Taming of the Shoe

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Abstract

The VSST (Viscometer Sag Shoe Test) is part of a long list of simple, inexpensive drilling fluids measurements used to monitor complex well behavior at the wellsite, which in the VSST case is barite sag. Issues have arisen regarding its use and interpretation, especially when comparing VSST results with field data. Ultimate success, understandably, depends on proper interpretation of results with due consideration and appreciation for the limitations exacted by the simplicity and low cost of the test equipment.

The primary focus of this paper is to address certain contentious issues related to the VSST and provide practical guidelines for maximizing its use to monitor a fluid's ability to mitigate barite sag. Design specifics of the Sag Shoe insert used in the VSST also are discussed to clarify test protocols and to deal with the few misconceptions that could undermine the test value.

Introduction

The definitive measure of barite sag is made in the field. It is recognized during drilling operations as a significant (> 0.5 lb/gal) drilling fluid density variation, lighter followed by heavier than the nominal fluid density. This is measured when circulating bottoms up, where a weighted fluid has remained uncirculated for a period of time in a directional well *[Bern, et al. 2010]*. For good reason, however, several wellsite and lab tests have been developed over the past two decades to better understand the phenomenon, to help identify and monitor key parameters, and to improve drilling fluid formulations. Fit-for-purpose flow loops generally are considered the best equipment to simulate and study barite sag, but they simply are neither practical nor cost-effective for wellsite use or for repetitive lab tests required for evaluation and screening.

The subject of this paper is the VSST (Viscometer Sag Shoe Test), a recent example of simple, inexpensive drilling fluids measurements used to monitor complex fluid behavior at the wellsite. The VSST *[Zamora and Bell 2004]* is an improved version of the VST (Viscometer Sag Test) *[Jefferson 1991]* introduced to roughly quantify barite settling in a dynamic drilling fluid. The VST was developed soon after barite sag was first recognized as primarily a dynamic settling problem followed by subsequent static settling and slumping *[Hanson, et al. 1990]*.

Functionally, both the VST and VSST determine the density increase at the bottom of a small container after consistent shearing of the test fluid. The major difference between the two devices is the sag "shoe" insert used in the VSST. This low-cost modification helps improve consistency, sensitivity, and accuracy of the standard VST. Additionally, it can provide a measure of sag bed re-suspension efficiency to assist with operational decisions prior to tripping out of the hole when barite sag is a possibility.

The VST has had its share of supporters over its 20-yr life (perhaps because it has been one of the very few sag tests available for wellsite use), but the VSST is gaining in popularity. If all goes according to plan, the VSST should soon achieve status as a standard API practice *[Bern, et al. 2010]*, but not without some level of controversy. Even the move from the VST to the VSST has been a matter for discussion, given that VSST values, by design, are always higher.

The ultimate success of any drilling fluid test depends on proper interpretation of results with due consideration and appreciation for the limitations exacted by its design. True to form, the fluids industry continually demands tests to be performed quickly and with simple, cheap, and robust apparatus. And when this is achieved, it sometimes searches for short cuts and results that can extend beyond the main purpose of the test. The Marsh funnel, a good case in point, still has detractors despite its longevity (>80 yrs), its ASTM-standard status, its universal use, and its ideal design for wellsite statistical process control. At least no one would ever consider directly correlating funnel viscosity and a pressure-while drilling measurement. The venerable funnel simply measures a fluid property, much like the VSST does. While the VSST will never achieve the level of acceptance of the Marsh funnel, it should be recognized for what it measures and for how the results correlate with field sag measurements.

The primary focus of this paper is to address certain contentious issues related to the VSST and provide practical guidelines for maximizing its value to monitor a fluid's ability to mitigate barite sag. The goal is not to provide extensive test results and detailed case histories. Design specifics of the Sag Shoe insert used in the VSST also are discussed to clarify test protocols and to deal with several misconceptions that could undermine the test value.

