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Detection Techniques Determining Weighting Material Sag in Drilling Fluid and Relationship to Rheology

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ABSTRACT

The most important issue in drilling operations is control of down hole pressures. To control these pressures, dense drilling fluid is one of at least two barriers preventing formation fluid or gas from entering the wellbore, causing a kick. Different types of particulate weighting agents are added to the drilling fluid to provide the desired density. To prevent particulate material from settling out of the drilling fluid causing instability, the rheological behavior of the fluid is of the outmost importance. No specific rheological parameter has yet been shown to be directly linked to the particle settling potential. This paper reviews different testing techniques available to detect the particle settling potential of the drilling fluid, and describes work performed to relate this to rheological properties. It also describes particular mechanisms affecting the settling rate during a drilling operation.

INTRODUCTION

Settling of weighting material in drilling fluids during drilling and completion operations can cause several problems. These range from having insufficient drilling fluid density for well control to fracturing the formation when re-suspending a weighting material bed. Additionally, the settling of barite may hinder the running of casing, as well as causing insufficient displacement efficiency during cementing operations. Settled weight material may also cause problems during completion operations.

Within the petroleum industry, the systematic study of the sag phenomenon started in the late 1980's. Hanson et al. [1] and Jefferson [2] focused on practical guidelines to prevent sag. They emphasized the importance of dynamic sag; i.e. sag occurring while drilling fluid is slowly circulating. They recognized that preventing dynamic sag is more difficult than preventing static sag. Further they discovered that the sag tendency is significantly higher in deviated wells than in vertical ones. This is due to a phenomena first discovered by the American physician A.E. Boycott [3], who noticed that blood corpuscles gravitates 3 to 5 times faster in inclined tubes that in vertical ones. This Boycott effect was found by all early investigators to be a major contributor to sag in drilling fluids. When the particles settle in the inclined pipe or annulus, low-density fluid is forced upwards while high-density fluid moves downwards along the low side of the hole. This creates a pressure imbalance, which accelerates the fluid motion and the separation process.

In the following different established sag testing methods are described as well as alternative techniques presently under development. Additionally, work investigating the effect of the drilling fluid's rheological properties on settling tendency is described.

SAG TESTING METHODS

For sag detection, several testing methods have been proposed. These range from simple methods using standard viscometers, commonly available in the field, to large-scale flow-loops with advanced instrumentation for extracting fluid parameters relevant for the sag performance. The following summarizes the methods used in the oil-field industry today with their advantages and disadvantages, and propose alternative methods used in other industries for detecting sedimentation potential. This includes techniques valid for testing of the basic physics related to sag, not necessarily considering their potential for use as a field test method.

Static sag testing

The most common method is to pour the drilling fluid into steel cells and then put it into a heating cabinet at set temperatures for a specified period of time. The density of the top and bottom segment of the fluid column is then measured and the sag tendency is expressed as the sag factor defined as:

$$SF = \left(\frac{MW_{bottom}}{MW_{bottom} + MW_{top}} \right)$$

where MW_{bottom} and MW_{top} are the densities of the fluid at the bottom and top of the cell respectively. A sag factor of 0.5 means a non-sagging fluid, while sag factors above 0.52 has been interpreted to potentially cause operational problems. This method is convenient for performing a large number of tests, but it is not simulating the operational conditions at low-shear-rates, which is most prone to provoke sag. The method is crude and gives problems with reproducibility. Neither does it take into account elements like syneresis, i.e. free liquid being displaced to the surface by the settling particles. One easily realizes that this is not a very accurate sag determination technique. Other expressions [4] have been proposed to accommodate for such effects comparing the bottom density to the initial one. However this method has proven difficult to implement and has not been adopted by the industry as a standard.

Viscometer Sag Testing

The Viscometer Sag Test(VST) was introduced as a low-cost practical on-site test [2] with the intention of reproducing the dynamic settling conditions and linking this to such standard viscosity measurements as the funnel viscosity (FV), yield point (YP) and the 100 rpm reading of a Fann 35 viscometer. One measures the density of the fluid at the bottom of the viscometer thermocup after been sheared for 30 minutes and compare this to the initial fluid density. This method is used as an indicator of sag, but the correlation between field and flow loop-data can only be said to be fair.
A modified VST field test using a sag "shoe" [5, 6] placed at the bottom of the viscometer cup to provoke sag, has been introduced to improve the reproducibility and sensitivity of the standard VST. The idea is that the sloping surface of the thermoplastic shoe helps to accelerate settling and to concentrate the weight material into a single collection well at the bottom of the thermocup. A computational fluid dynamics (CFD)-analysis was used in the design phase to compare the fluid dynamics of the standard VST and the modified version. The results from this method have been compared with results both with the VST and sag flow loop tests with promising results. For expressing the sag tendency, the "sag register" is used:

$$S_R = \left(-k \frac{\Delta MW}{MW} \right)$$

where ΔMW is the difference in drilling fluid density between two runs compared towards the initial density, MW, and k is a correlation constant fitted to 10.9 for the modified VST and 50 for flow-loop data. S_R value of 1.0 means no sag, while lower values indicates poor sag performance.

Low Shear Rate Viscometer

Using knowledge of the importance of ultra-low shear rate viscosty impact on weighting material sag, an instrument called the RJF viscomenter, has been developed that can illuminate this effect. As drilling fluids are shear thinning, the use of standard rheological models like Bingham, Power-law, Herschel-Bulkley etc. is not sufficient to predict the fluids' flow behavior at ultra-low shear rates. The RJF viscometer makes it possible to extend stanard viscosity measurements to shear rates below 2 s^{-1}. From this, a sag window is defined where one should operate within to avoid barite settling. Like for the VST and the modified VST, the preliminary investigation shows promising results for certain conditions while other conditions and other alternative weighting materials show poor correlation with reference to flow-loop measurements.

Sag Flow Loop

The sag flow loops makes the baseline for sag detection and is still considered as providing the most reliable data. The disadvantage of the sag flow loops are the need for sophisticated instrumentation, relatively large fluid volumes and space requirements, which makes them inappropriate for direct fluid optimization. Even with a flow-loop it is often hard to actually reproduce downhole conditions, due to limitations in reproducing temperature effects, hole geometries, effects from drill string rotation etc.
The first real flow loops for the oil industry were developed in the early 1990's [1] in conjunction with hole-cleaning studies, where sag was observed as an artifact in the tests. These initial tests also confirmed the belief that sag is a dynamic settling problem rather than a static phenomenon, and also confirmed the importance of the Boycott effect.
Many flow loops have since been built to improve the understanding of the sag phenomenon, and currently all drilling fluid suppliers, several oil field operators and universities can provide large-scale testing using flow-loops. Most of these are built with the possibility of inclining the casing to illuminate the Boycott effect. Tests run in the flow loops are often used as baselines when developing new sag stable fluid systems and as the final approval before applying in the field. However, the full potential for studying the basic mechanisms of sag may not have been fully exploited using the flow-loops. Applying more sophisticated and accurate monitoring equipment can aid this by providing additional information of how particles settle under different conditions.

High Angle Sag Test Device

In order to make a more suitable sized and accurate sag testing device, the HAST (High Angle Sag Test Device) [7] was developed. The instrument is designed to simulate sag at more realistic downhole-like conditions, also taking into account temperature, pressure, inner string rotation and hole angle effects. In the HAST a fluid sample is placed in a tube which is sitting on a pivot at specified angle and the sample is heated to desired pressure and temperature. The change in the center of mass of the sample is measured indirectly as a change in the torque about the pivots holding the tube in place. This torque is measured by energizing external coils such that the upper end of the tube and the shear shaft assembly are pushed back to their initial positions. As the weighting material settles the fluid sample's center of mass moves, and this is monitored and plotted as a function of time. The results is fitted a function of form:

$$X_{cm}(t) = \left(\frac{At}{B+t} \right)$$

These fit parameters both have clean physical interpretations. A is the maximum shift in center of mass and B is the time taken for the center of mass to reach $A/2$, i.e. the time for half of the material to have settled. Typically the correlation coefficients when using the HAST extend 0.95. It is stated that integrating this function with respect to time, gives the sag coefficient (SC) which indicates the total sag that has occurred within the time interval:

$$SC = \int_{t=0}^{t=1200min} X_{cm}(t)dt$$

The physical interpretation of this expression is not clear. If the movement in center of mass is zero, i.e. no sag, the SC will also be zero. Due to the limited volume and geometry of the cell, the SC has an upper and lower limit.

Ultrasonic measurements for sag detection

Ultrasonic techniques offer potential for fast non-invasive on-line monitoring of fluid properties, including the particle sedimentation potential. Other industries, especially the food industry, uses ultrasonic measurements for detection of density stratification in fluids or slurries. The principle of the technique is based on ultrasound signal reflection being dependent of the sound velocity of the base fluid, the density of the same, the longitudinal and transverse speed of sound in the material reflecting the signal as well as particle shape, size and concentration.

