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"Improvised" Barite Sag Analysis for Better Drilling-Fluid Planning in Extreme Drilling Environments

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Abstract

Drilling fluids often require an optimized design to meet well-control challenges. Barite or weight-material sag is one such challenge in need of better tests/analysis. This paper focuses on a sag testing device, a dynamic high angle sag tester, and its modified application for analysing sag in drilling fluids. The paper is a continuation of previous work [1].

The sag testing device was used to measure the "dynamic" barite settling rate (mm/hr) under high-temperature (320°F) and pressure conditions at various shear rates. Contrary to standard test protocols employing an "ascending" shear rate sequence, this paper discusses the application of various modified shear rate sequences on the sag testing device to measure the dynamic sag rate of drilling-fluid samples. Sag rates measured at each particular shear rate from different shear rate sequences, including the ascending and descending sequences, were then compared. The observation from these modified tests—about the sag rate dependence on the fluid's shear history—was helpful in correlating test results to the observed sag behaviour in the field.

The sag rate information from the modified test protocol was also found to be responsive to changes in fluid formulations and aided in designing "low-sag" fluids. Along with conventional sag testing, rheological measurements, and operational practices, the improvised protocols employed on the sag testing device become powerful tools for designing "low-sag" fluids and understanding sag occurrence in the field. This type of comprehensive sag analysis could help stabilize drilling fluids in extreme high-pressure/high-temperature (HP/HT), harsher, deeper environments.

Introduction

Barite (or weight material) sag is a well-known term. It has been defined most appropriately by the API Work Group 3, formed under the aegis of API 13D subcommittee[2], as follows: "Weight-material sag is recognized by a significant (> 0.5lbm/gal) mud density variation, lighter followed by heavier than the nominal mud density, measured when circulating bottoms up where a weighted mud has remained un-circulated for a period of time in a directional well". It was noted that both drilling operational parameters and drilling fluid properties play significant roles in the occurrence of barite sag.[2, 3]

With regard to operational parameters, it is known that sag is often more prevalent in deviated holes (Boycott effect) and more specifically under specific dynamic conditions[3, 4]. This makes accurately measuring the "sag potential" of a fluid in the laboratory a more difficult task.

With regard to drilling fluid properties, several different measurements such as plastic viscosity (PV), yield point (YP) low shear rate viscosity, low shear yield point τ_0 and gel properties coupled with different static sag testing methodology have been used to estimate degree to which a fluid would sag[5, 6], but these have often proven unreliable indicators of sag, especially when applied to field conditions and observations.

Thus, there was a need to develop a method to accurately determine the degree to which a fluid will sag under specific dynamic and static conditions. In the recent years, the research focus has been towards finding appropriate equipments that can measure barite sag at the rig site. One such tool is the dynamic high angle sag tester that measures dynamic barite sag rate *U* (*mm/hr*) in an inclined tube where the fluid in the tube can be subjected to various shear, temperature and pressure conditions. Detailed information on this instrument has been presented earlier[7, 8] to predict weight material sag in terms of settling rate (*mm/hr*) under the given conditions of temperature, pressure and shear. The settling rate obtained from the dynamic high angle sag test is indicative of sag potential of the fluid under given conditions; data from the test has been used to investigate the effect of parameters like particulate size and concentration on sag response of the fluid[9, 10].

The objective of this paper is to provide a method to extract more reliable information from this dynamic test for different type of drilling fluids. The method is based on varying the shear rate sequences applied to the fluid; it was observed that the "low-sag" fluids vs. "high-sag" fluids response is significantly different on the basis of shear history.

Materials and Methodology

Fluids: Three different non-aqueous based drilling fluid samples were procured from field. The samples were labeled as Field Sample 1, 2 and 3. All these samples were invert emulsion drilling fluids with varying densities, oil/water ratio (OWR), barite type (standard API barite or extra-fine barite) and base oil type. **Tables 1-3** provide some of the basic characteristics of these fluid samples.