Design by Boundaries and Limitations

The VSST designation is derived from the rotational viscometer that provides the dynamic environment and the

Sag Shoe insert designed to intentionally concentrate settled weight material in a small area in the bottom of a standard API viscometer thermocup. The latter is unlike the original VST in which the barite particles tend to agglomerate directly underneath the bob and are difficult to sample *[Zamora and Bell 2004]*, giving rise to lower bed density measurements when compared to the VSST.

The VSST makes liberal use of equipment readily available in a standard mud kit (**Fig. 1**), except for the digital balance required to determine sample density. It should be noted that the VG meter is used primarily as a mixer to provide a consistent shear environment for the test procedure. The thermocup permits heating the fluid sample to a standard temperature (120°F recommended) to consider thermal effects on fluid viscosity.
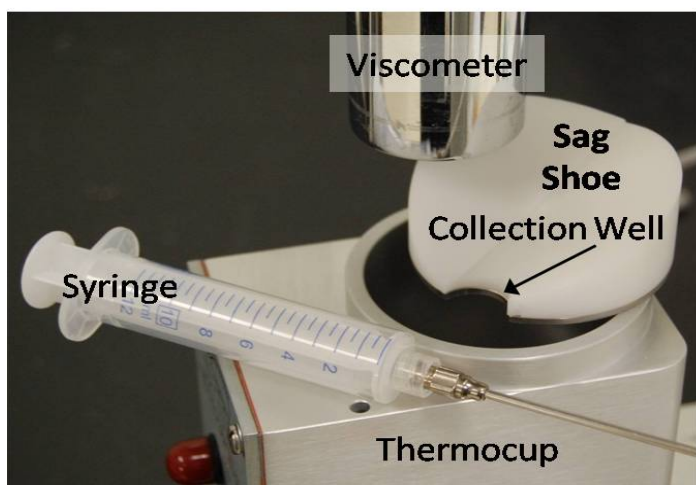

Fig. 1 - Test equipment required for the VSST, excluding the digital balance required for determining sample density.

The Shoe is machined from a thermoplastic resistant to water, synthetic and oil-based drilling fluids at temperatures up to the 200°F maximum recommended by the API for use with a VG meter. Physically, its diameter is 2.35 in., the maximum size that still permits easy insertion and removal in a standard API thermocup. It weighs 106 g with the steel plate attached to the bottom that was later added after it was noted that the Shoe could float in very dense fluids. The maximum height of the Shoe is 1.125 in. along the edge, compared to the 3.5-in. depth of the thermocup. On occasion after extended use, the Shoe can tend to stick in the heat cup, so it should routinely be cleaned and maintained.

The Shoe design is very much constrained by the physical boundaries and limitations of the geometry of the viscometer and thermocup equipment. The maximum fluid capacity of the thermocup is 250 mL and the displacement of the Shoe is around 43 mL. The recommended test fluid volume is limited to 140 mL to minimize spillage when rotating at the 600-rpm speed used for mixing and for the bed pickup test. These volumes only work out if the bottom of the VG meter sleeve is set 7 mm above where the sleeve touches the top of the Shoe. As a matter of fact, repeat VSST measurements on a fluid that

had been evaluated previously showed dynamic sag values considerably higher than before. On detailed examination, it was noted that the gap between the bottom of the sleeve and the Shoe inadvertently had been set to about half of the recommended distance. Correcting the gap to 7 mm resulted in a significant improvement in the results.

