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Hindrance Effect on Barite Sag in Non-Aqueous Drilling Fluids

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Abstract

The phenomenon of barite sag requires better understanding, especially in non-aqueous drilling fluids (NAF) where it causes density variations leading to well stability issues. Sag is considered a dynamic phenomenon that can be severe in highly deviated and complex wells. Tackling this challenge calls for experimental/empirical methods to predict barite sag for different fluid compositions and well environments.

Hindered particle settling caused by presence of nearby particles is usually a strong function of particle concentration (φ) in the suspension. Empirical methods to predict hindered settling have been well established for suspensions with Newtonian liquids as continuous phase. Here, these empirical methods for hindered settling have been extended to NAF with varied barite concentrations (mud weights).

To develop the hindrance model, experimental data on sag rate *U (mm/hr)* in a NAF is obtained from the Dynamic High Angle Sag Tester (DST) at chosen conditions of temperature, pressure and shear rate. The sag rate represents average sag rate over a period of the initial three hours after the DST experiment begins, starting from a uniform suspension. The DST sag rate is obtained for a drilling fluid with initial uniform suspension having a reference barite volume fraction φ; using which the hindrance model predicts sag rates for other fluids with different initial barite concentrations. Predictions are in excellent agreement with experimental sag rates from the DST at the respective barite concentrations.

During the drilling process, the desired barite φ in the NAF may change as per equivalent circulating density (ECD) requirements. The hindrance model can predict sag behaviour at different φ using the DST data at reference φ, and it has been validated for a range of NAFs. The proposed hindrance model also provides sag flux ($U*\varphi$) vs. φ behaviour, explaining the increased severity of sag in a NAF with mud weight in the range of 12.5-13.5 ppg.

Introduction

The barite sag or weight material sag phenomenon is defined most appropriately by the API Work Group 3, formed under the aegis of API 13D subcommittee[1], 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". Mud weight variations have been reported to be in the range of 1.0 – 1.5 ppg. Both the drilling fluid properties and drilling operational parameters play significant roles and require appropriate monitoring/maintenance in controlling barite sag.

Weight material sag, can be broadly viewed as the settling of barite particles in a non-Newtonian drilling fluid under different mechanisms. The different mechanisms may include vertical settling of the weight material and/or sliding along inclined walls. After a long period of research on barite sag, subject matter experts tend to agree on the following factors that may lead to potential barite sag scenarios[1]:

- Barite sag is mostly a dynamic phenomenon, not static, noticed mostly in inclined wells (where Boycott effect comes into picture)
- Oil base drilling fluids tend to sag more compared to water based.
- Barite sag occurs in drilling fluids exhibiting "low" low-end rheology.
- Barite sag occurrence is associated with low shear environments or with low shear environments followed with longer static environments.
- Barite sag usually occurs while circulating with average annular velocities (AV) of 100 ft/min (0.51m/s) or less.

In the recent years, the research focus has been towards finding appropriate equipments that can measure barite sag at the rig site or lab and in developing numerical methods for predicting barite sag from rheology numbers (e.g. Fann 35 SA viscometer data). In this respect, many publications have reported that the viscometer sag shoe tester (VST) can potentially be used to predict barite sag from sag factor calculations. The DST is another tool that measures dynamic barite sag rate *U* (*mm/hr*) under controlled conditions using a specialized rotating shaft device to provide the low shear environment that can lead to barite sag under different temperature and pressure conditions. Work on DST has been presented earlier[2, 3] and to our knowledge, it is by far one of the best equipments available in the industry to predict weight material sag in terms of settling rate (*mm/hr*) under the given conditions of temperature, pressure and shear rates. The settling rate obtained from DST is indicative of sag potential of the fluid under given conditions. It is easy for a mud engineer to quantify barite sag in terms of settling rate rather than giving numbers like sag factors and then taking time to explain its relevance to barite sag.

