AADE-18-FTCE-048

Barite Sag Measurements Using a Portable Dynamic Flow Loop

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Abstract

Drilling fluid density is typically provided by dense, homogenously-dispersed, fine solids. Density fluctuations can occur if solids are no longer homogenously suspended. These fluctuations, commonly termed sag, can affect well integrity and increase the cost to completion. Various sag tendency prediction methods exist, but vary in their ability to provide quick and reliable measurements. This paper will focus on the performance of an innovative technology, the portable dynamic sag flow loop (PDSFL), and compare it to existing technologies and methods.

Introduction

Drilling fluid performance becomes increasingly critical as a well increases in depth, temperature, or angle. Operational parameters and practices, and well design may create or exacerbate fluid stability issues at critical areas. A small unwanted change in density is magnified over the length of the well and in extreme cases can lead to a loss of control. It is vital to ensure that a drilling fluid can maintain its integrity and provide a homogenous density throughout the length of the well.

Various sag tendency prediction methods exist, most utilize rheological parameters or associated equipment to estimate sag. While these methods are well suited to rig site testing, they do not fully replicate the primary drivers to barite sag[1,2]. The prediction method most analogous to drilling operations typically requires a variable angle flow loop with annular geometry, axial flow, inner pipe rotation, and direct measurement of circulating fluid density.

Existing sag flow loops have volume requirements that limit portability to remote labs or rig sites, potentially restricting their use to fluid development, well planning, or post event investigation[3,4]. The newly developed portable dynamic sag flow loop (PDSFL) is fully automated, requires minimal volume (0.5 gal), and features an annular test section providing axial and rotational shear to a test fluid. The PDSFL determines fluid sag potential by adjusting rotational and axial shear rates while measuring circulating fluid density. A sag favorable condition can be generated by providing minimal axial flow with little to no pipe rotation.

Current Sag Prediction Technologies

Fixed Barite Sag Flow Loop[3]

With the ability to control annular flow, pipe rotation, and pipe eccentricity, this equipment, when compared to other methods and apparatus, is typically viewed as the most accurate representation of what transpires downhole. The flow loop consists of three primary components: a fluid pump, test section, and measurement section.

The test section consists of an annulus with a rotating inner pipe and the ability to change eccentricity from 0% - 90%. A flowmeter-densitometer is used to measure flow rate and circulating density, allowing fluid flow feedback control. The test, shown in Fig. 1, begins by sufficiently shearing the fluid using high flow and pipe speed to obtain a uniform circulating density (Fig. 1- *Section A*). Next, the test section is set to the desired angle and both flow and pipe speeds are dramatically reduced to create a sag favorable condition (*Section B*). The total change in density after a specified amount of time is the test's first metric. Next, pipe speed is increased to observe density recovery (*Section C*). These two metrics represent the primary reportable measurements provided by the fixed barite sag flow loop.

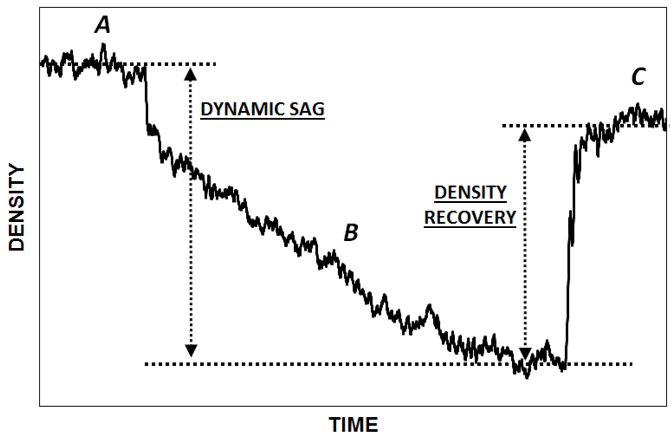

Fig. 1 *– Sag Flow Loop Metrics*

While the flow loop described in *Bern et al.*[3] has been critical to the study of barite sag and instrumental in finalizing the development of sag reducing additives and low sag drilling fluid systems, a volumetric capacity of 3.5 gallons makes rapid testing labor intensive. Measuring *(L x W x H)* 11 x 6 x 9 ft field application of this loop is also difficult. These factors typically result in many field and laboratory personnel to rely on viscometer sag shoe test (VSST), static sag, and other methods for procedural testing and only use the sag flow loop for fluid development, critical wells, or special request.