Fort et al. [8] used a single transmitter-receiver pair operating at one frequency to track slurry concentration in a vessel during mixing to define the homogenity. Shen et al. [9] worked with a similar system employing two opposing transducers to measure both the backscattering coefficient profile and the path integration attenuation a concentration with up to 47 kg/m^3 of glass spheres in water. Later research discovered some problems when using ultrasonic measurement techniques. For measuring at higher concentration as is typical for a drilling fluid (20-40 %V/V), Hipp et al. [10, 11] made a theoretical study as well as an experimental analysis to determine the signal disturbance occurring at high particle concentration. No linear relationship between concentration and sound attenuation exists due to multiple scattering or particle-particle interactions. Bamberger et al. [12] also recognized the difficulties in signal interpretation using ultrasound for concentration profiling, addressing several issues:

1. Viscous losses in the particle boundary layer in the host fluid
2. Volumetric expansion and contraction of the individual particles
3. Scattering of sound by individual particles caused by acoustic impedance mismatch between the host fluid and the particulate material
4. Thermal effects associated with contraction or expansion of either constituent
5. Particle sound attenuation properties

Bamberger's subsequently work [13] developed an on-line technique for monitoring mixing efficiency in a nuclear waste handling plant, where the density stratification expressed the mixing efficiency. Several ultrasonic sensors were placed in the mixing tank at different heights and solid concentration profiles were determined thereof. For these experiments solids concentration up to 50 $\%V/V$ were detected.
Using ultrasonics, density stratification in a closed vessel can be determined. The measurement accuracy is dependent of the particle concentration, but this can nevertheless be an alternative technique for sag potential determination, although the techniques is more difficult to use when the solids concentrations are high.

Direct weight measurement

Another alternative solid concentration profiling technique is using direct weight measurements [14]. This technique is based on Archimedes' principle of bodies immersed in liquid, providing an inexpensive field test differentiating the sag potential of various fluids. As shown in Fig.1, the device consists of two concentric cylinders, where the inner cylinder is attached to a laboratory scale which continuously

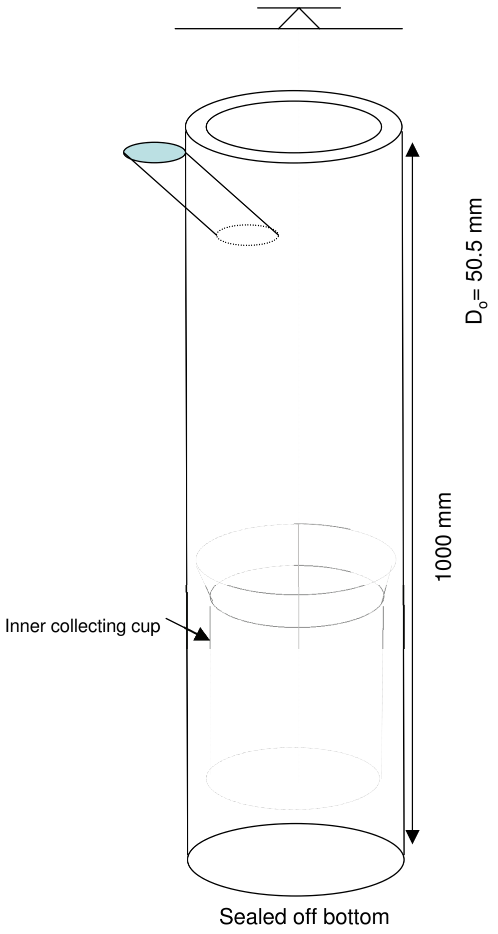

Figure 1: Sag testing device where the sedimenting material is collected in an inner cup and weighed using guitar string attached underneath a standard lab-scale.

monitors the weight of the settling material.

The method assumes the following:

1. Hydraulic communication of the fluid above and below the settling material
2. The accuracy is directly related to the measuring accuracy of the scale
3. Static surrounding conditions, though the system can be modified to accommodate dynamic situations

To validate the testing method, several experiments have been run. One experiment used two oil based drilling fluid being subjected to different shear energy and clay content, parameters which are known [4] to provide different settling potential. The results of this experiment are shown in Fig.2.