Hindered Settling (Model)

The settling/sedimentation rate of an isolated particle (U_0) in a liquid where particle volume fraction $\varphi \approx 0$ (infinite dilution) is different from settling rate of the particle in a suspension made of finite particle concentration in the same liquid. In a suspension, the settling rate of the particle is affected by the surrounding particles owing to *hindrance* effect. The particle volume fraction φ strongly influences the particle settling rate U_φ (or *hindered* settling velocity) in the suspension. For a suspension with Newtonian liquid as continuous phase, the settling rate U_φ has been estimated in terms of U_0 and φ based on below empirical equation[4].

$$\frac{U_\varphi}{U_0} = (1-\varphi)^n \qquad \textbf{Eq. 1}$$

Under Stokes law conditions (low Reynolds number flow) n is reported to be *4.6*. **Eq. 1** may be rearranged to express U_φ as a function of the particle settling rate U_{φ_ref} in suspension with reference volume fraction φ_{ref} as

$$\frac{U_\varphi}{U_{\varphi-ref}} = \frac{(1-\varphi)^n}{(1-\varphi_{ref})^n} \qquad \textbf{Eq. 2}$$

Weight material sag, can be broadly viewed as the settling of barite particles in a non-Newtonian drilling fluid. This work attempts to extend above the empirical expression of particle settling in a Newtonian fluid to barite settling rates in drilling fluids. Although the drilling fluids are significantly non-Newtonian (shear thinning, yield stress behavior), it was found that they still obey **Eq.2.**

Consider a drilling fluid-set that has fluids with same base fluid composition (i.e., fluid composition without barite) while the amount of barite in the particle-phase varies to make the fluids of different mud weights. One of the fluids in this fluid-set is a reference fluid. For the reference fluid, the average sag rate U_{φ_ref} over a period of initial three hours, is obtained from the DST at a given temperature, pressure and shear rate conditions. With this sag rate information and Eq. 2, the sag rates U_φ may be predicted (under same external conditions) for other fluids of different mud weights in the same fluid-set. Note that the sag rate term here is characteristic of the fluid with initial uniform suspension; the density variation along the fluid column length as the settling continues is not discussed in this work.

As the density of the drilling fluid in the field is frequently manipulated to manage the ECD requirements, the above method will be helpful to predict the sag potential of different mud weight fluids (with the same base fluid composition) if the sag potential at one of the barite concentrations is known.

The information obtained from the DST along with the hindrance equation may also be used to identify worst sag conditions with respect to the drilling fluid mud weight. Using the sag flux vs. mud weight response, the worst sag condition was exhibited for NAF fluids with densities in the range of 12.5 ppg – 13.5 ppg, which is consistent with the widely observed condition for worst sag in the field.

Methodology and Experimental Procedures

Drilling Fluid Formulations

NAFs were formulated with commercially available mineral base oils, invert emulsifiers, lime, polymeric viscosifiers, high-pressure high-temperature (HPHT) filtration control agent, sized calcium carbonate (mean particle size 5 microns) and barite. Four fluid-sets *A*, *B*, *C* and *D* were prepared. The reference fluids present in each of these fluid-sets are *A1*, *B1*, *C1* and *D1* respectively. The reference fluids are 12.0-ppg organoclay-free NAFs that are formulated by varying OWR, additives and low gravity solids contents as shown in **Tables 1-4**.

The amounts of base oil, brine and weighting material used to formulate these fluids with the desired specifications are estimated as per mass balance. In each fluid-set, the drilling fluids are formulated such that they have same continuous phase and low gravity solids (LGS) composition as that of the reference fluid (i.e., same base fluid composition) in the respective fluid-set while the amount of barite is varied to obtain different mud weights. For example, in fluid-set *A*, fluids *A2* and *A3* have same base fluid composition as that of reference fluid *A1* (12.0 ppg) while the amount of barite is varied to get the fluid *A2* of 14.5 ppg and fluid *A3* of 10.0 ppg (**Table 5**). Fluid sets *B*, *C* and *D* are prepared in the same manner.

The fluids were mixed in stainless steel mixing cups on a five spindle multi-mixer model 9B with a rotational speed of 11500 RPM with sine-wave impeller blades. After mixing, the fluids were conditioned at 150 ^{o}F for 16 hours.