Table 1 – Field Sample 1 Properties

Mud weight, ppg	**16.5**
OWR	**85/15**
Base Fluid	**Paraffinic**
Barite type	**API barite**
ASG	**4.1**
Salt Conc. (wt %:)	**20%**

Table 2 – Field Sample 2 Properties

Mud weight, ppg	**16.7**
OWR	**80/20**
Base Fluid	**Paraffinic**
Barite type	**Fine barite**
ASG	**4**
Salt Conc. (wt %:)	**19%**

Table 3 – Field Sample 3 Properties

Mud weight, ppg	**16.3**
OWR	**81/19**
Base Fluid	**Paraffinic**
Barite type	**API & fine barite mix.**
ASG	**4**
Salt Conc. (wt %:)	**18%**

Static sag measurements: This test was used to determine severity of static sag in vertical conditions. The fluid capacity of the aging cells was 500 ml, having a length of about 16 cm and an inner diameter of about 6.3 cm. Approximately 1 lab barrel (350 ml) of the well-mixed drilling fluid was poured into the cell. The fluid was aged at specific temperature for given amount of time. Following the aging process, the fluid was cooled down. Any separated top oil was removed with syringe and measured. Then the top portion of the fluid was decanted off, leaving the bottom 2.5 cm of the fluid which is normally heavier than the initial fluid owing to barite settling. The density of this bottom portion of the fluid was measured by placing it in a pressurized mud balance cup. The difference between bottom portion mud weight and initial fluid mud weight was denoted as ΔMW**.** The method provided a reliable way of comparing static sag tendencies of the fluids.

Dynamic sag measurements: The dynamic sag tester measures the sag potential of a drilling fluid in terms of particulate settling rates (*mm/hr*) and further details on the instrument can be found in the earlier published literature[7, 8]. The tests can be carried out under static or dynamic shear conditions and at elevated temperatures and pressures as desired. The instrument consists of a tube filled with the testing sample (drilling fluid) as shown in **Figure 1**. The tube is set at an angle of 45° from vertical (an inclination which is known to cause severe barite sag conditions in the field). There is a rotating shaft inside the tube which shears the sample for simulating dynamic conditions in the field. The gap between the rotating shaft and the inside wall of tube is small and the average shear rate generated is estimated to be equivalent to 0.35 times the RPM of shaft. Hydraulic pressure is applied to pressurize the sample to desired level. The tube is simultaneously heated to raise the fluid temperature as desired.

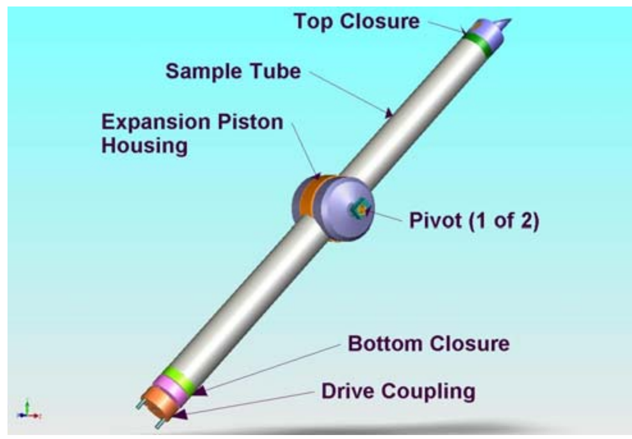

Figure 1: Schematic of the sag tube of dynamic sag tester.

Although the fluid is initially uniform, the particulates (barite) in the fluid start settling during the course of test and therefore, the center of mass of the inclined tube changes. The force required to maintain the tube in the equilibrium position is measured in terms of electrical signal. As more and more particulates (barite) settle, the amount of voltage required to maintain the tube in to equilibrium also increases. Finally, this voltage is converted into the rate of particulate settling (based on calibration data). Thus, as output, the dynamic sag tester provides sag potential of the fluid in terms of the particulate (barite) settling rate *U* in *mm/hr*. For settling rate calculations, the information on fluid composition parameters like density, OWR, percentage of salts, and type of base oil are also used.

For the purposes of the present work, the test on the dynamic sag tester was conducted by pressurizing the fluid to 2000 *psi* while the temperature (*T*) was maintained at 320 *F*. In a given test, the fluid is subjected to various shear rates in a sequence. One example of such shear rate sequence is [5, 10, 15] RPM. The fluid was maintained at each of these shear rates (e.g. 5 RPM) for a period of 3 hrs; the average settling rate or sag rate over this period of time is measured and it represents settling 'characteristic' of that fluid under give conditions. The test runs for about 11 hours (including 2 hours of warm up). The average shear rate is also recorded for the initial warm-up period. A number of tests were run on a given fluid sample under various shear rate sequences (each test starts with a fresh batch of the fluid) so as to investigate the effect of shear history on the test data. Representative data and results are discussed below.