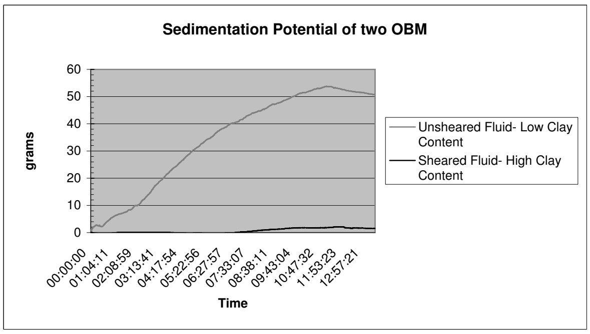

Figure 2: Sedimentation rate (gradient) of an oil based drilling fluid exposed to different degree of shear and having high and low clay content.

Experiments were also performed using two otherwise identical oil based drilling fluids which had two distinct different particle size distribution of the weighting agent. The results of these experiments are shown in Fig.3.

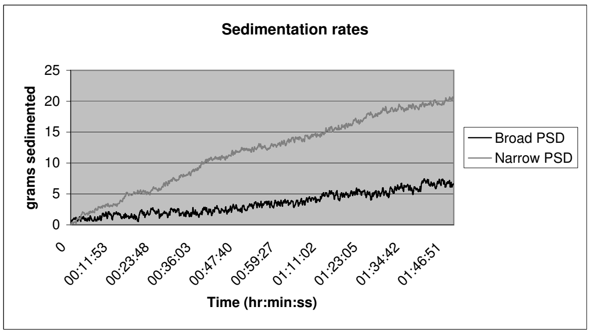

Figure 3: Sedimentation rate (gradient) of an oil based drilling fluid with two different particle size distributions of the weighting agent.

The basis for this approach is based on work performed [15] using force balance derived from the Bernoulli equation to develop a flux balance model to determine the settling rate of a poly and monodisperse solutions. The work showed the effect of particle size distribution (PSD) on the settling rate. Broadening of the PSD was observed to reduce the settling rate. Applying this knowledge to weight material sag, one finds that a narrow size distribution can increase the sag potential, something which was confirmed by the test performed using the direct weight measurement technique. The direct weight measurement can optionally include elements that mimic real operational effects. This includes elements like vibration, circulation, pressure, temperature, wellbore inclination, etc.

Sag detection using NMR

Nuclear Magnetic Resonance (NMR) is commonly used within the petroleum industry to determine petrophysical properties of the rock. Rismanto and van der Zwaag [16] used this technique for several purposes characterizing various fluid properties. One aspect of this work detected sag using a 1D profiling experiment. Like for the ultrasonic measurement, the technique offers the possibility of analyzing the fluid non-invasively. The technique is not affected by solids content as the ultrasonic techniques can be. It concerns the detection of nuclear spin precession under the influence of a strong magnetic field. In the work performed, the presence of the hydrogen nuclei causes responses making it possible to determine the solids content, i.e. density stratification continuously downwards in the sample cell as the solid material would give little or no magnetic response. The applicability of this technique has yet not been fully exploited, but will be a continuing work which at the moment shows significant promise for an alternative sag determination technique.

LINKING RHEOLOGY AND SAG

The critical shear rate when particles will start moving downwards in the fluid column, depends on the particle diameter and density as well as the suspending fluid's viscosity and density. This is governed by Stoke's law:

$$V_T = \frac{2Rg(\rho - \rho_0)}{9\eta}$$

where ρ_0 is the density of the fluid in which the particle is suspended in, ρ is the density of the particle, R the radius of the particle and η the base fluid's viscosity. This applies only for a single particle settling in a fluid and does not take into account particle-particle interaction, temperature effects etc. Nor does it take into account a polydisperse particle distribution, as in drilling fluid weighting materials.

Focusing on the viscosity parameter in Stoke's law, it was early realized that the attempts of relating standard viscosity measurements to sag performance was an inadequate approach. A study [17] investigating the relationship between plastic viscosity (PV), yield yoint (YP), 10-second gel strength and 10-min gel strength found that all of these parameters are poor indicators of sag. Saasen et al. [18], investigated the fluid's viscoelastic properties effect on weighting material sag, showing a significant better correlation than using the industry standard viscometer which is not measuring a true gel structure due to excessive shear rates. The question was raised wether a true gel structure exist for an oil based drilling fluid or not. To answer this, some approached the issue focusing on modeling of the fluid behavior applying different rheological models [19, 20]. Roberts et al. [21] worked with a significant number of various fluid fitting their behavior to different rheological models, e.g. Cross and Ellis, Bingham, Casson or Herschel-Bulkley. Through this approach one predicts that a yield stress exists for these fluids through the use of flow curves generated by up and downwards ramping of shear rates or shear stress.