Viscometer Sag Shoe Test

The VSST is an API approved procedure for the qualitative measurement of barite sag. The test uses a standard oilfield R1B1 viscometer to induce shear in a heated mud sample. Sag is initiated in the low shear zone between the rotor and mud thermo-cup. An apparatus referred to as a "sag shoe" (Fig 2.) is placed in the thermo-cup prior to testing and serves to catch and concentrate deposited solids and fluid in a central location. The sample is removed via syringe and weighed.

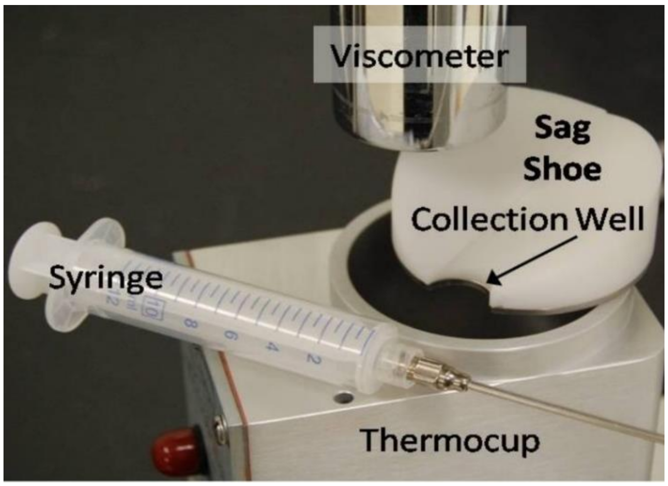

***Fig. 2** – VSST Equipment*[5]

There has been much discussion as to the validity and repeatability of this method in literature[6,7]. The primary drawback is that the method and equipment do not adequately represent the conditions a fluid is subjected to during drilling operations, such as pipe rotation, eccentricity of the pipe, annular (axial) flow, well inclination, and contamination[5]. Repeatability is also hampered by the test's small sample value (10mL) and density measurement method.

The VSST should be viewed as a qualitative test of sag tendency. The test is suitable for rapid screening, bulk testing, and to determine trends and changes to a fluid at the well site. A meaningful prediction of the amount of sag that will occur downhole was never the purpose of the test and should therefore not be expected[5].

Critical Wall Shear Stress/Sag Window

An API approved mathematical approach[8] uses fluid rheology and wellbore geometry to estimate the maximum potential sag that may occur. The method first requires the user to resolve the yield stress of the fluid using the Herschel-Bulkley model. The critical wall shear stress is then defined as the following:

$$\boldsymbol{\tau_W = \tau_Y + (b \times v_a)}$$

$\boldsymbol{\tau_W}$ is the critical wall shear stress, $\boldsymbol{lb_f/100\ ft^2}$
$\boldsymbol{\tau_Y}$ is the fluid yield stress, $\boldsymbol{lb_f/100\ ft^2}$
$\boldsymbol{b}$ is the relationship between annular velocity and shear stress at the wall (in laminar flow)
$\boldsymbol{v_a}$ annular velocity, $\boldsymbol{ft/min}$

In the calculation, the annular velocity, $\boldsymbol{v_a}$, is experimentally recommended to be 30 ft/min to obtain maximum sag potential. Once the value of $\boldsymbol{\tau_W}$ is obtained, the user graphically interpolates the predicted sag directly from the chart supplied in the API manual. While this method has the advantage of minimal required testing, there are significant subsequent computations that must occur. Furthermore, graphical interpolation of a dataset that visibly has 0.5 lb/gal scatter may be viewed as questionable by current measurement standards.

As a result, many fluid engineers prefer to utilize the sag window method described in *Dye et al*[2]. This method uses an empirically derived "window" of viscosity and shear rate to estimate the potential for sag (Fig. 3).