The upper surface of the Shoe consists of two inclined hemispherical sections separated by a small "lip" (**Fig. 2**) that discourages settled barite from being recirculated during the sag-deposition phase. Surface "A" has the desired curvature, but surface "B" in the figure is flat because of manufacturing limitations. Both surfaces would be curved in the preferred design. The lip separating "A" and "B" is not so high that it will prevent bed pickup at the high viscometer speed used during the optional bed pick-up phase. The complex surface, the result of CFD modeling and visual experimentation, facilitates settling and helps concentrate the settled weight material into the "collection well" at the bottom of the thermocup as suggested in **Fig. 1**. The half-moon "collection well" provides a singular location for collecting and sampling the barite bed using the syringe fitted with a blunt cannula. This not only improves consistency, but also permits reinjection of bed samples and measurement of the fluid's ability to pick up a sag bed out of the collection well, even though the re-injected bed may not adequately resemble the original. Alternatively, the two tests can be combined, but skipping the sampling between the two tests. Nevertheless, the pick-up option can serve as a reminder that most barite beds can easily be fluidized, as demonstrated in the field by slumping downhole and removal when circulating bottoms up.
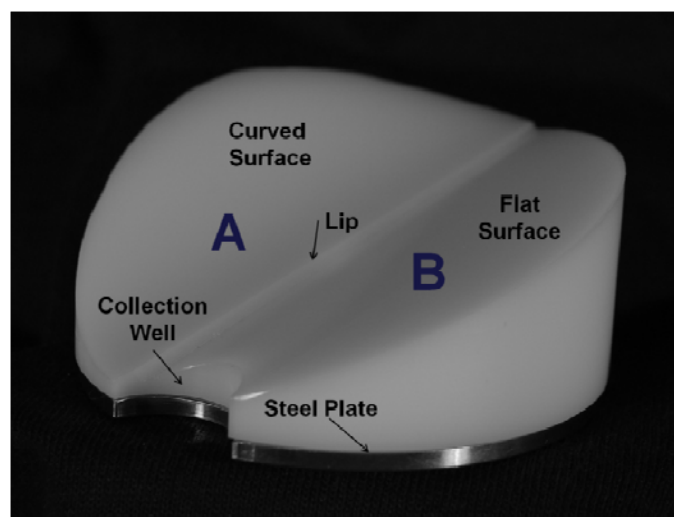

Fig. 2 - Close-up view of the Sag Shoe. Curved-surface "A" and flat-surface "B" are separated by a small lip designed to capture and guide settled weight-material particles to the collection well.

Increasing the 20° slope of the Shoe lip clearly would increase the slumping rate along the top and perhaps result in a higher bed density, but the increased displacement of the Shoe unfortunately would disrupt the balance of the different volumes described earlier. Some have asked for an inclination

around 45° to better simulate Boycott settling, but the VSST geometry has very little to do with the well-known settling phenomenon illustrated in the comparison in **Figs. 3a-3b**. At best, the VSST measures under dynamic conditions the vertical settling velocity v_0 during hindered settling (**Fig. 3a**) and Boycott settling (**Fig. 3b**). The contribution of v_0 to the kinetic model for Boycott settling (named the "PNK model" for its developers) is seen in the following equations:

$$S(t) = v_0 \frac{b}{\cos(\alpha)}\left[1 + \frac{H}{b}\sin(\alpha)\right] \qquad Eq.\,1$$

$$\frac{dH}{dt} = -v_0\left[1 + \frac{H}{b}\sin(\alpha)\right] \qquad Eq.\,2$$

S(t) in **Eq. 1** is the effective settling rate (the volumetric rate at which clarified fluid is accumulated per unit depth) which is proportional to v_0, the particle settling velocity ("slip velocity") in the suspension; α is the inclination; H is the suspension height; and b is the distance between the plates. In **Eq. 2**, dH/dt is the rate of change of the suspension height with respect to time.
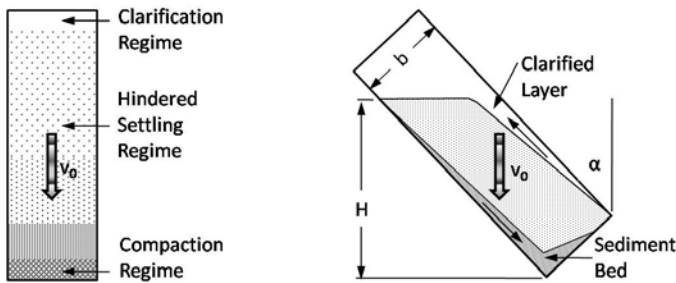

Fig. 3 – (a) Hindered and (b) Boycott settling comparison, highlighting the role of the (dynamic) settling velocity which is inherent in the VSST design.