Table 1: 12 ppg reference fluid A1 (OWR = 65:35)

Component	Concentration, ppb
Base Oil (mineral oil)	As required
Emulsifier	8

Lime	1.5
200000 ppm CaCl2	As required
Fluid Loss additive	1.5
Primary Viscosifier	1.5
Inorganic Viscosifier	2
Calcium Carbonate - 5	10
Drill Solids	10
Barite	As required

Table 2: 12 ppg reference fluid B1 (OWR = 75:25)

Component	Concentration, ppb
Base Oil (mineral oil)	As required
Emulsifier	8
Lime	1.5
200000 ppm CaCl2	As required
Fluid Loss additive	2.5
Primary Viscosifier	3
Inorganic Viscosifier	5
Calcium Carbonate - 5	20
Drill Solids	20
Barite	As required

Table 3: 12 ppg reference fluid C1 (OWR = 80:20)

Component	Concentration, ppb
Base Oil (mineral oil)	As required
Emulsifier	8
Lime	1.5
200000 ppm CaCl2	As required
Fluid Loss additive	2.5
Primary Viscosifier	3
Inorganic Viscosifier	5
Calcium Carbonate - 5	20
Drill Solids	20
Barite	As required

Table 4: 12 ppg reference fluid D1 (OWR = 90:10)

Component	Concentration, ppb
Base Oil (mineral oil)	As required
Emulsifier	8
Lime	1.5
200000 ppm CaCl2	As required
Fluid Loss additive	2.5
Primary Viscosifier	3.5
Inorganic Viscosifier	5
Calcium Carbonate - 5	20
Drill Solids	20
Barite	As required

Testing on DST

The DST unit has been reported in previous publications[2,3] and it measures the sag potential of a drilling fluid in terms of settling rates (*mm/hr*) under dynamic shear conditions and at elevated temperatures and pressures. It usually consist of a tube which is filled with the testing sample (drilling fluid) and set at an angle of 45^0 with vertical, angle which is known to cause severe barite sag condition on the field. Inside the tube, there is a rotating shaft which shears the sample for inducing dynamic conditions. The gap between the rotating shaft and the inside wall of tube is small and generates shear rates equivalent to 0.35 times the RPM of shaft. The desired pressure is applied on the fluid sample and the tube is heated to maintain the desired temperature. As the experiment began with a uniform drilling fluid, the barite settles and hence, the center of mass of the tube changes. The force required to maintain the tube in the equilibrium position is measured in terms of electrical signal. As more and more barite settles, the amount of voltage requires to the tube in to equilibrium also increases. Finally, this voltage is converted into the settling rate of barite. Thus, as output, DST provides sag potential of the fluid in terms of the barite settling rate U in *mm/hr*. Sample parameters like density, oil water ratio (OWR), amount of salts, and type of base oil would be required as input for estimating the settling rate. In the present work, the pressure (P) on the fluid is 2000 *psi* while the temperature (T) is 150^0 F. An external shear rate of $\approx 5\ s^{-1}$ is applied. The measured settling rate is averaged over a period of 3 *hrs* after beginning of the experiment. The averaged settling/sag rate is reasonably considered to be a characteristic of the fluid with initial uniform suspension; note that the density variation along the DST tube as the settling continues is not discussed in this work.

The sag rate data obtained from DST will be used to validate the hindered settling model (Eq. 2) for drilling fluids in the below section.

Results and Discussion

The reference fluids in the fluids-sets *A*, *B*, *C*, *D* were 12 ppg fluids and had variation in terms of OWR ranging from 65:35 to 90:10 as shown in Table 5. The table also shows barite volume fraction φ in these fluids.

In addition, Table 5 presents DST sag rates U for the chosen reference fluids obtained at T = 150° F, P = 2000 *psi* and shear rate of 5 s^{-1}. These experimentally obtained sag rates along with Eq. 2 were used below to demonstrate the changes in the sag rate as amount of barite in the fluid changes.

