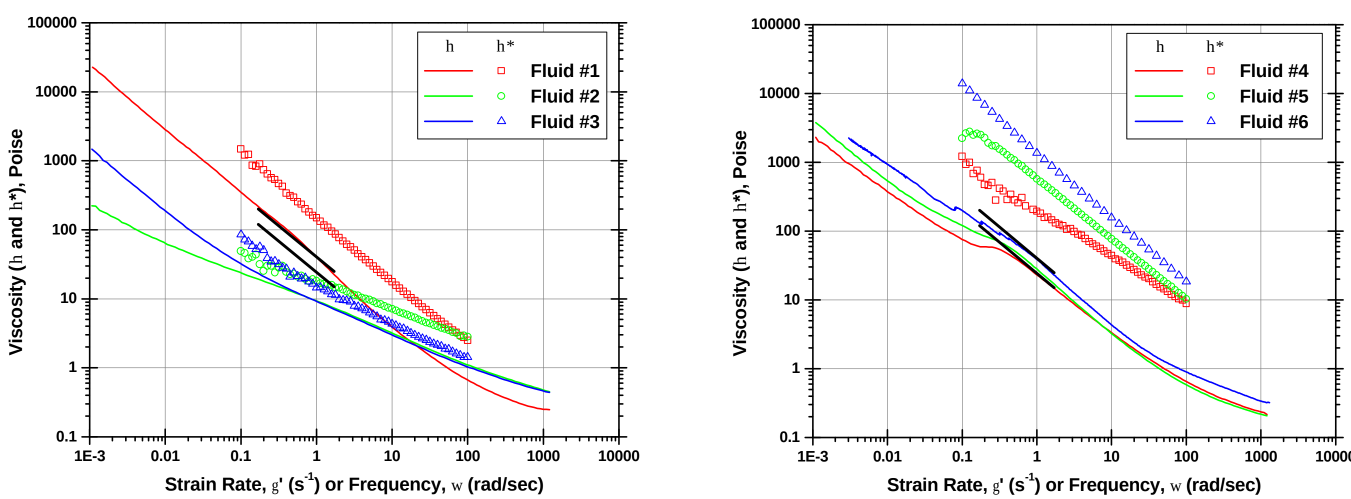


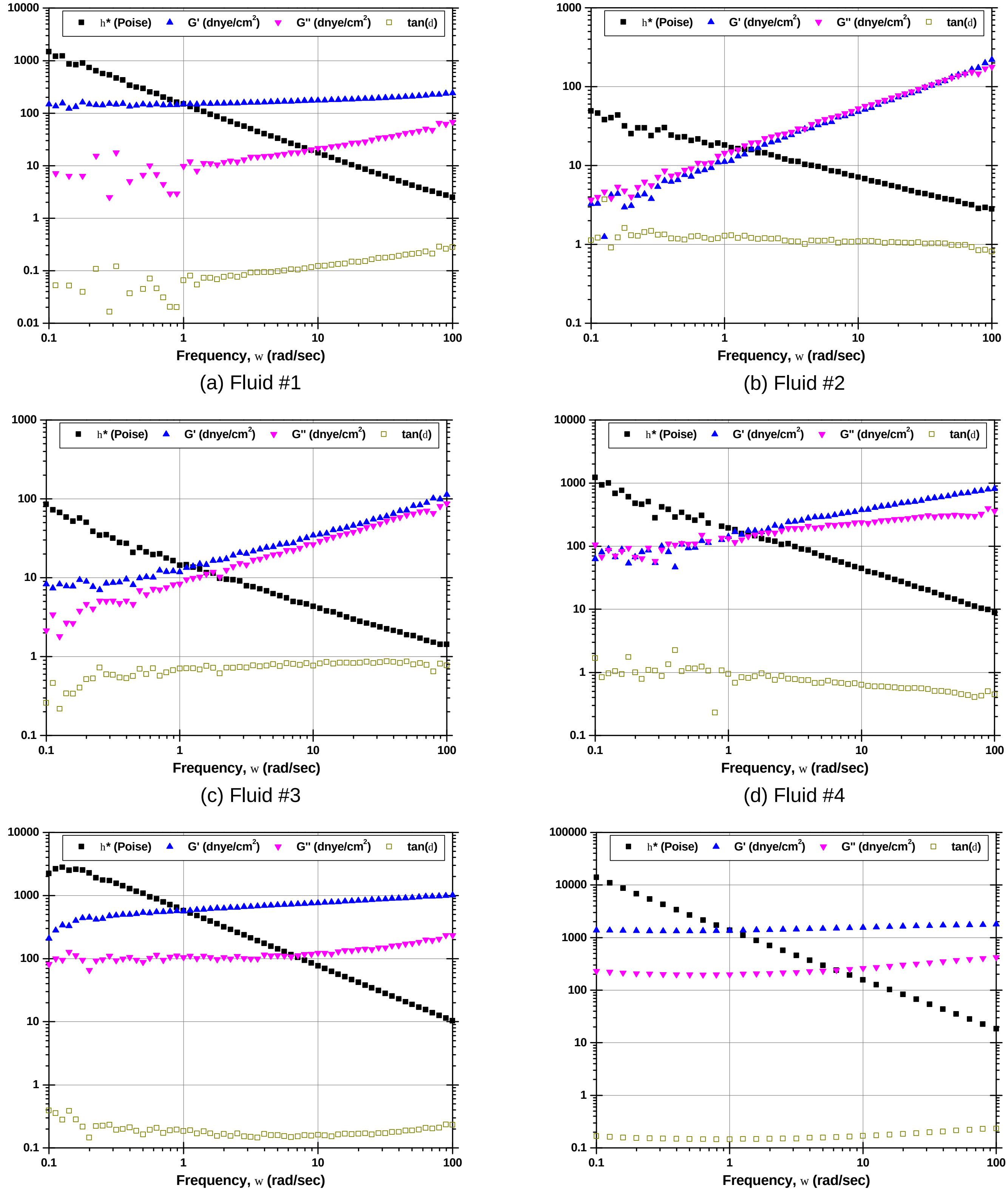
Figure 2 – Thixotropic loop for Fluid #1 at 120°F.