Running Shoe - VSST Procedure Issues

The basic VSST test procedure involves inserting the Shoe and then heating 140 mL of weighted drilling fluid in the thermocup to the 120°F test temperature. The data in **Fig. 4** raised an alert that most consistent results are obtained if the starting fluid temperature is close to the test temperature to minimize settling during heating. The low viscosity invert-emulsion mud (IEM) formulated in the lab to help evaluate the effectiveness of different additives created a bed 1.5 lb/gal greater that its initial 13.0-lb/gal density during a 10-min warm-up period. Various treatments significantly reduced the premature barite settlement. Rather than being a VSST weakness, the Shoe in fact demonstrated a potential issue when heating up a low-viscosity, weighted mud even for rheological testing. To ensure consistency, pre-heating should become part of the procedure if possible.

The sag bed is sampled from the collection well after 30 min with the VG rotating at 100 rpm. This speed is used strictly for practical reasons, since the next lower speed (6 rpm) available on standard 6-speed field viscometers could be insufficient to prevent gel formation that could skew the results. The 100-rpm setting has been a concern even with the original VST because of the implied high shear rate of 170 s^{-1}. However, this shear rate is between the rotating sleeve and bob (approximately 7% of the test volume); the nominal shear rate for the bulk of the fluid contained between the sleeve and the thermocup is 39 s^{-1}. This duality in shear fields is not ideal, but it is a result of the boundaries and limitations of the equipment design.
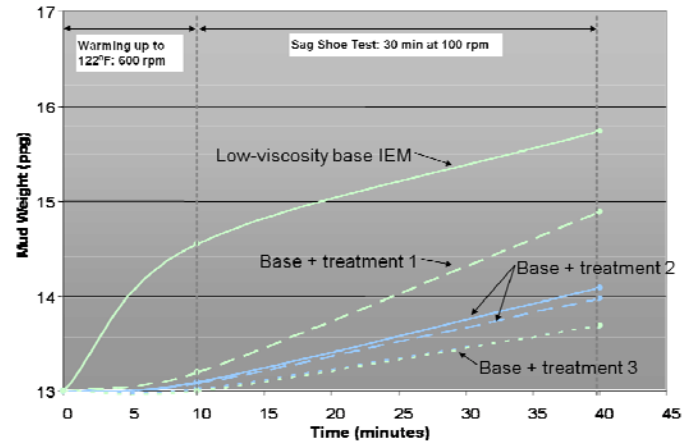

Fig. 4 - VSST results demonstrating that weight material can settle in a thermocup during the warm-up period.

A 10-mL sample is extracted by the syringe after the 30-min period. Arguably, the time could be reduced to maybe 15 min, but resolution could suffer. The 30-min test period for the VSST is a carryover from the VST. Even the sample size has come under question. Some have suggested using a 20-mL sample size to reduce error. However, the higher sample volume significantly dilutes the sag-bed density and somewhat defeats the purpose of concentrating the barite settlement.

After sampling the bed using the syringe, most lab personnel prefer using a pycnometer to determine the density because of speedier air-bubble removal and accuracy. Most field personnel are okay with weighing the filled syringe and accepting any small errors in determining the density. The density measured at the beginning of the test is the base density (MW_1); the density of the second sample taken from the collection well at the bottom of the heat cup after 30 min of shear is the density of the sagged weight material (MW_2). The difference in the two ($MW_2 - MW_1$, or maximum minus nominal mud weight) known as the B_{VSST} is comparable to the maximum-minus-nominal mud weight definition *[Bern, et al. 2010]* of field sag that will be specified by the API. However, the density difference from the VSST is related only to fluid properties without regard to the conditions under which the fluid has been or will be used in the field. As such, adjustments are required in order to permit reasonable comparison to field data.