Table 5: Experimental sag rates from DST for 12 ppg reference fluids with different OWR (*T* = 150° *F*, *P* = 2000 *psi,* shear rate 5 s^{-1})

Drilling Fluid	$\varphi = \varphi_{ref}$	Expt. U_{φ_ref} (mm/hr) [DST]
A1(OWR = 65:35)	0.14	3.5
B1(OWR = 75:25)	0.145	3.9
C1(OWR =80:20)	0.15	4.8
D1(OWR = 90:10)	0.16	5.9

Table 6 shows the DST sag rates *U* of the fluids (other than the reference fluids) in the fluid-sets *A*, *B*, *C*, *D*. The experimental sag rates matched against sag rate predictions that were obtained as follows using the hindrance method. Consider the fluid set *A*. The fluids in this fluid-set, *A1*, *A2* and *A3* have same base fluid composition (i.e., fluid composition without barite) while the amount of barite differs so that the mud weight varies as 12.0 ppg (*A1*), 14.5 ppg (*A2*) and 10.0 ppg (*A3*).

Table 6: Predicted (Hindrance model) and experimental (DST) sag rates for fluids in sets A, B, C and D (*T* = 150° *F*, *P* = 2000 *psi,* shear rate 5 s^{-1})

Drilling Fluid	φ	Predicted U_φ (mm/hr) [Hindrance model]	Expt. U_φ (mm/hr) [DST]
A2 (14.5 ppg) (OWR = 65:35)	0.22	2.2	2.1
A3 (10 ppg) (OWR = 65:35)	0.07	5.0	5.2
B2 (14.5 ppg) (OWR = 75:25)	0.23	2.4	2.8
B3 (10 ppg) (OWR = 75:25)	0.07	5.7	5.9
C2 (14.5 ppg) (OWR = 80:20)	0.24	2.8	2.6
C3 (10 ppg) (OWR = 80:20)	0.08	6.9	7.2
D2(14.5 ppg) (OWR = 90:10)	0.25	3.5	4.0

For the fluids *A1*, *A2* and *A3*, as the surrounding base fluid around the barite as well as the applied DST temperature, pressure and shear rate conditions are the same, only the changes in barite concentration φ induce the changes in sag rates (U_φ) in these fluids. Therefore, to predict the sag rate for the fluids *A2* and *A3*, the hindrance model (Eq. 2**)** along with sag rate data of the reference fluid *A1* may be used.

The U_φ for *A2* was predicted using Eq. 2, where $\varphi_{ref} = 0.14$ and $U_{\varphi\_ref} = 3.5$ *mm/sec* (fluid *A1*, Table 5) $\varphi = 0.22$ (fluid *A2*, Table 6) and $n = 4.6$ (as all the experiments satisfy Re <<1); with this information $U_\varphi = 2.2$ *mm/hr* for fluid *A2* was obtained, which closely matches with the DST experimental sag rate for *A2* as shown in Table 6. The same process was repeated to obtain and validate the sag rate prediction for the fluid *A3*.

In the same manner, the sag rates were predicted for the fluids in the fluid-sets *B*, *C* and *D* (Table 6) using Eq. 2 along with the sag rate data of the respective reference fluids as indicated in Table 5.

The Root Mean Square Error (RMSE) between the predicted and measured values of sag rates for the fluids presented in Table 6 is only around *0.3 mm/hr*; this error is within the instrumental error expected for the DST. Thus, even though the non-Newtonian characteristic of the NAF fluids was widely changed by changing the OWR from 65:35 to 90:10, it was observed that the hindrance method still holds and was able to predict the changes in sag rate as the concentration of barite changes.

As established above, the hindrance model (Eq. 2) successfully predicted the changes in sag rate as the barite φ (or mud weight) changes. Here, the hindrance model was extended further to plot U_φ vs. Mud Weight as shown in **Fig. 1** based on the reference data of fluid *A1* (Table 5).