Jachnik [22] used a similar stepped stress technique to determine the possible yield stress and the strength of the gel structure and stated that this was detected at a shear rate in the region of 1 e^{-5} to 1 e^{-2}. When the network is broken, creep tests showed that a permanent deformation of structure had occurred and that significant time was required to re-establish any structure. Taking a closer look at the gel structure, one realizes that it must be strong enough to overcome the gravity force exerted by the particle minus the buoyancy force. Saasen [23] determined the necessary strength of the gel structure to keep particles in suspension to be:

$$\tau_g \geq \frac{gD\Delta\rho}{6}$$

where $\Delta\rho$ is the density difference between the particle and the fluid in which the particle is suspended in and D is the particle diameter. The strength of the gel needed will depend on the base fluid and particle type, but more importantly of how the gel structure is created. There are generally two types of water based drilling fluids having two distinct different additives building gel structures. For a polymer based fluid, the gel structure can be relatively robust as the polymers form a strong network suspending the particles. For water based systems using clay minerals, the gel structure is weak and these fluids tend to be more prone to sag. The same is the case for conventional oil based drilling fluids.

Fard et al. [24] worked on determining the effect of different gel structures for various drilling fluids to distinguish the solid-fluid separation potential. When using clay as viscosfier in the water based drilling fluid, low or no gel strength were detectable using a Fann 35 viscometer when imposing vibration to the fluid. This is in correspondence with field experience where one has experienced several cases of sag in water based drilling fluid when using bentonite clay as viscosifier. The same applies for oil based drilling fluids where typically organophilic clays are used for viscosifying. In general oil based drilling fluids are significantly more prone to sag than water based polymer systems are due to the make up of these systems.

Fluid composition and operational effects

The objective when designing a new drilling fluid system is to minimize excessive pump initiation pressures and still maintain a stable fluid system. The focus is often on developing systems with fragile gels. In the future it will be essential to develop fluid systems that do not limit operational efficiency and compromise safety. As observed in the previous sections, much work has been performed to identify sag critical parameters. For the drilling fluid, focus has been on providing optimal rheological properties to hinder weighting material settling. Especially the use of different types of additives, like various organophilic clays, block copolymers, resins etc. and their effects on rheology and sag have been studied. The other constituents, like emulsifiers, additives for neutralizing electric surface charges, internal brine phase composition and different weighting agents, have to a certain extent also been studied.

Operational practices often dictates the degree of sag. Operational sequences related to nine sag incidents, given in Table 1 show that focus must be kept on avoiding low shear rates breaking whatever gel structure present. Trips to changer the bottom hole assembly (BHA trip) refers here to pulling the drilling string out of the hole and re-enter it with another tool. Running casing or liner refers to operations where one seals of the open hole section while re-drilling was due to operational problems potentially caused by the sag incident.

Table 1: Operational sequences related to nine different sag incidents.

Operation	**Trip**	**Casing run**	**Re-drill**
Incidents	3	5	1

This includes special awareness during casing running, wire-line operations or any low rate pumping. The effect of drill string and other vibrations' impact on settling rate has yet not been studied to any degree, despite laboratory experiments showing a potential effect. The impact from effective use of solids control equipment has to some degree been dealt with [14]. Solids control equipment can help remove undesired drilled cuttings which contribute to increasing the viscosity, but do not aid particle suspension. Having control of the shaker screen performance is also a prerequisite for knowing the particle size distribution of the material sent back into the well.

CONCLUSION

Due to the lack of a good sag testing technique for studying the basic mechanisms causing the settling, huge efforts have been made to optimize properties that have an impact on the sag performance. Establishing simple field and laboratory methods for sag detection is critical to establish a baseline for further work. Several methods show promise for obtaining this objective.

Focus on rheology has significantly increased our knowledge of how different drilling fluids build structure, but a single rheological parameter linking to sag performance has not been discovered.

The effect of different operational sequences has been studied through field cases, but these are often inconclusive due to lack of accurate data. Neither does one have a good picture of the complete operation, not knowing which elements are actually dominant for causing sag. In the meantime one needs to be alert when performing operations which experience have shown to provoke sag.

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