For the optional bed pickup test, the 10-mL sagged weight-material sample in the fluid-filled syringe is first gently re-injected into the collection well. After running the viscometer at 600 rpm for 20 min, a new extracted sample is weighed and converted to density (MW_3). The fraction of the sag bed re-

suspended by the higher shear rate is calculated and reported as R_{BPU} (%). The goal is to determine how easily a barite bed might be removed by high circulation rates and even pipe rotation. However, lack of reports from the field suggests that the test is not run that often, so benefits have not materialized as hoped. As such, it remains an option.

Matching Up with Field Results

Perhaps the most prevalent issue with the VSST is related to direct correlation with field results. Some researchers, after correctly noting that "dynamic barite sag in the field should be viewed as the combined effects of annular velocity, pipe rotation, eccentricity, inclination angle and rheological properties of the drilling fluids," further conclude that the VSST should not be used to predict dynamic sag in the field *[Nguyen et al. 2009]*. Their reasoning is that the test itself induces separation of solid particles and does not compare with the known mechanisms that produce dynamic sag in field conditions. It is unfortunate that these researchers seemingly have totally missed the intent of the VSST, which is to measure the relative ability of a fluid to suspend weight-material under dynamic conditions. Indeed, the VSST is excellent for pilot testing in the field and for comparing testing of fluids and anti-sag additives. Direct correlation should not be expected in the same manner that yield point and funnel viscosity do not to correlate directly with pressure loss without due consideration of numerous well parameters and conditions.

This concern was recognized during development of the original VST, but the adjustment suggested in the VST paper has largely been ignored, perhaps because VST results on most drilling fluids have not been high enough to cause alarm. This can be of more concern with regard to the VSST, since it can do a better job of concentrating the barite in a small area *[Zamora and Bell 2004]*.

Table 1 is a revised Sag Index suitable for use with the VSST *[Zamora 2009]*. The index is the product of B_{VSST} and four empirical constants based on hole angle, annular velocity, rotary speed and interval length depending on field conditions. The constants are based on considerable testing with flow loops and field experience. Suppose a B_{VSST} of 1.5 lb/gal is measured for a well drilling a 4,000-ft interval ($K_z = 1.0$) at 37° inclination ($K_a = 0.7$). Annular velocity opposite drill pipe is 125 ft/min ($K_v = 0.6$) and rotary speed is 140 rpm ($K_r = 0.5$). The Sag Index would be 1.5 * 1.0 * 0.7 * 0.6 * 0.5 = 0.315 lb/gal. This result would be compared to the barite sag reported in a trip report as the difference between maximum and nominal mud weights.

The inclination constant K_a parallels the profile-versus-angle generally recognized by the industry. Also, K_v at annular velocities below 50 ft/min and K_r at rotary speeds less than 75 rpm reflect the fact that these low ranges can actually aggravate barite sag in the field. Both K_v and K_r imply full eccentricity which may not be true for a specific well case. Although the constants are based on considerable data, those wanting to use this technique are encouraged to adjust the constants or add new ones as necessary to improve correlation

in local areas.

Awareness of the Sag Index has helped field personnel better understand the intent and significance of the VSST overall. Prior to this, they were unnerved by the notably higher VSST values when compared to the VST and other measurements. The Sag Index also has served to remind them of the impact different variables have on barite sag in the field.

Angle (°)	Ka	Ann Vel (ft/min)	Kv	Rotary (rpm)	Kr	Length (ft)	Kz
<5	0	<2	1.0	<5	1.0	<1000	0.5
5-10	0.03	2-50	1.2	5-75	1.1	1000-2000	0.7
10-30	0.3	50-100	0.9	75-100	0.8	2000-5000	1.0
30-40	0.7	100-150	0.6	100-150	0.5	>5000	1.2
40-70	1.0	150-250	0.3	>150	0.3		
70-80	0.8	>250	0.1				
80-90	0.6						

Table 1 – *Drilling parameter constants for the VSST Sag Index calculation.*

Reserving a Spot on the Research Bench

The VSST was never intended for use in research, but it is being used in different research labs. Because of the industry focus on drilling fluid rheology as a means to mitigate sag, the VSST is proving to be an ideal tool for measuring sag tendencies of experimental fluid formulations. A drawback to this type of research is that it can lead to mischaracterization of barite sag as primarily a mud problem. Tests are quick, simple, reasonably reproducible, and conducive to measuring rheological effects to the exclusion of other parameters. Flow-loop studies cannot satisfy these needs for purely practical reasons, and are best saved for final testing and for running parametric studies to help establish best practices.