(a) Water-based muds

(b) Oil-based muds

Figure 3 – Rotational and complex viscosity curves for the sample mud systems at 120°F (solid black lines indicate the Dynamic Sag Window reported by Dye, Mullen, and Gusler[13]).



(a) Fluid #1 (b) Fluid #2

(c) Fluid #3 (d) Fluid #4

(e) Fluid #5 (f) Fluid #6

Figure 4 – Dynamic frequency sweeps at 120°F for the sample mud systems.

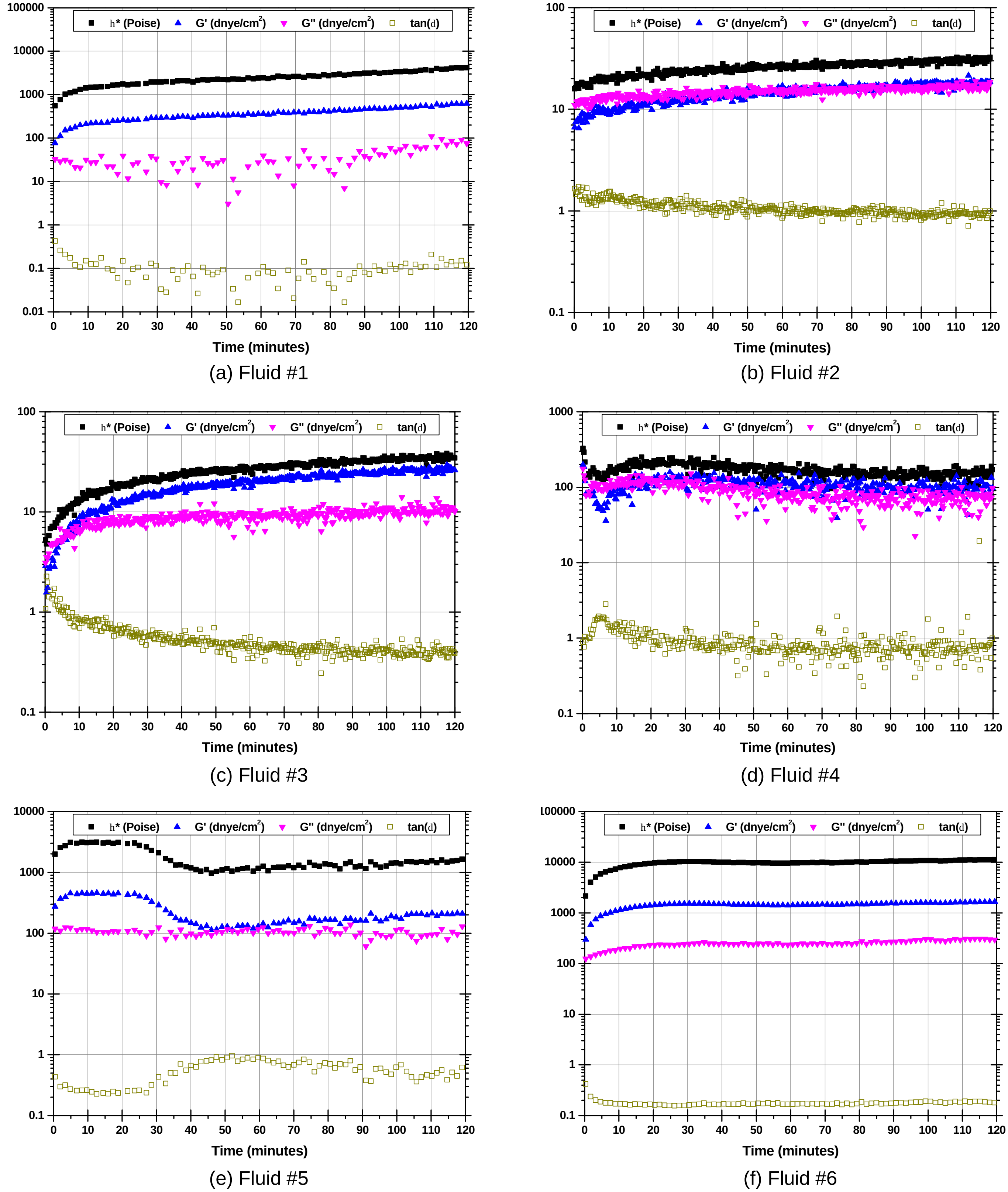


Figure 5 – Dynamic time sweeps at 120°F for the sample mud systems.