Results and Discussion

Figure 2 presents data from the dynamic sag tester on Field Sample 1 under different shear rate sequences at *T = 320 F* and *P = 2000 psi*. In the first test, a shear rate sequence of [5, 10, 15] RPM was applied following the warm-up of the fluid to the desired temperature. The average sag rate at each of this shear rate interval was recorded and presented in **Figure 2** (black curve). The data indicates that the sag rate or settling tendency of the particulates in the fluid increases with increase in applied shear rate up to 15 RPM.

The second test was run on fresh batch of the same field sample 1 where a reverse shear rate sequence of [15, 10, 5] RPM was applied to the fluid at same *T* and *P* conditions. Figure 2 shows that although the shear rate sequence was reversed, the sag rate vs. shear rate (green curve) coincides with that of first test (black curve). Thus, the sag rate at a given shear rate remains independent of shear history of the fluid. This is a very important observation while extracting reliable information from the dynamic sag tester.

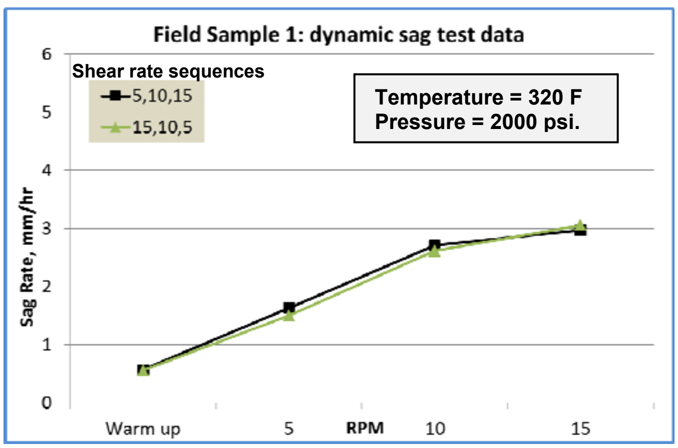

Figure 2: Comparison of the sag rate data for different shear rate sequences for field sample 1 at same T & P conditions obtained using the dynamic sag tester.

Figure 3 presents data from the dynamic sag tester on Field Sample 2 under different shear rate sequences at *T = 320 F* and *P = 2000 psi*. Similar to the earlier sample, two tests were conducted on this fluid with variations in the applied shear rate sequences: [5, 10, 15] RPM and [10, 5, 15] RPM. Figure 3 shows that although the shear rate sequence was altered, the sag rate vs. shear rate data coincides (blue and red curve). Again, the sag rate at a given shear rate remains independent of shear history of the fluid.

Figure 4 presents data from the dynamic sag tester on Field Sample 3 under different shear rate sequences at *T = 320 F* and *P = 2000 psi*. Three tests were conducted on this fluid with variations in the applied shear rate sequences:
[5, 10, 15] RPM, [10, 5, 15] RPM and [15, 10, 5] RPM. As shown in **Figure 4**, the average sag rate is high (≥ 5 mm/hr) in the *first* shear rate interval of *each* sequence (as marked by black circles). Then, for the consequent shear rates, the sag rates drop in all three tests; this might be interpreted as significant particulate settling happening in the *first* three hours (*first* shear rate interval) resulting in depleted fluid with a much lower number of particles available to settle in the following intervals. Thus, contrary to the first two fluids, the data for Field Sample 3 shows strong dependence on shear history. In other words, it suggests that data from only *first* shear rate interval can be reliable, i.e., truly indicative of the sag at that condition.