Some labs have run hundreds of tests using the Shoe to screen promising additives, different weighting materials, formulation effects, and to help isolate the true rheological properties that impact sag. This does not imply that that the VSST is considered a precision scientific test. It simply serves a purpose that seemingly is not being satisfied otherwise.

Early tests with the Shoe were aimed at quantifying improvements achieved from using micronized weight material. Studies supported field results that showed that reducing the mass of the weight-material particles could significantly reduce and virtually eliminate sag in many wells.

Other studies have focused on conventional rheological properties, particularly yield stress, other low-shear-rate parameters and gel strengths. On occasion, however, very viscous muds with acceptable low-shear-rate viscosities have exhibited unexpectedly high VSST results, strongly suggesting that other rheological properties may be in play.

One paper, for example, asked if brine phase treatment could improve rheology and mitigate barite sag *[Tehrani and Popplestone 2007]*. Studies run on a number of fluids containing clay-based and polymeric brine viscosifiers showed, among others, that VSST dynamic sag correlated well with the LSYP (low-shear yield point) of the test fluids. Another study focused on sag in invert emulsion drilling fluids *[Tehrani and Ayansina 2009]*. Dynamic sag measurements

were made using the VSST, but a major part of the study was devoted to evaluating the choice of viscometer speed in the VSST procedure. They concluded that the 100-rpm speed was not an issue for VSST use at the wellsite, but felt that a lower speed (60 rpm) might be more suitable for comparative testing of certain products in a laboratory setting.

In a recent paper *[Tehrani, et al. 2010]*, the authors found that a rheometric method is an improvement for quantifying dynamic barite sag in the laboratory. Rheological tests were run on a Bohlin Gemini 150 Rheometer in addition to the traditional VG meter. The relative change in shear stress measured by the Bohlin rheometer was converted into a good indicator of dynamic sag. The authors concluded that the new method produced dynamic sag indicator values that are in excellent agreement with those measured by the VSST.

Conclusions

1. The VSST based on the Sag Shoe is one of the very few methods available for measuring elements of dynamic barite sag at the wellsite.
2. For maximum benefit, the VSST must be used and interpreted properly. Understanding its purpose and limitations is paramount.
3. The density of the VSST sag bed is proportional to, but does not directly correlate with, field sag results. VSST measurements should be adjusted using a Sag Index to achieve results that can be compared.
4. The VSST is not a measure of Boycott settling. Instead, it is a relative measure of a fluid's ability to suspend weight material under certain dynamic conditions.
5. Sag Shoe design is based on the geometric boundaries and limitations of the available equipment used in the test in order to lower the cost and improve availability of equipment.
6. The VSST was never intended for research activities; however, it is an excellent test for pilot testing, evaluating test methods and comparing anti-sag additives.

Acknowledgments

The author thanks M-I SWACO management for its support and the countless field engineers, technical support lab personnel and researchers for using the Sag Shoe and VSST to monitor and evaluate barite sag.

Nomenclature

B_{VSST} = *increase in density measured by VSST, lb/gal*
K_a = *Sag Index constant for hole angle, dimensionless*
K_r = *Sag Index constant for rotary speed, dimensionless*
K_v = *Sag Index constant for annular velocity, dimensionless*
K_z = *Sag Index constant for interval length, dimensionless*
MW_1 = *initial density of sample extracted from the Shoe collection well, lb/gal*
MW_2 = *density of sample extracted from the Shoe collection well after 30 min at 100 rpm, lb/gal*
R_{BU} = *calculated percent of bed picked up in optional VSST procedure, %*

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