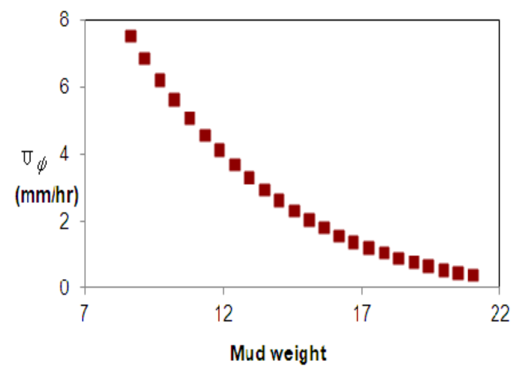

Figure 1: U_φ vs. Mud Weight based on hindrance model (Eq. 2) along with reference data of the fluid *A1*.

The plot in Fig. 1 shows predicted sag rates of the fluids having same base fluid composition as of *A1* while different barite φ to obtain variation in mud weight ranging from 9.0 ppg to 21.0 ppg. As expected, owing to the hindrance effect, the plot shows decline in the predicted sag rate U_φ as the mud weight (or barite φ) increases.

The above data in Fig. 1 was reorganized to plot (U_φ*φ) vs. mud weight as shown in **Fig. 2** which gave an useful illustration as described below.

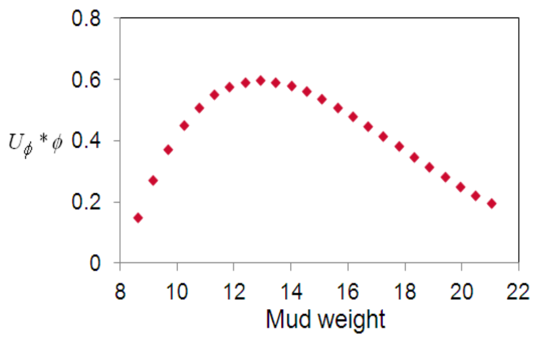

Figure 2: U_φ vs. Mud Weight plotted by reorganizing the data in Fig. 1.

The term $U_\varphi*\varphi$ represents barite mass flux or sag flux which is an obvious demonstration of sag severity under given conditions. In the recent literature on drilling technology, the sag flux response has been studied assuming that the fluid is Newtonian[5]; however the idea had not been extended to the actual drilling fluids by quantitatively incorporating the sag rate data. Here, the plot in Fig. 2 was generated by using the hindrance model (validated for NAF fluids) along with the actual sag rate information of a reference fluid *A1*. Fig. 2 shows that sag flux increases from 9.0 ppg to 12.5 ppg, stays almost steady between 12.5 ppg to 13.5 ppg while dropping further beyond 13.5 ppg. Thus, with the hindrance method it was quantitatively shown that NAF fluids exhibited worst sag condition in the density range of 12.5 ppg–13.5 ppg; this interpretation is consistent with the widely observed condition of worst sag in the field.

Conclusion

- Barite sag can be viewed as settling of particles in a non-Newtonian fluid under concentrated particulate environment.
- The hindrance model for Newtonian fluids under Stokes flow condition was extended to drilling fluids; based on the reference sag rate data from DST, the hindrance model successfully predicted changes in sag rate as the barite concentration (φ or mud weight) changes.
- The hindrance model was found to be applicable for NAF fluids even though the non-Newtonian characteristics (yield stress, shear thinning response) of the fluids were widely changed by changing the OWR and additive concentrations.
- Using the hindrance model, for the first time, it was quantitatively shown that the barite sag tends to be much more severe for fluids with mud weights in the range of 12.5 ppg -13.5 ppg which is consistent with the widely observed condition of worst sag in the field.

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Nomenclature

NAF -	*Non Aqueous drilling Fluids*
OWR -	*Oil Water Ratio*
U -	*Barite settling rate (mm/hr)*
U_0 -	*Settling/sedimentation rate of isolated particle in a liquid with infinite dilution*
U_φ -	*Settling/sedimentation in a suspension with particle(barite) fraction* φ
U_{φ_ref} -	*Settling/sedimentation in a suspension with reference particle(barite) fraction* φ_{ref}
$U_\varphi*\varphi$ -	*Barite Mass flux or Sag Flux*
φ -	*Particle (barite) volume fraction or concentration*
φ_{ref} -	*Reference particle (barite) volume fraction*

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