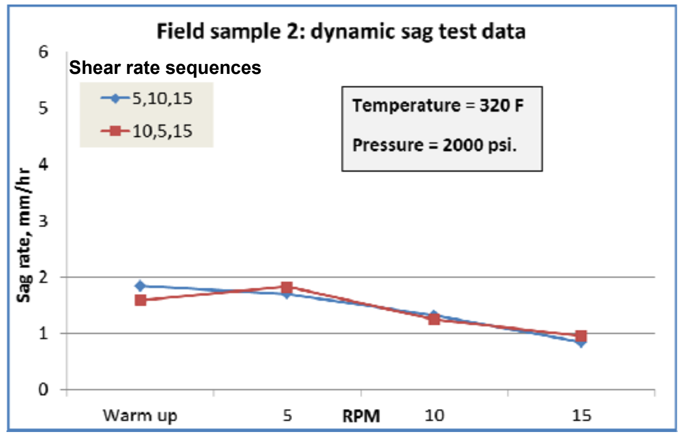

Figure 3: Comparison of the sag rate data for different shear rate sequences for field sample 2 at same T & P conditions obtained using the dynamic sag tester.

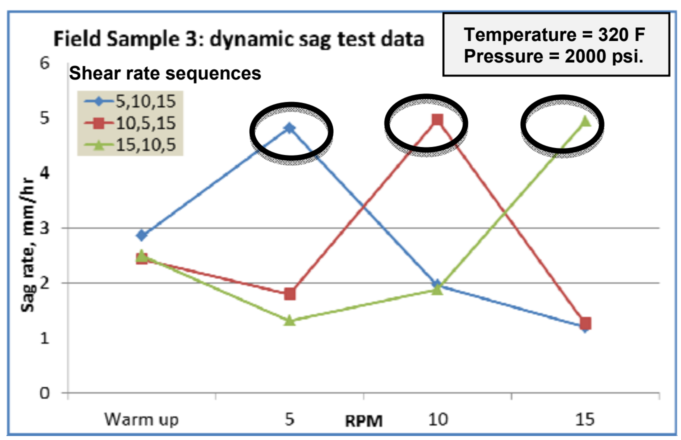

Figure 4: Comparison of the sag rate data for different shear rate sequences for field sample 3 at same T & P conditions obtained using the dynamic sag tester. The black circles mark the sag rate in the *first* shear rate interval of *each* sequence.

The above study shows that if the sag rate on the dynamic sag tester (at given shear rate) is <3 mm/hr, the consequent sag data is independent of shear history, i.e., data at consequent conditions in the shear rate sequence can be considered as truly indicative of sag potential at those conditions. We term these fluids as *low-sag* fluids (Field Samples 1 and 2) on the dynamic sag tester.

On the other hand, if the sag rate on the dynamic sag tester (at given shear rate) is $\geq$ 5 mm/hr, the consequent sag data is dependent of shear history, i.e., data at consequent conditions in the shear rate sequence is *not* useful as indicative of sag potential at those conditions. For such fluids, only the data collected up to the high sag rate situation is reliable. We term these fluids as *high-sag* fluids (Field Sample 3) on the dynamic sag tester.

Static sag measurements were performed on the field samples at 320 F with 16 hours of aging. Consistent with above dynamic measurements, the *low-sag* fluids on dynamic sag tester also showed lower settling in the static tests (Δ MW ~ 0.2 ppg). In addition, the *high-sag* fluids on dynamic sag tester correspondingly showed more settling in the static tests (Δ MW ~ 0.9 ppg) as shown in **Table 4**.

Table 4 – Dynamic and static sag properties of the field samples (at 320 F)

Sample Name	Static sag: 16 hrs aging Δ MW (ppg)	Dynamic sag
Field Mud 1	0.2	*Low-sag*
Field Mud 2	0.2	*Low-sag*
Field Mud 3	0.9	*High-sag*

Conclusion

- The above analysis based on altering the shear rate sequences could help to extract more reliable information from the dynamic sag tester device for different types of drilling fluids.
- The method showed that the "*low-sag*" fluids vs. "*high-sag*" fluids response on dynamic sag tester is significantly different on the basis of shear history.
- Dynamic and static measurements showed consistencies in the sag tendencies of the fluids.
- Such comprehensive sag analysis could help better designing drilling fluids for sag-prone high-pressure/high-temperature (HP/HT) and inclined wells.

Acknowledgments

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Nomenclature

OWR = *Oil to water ratio*
ASG = *Average Specific gravity*
ppg = *pounds per gallon*

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