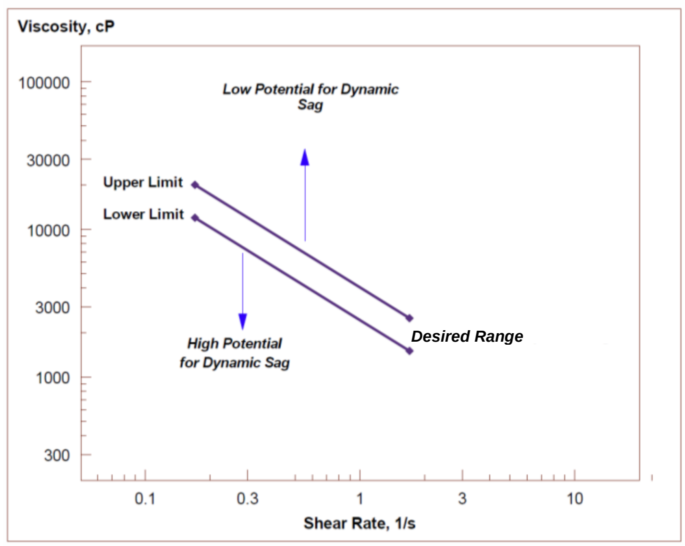

***Fig. 3 –** Dynamic Sag Window*[2]

If the low shear rheology data is confined within the upper and lower limits shown above, then the fluid is said to have a low sag potential. If rheology falls below the lower limit, it may have a high sag potential depending on numerous factors. Fluid rheology above the upper limit has a low sag potential, but may be undesirable depending on factors such as fracture gradient and pump pressure. Low shear rheometers that typically require additional support equipment (i.e., computer) are generally needed to test at these rates (0.17 s^{-1} to 1.7 s^{-1}). These methods also assume that the barite sag process is controlled entirely by fluid rheology parameters.

Portable Dynamic Sag Flow Loop

The PDSFL was developed to measure dynamic sag in a true lab scale device that is also field serviceable. Optimization of minimum fluid capacity with adequate measurement resolution was the primary goal during development. The final iteration of the device has a volumetric capacity less than 0.5 gal and a dimensional footprint of *(L x W x H)* 3 x 3 x 5.6 ft.

The PDSFL consists of the same primary systems as the fixed sag flow loop (Fig. 4): pump, test section, and data acquisition/control.

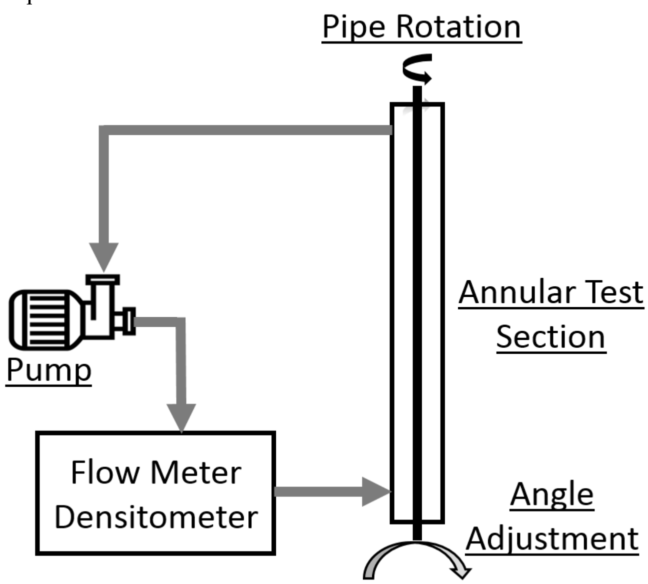

Fig. 4 *– Portable Dynamic Sag Flow Loop*

A progressing-cavity pump circulates fluid through a test section consisting of a 0.8 in. x 0.3 in. annulus with a length of 3 ft.

Sizing of the annulus was primarily based on an annular shear rate range of approximately 40 s^{-1} to 400 s^{-1}, with additional consideration given to Reynolds values. These considerations had to be balanced against pump availability, size/capacity, and flow rates within certain sections. Fluid flow is controlled during testing by a programmable logic controller (PLC) used in conjunction with a variable frequency drive (VFD) having feedback control. This control enables a constant flow rate if temperature related viscosity changes occur.

Testing of the PDSFL is similar to the fixed flow loop in which a solids bed is deposited and the change in density measured. The ability of the solids bed to be returned to the flow stream via the rotating pipe is abridged during PDSFL testing as only one pipe speed is used. A single speed was chosen to maintain a reasonable test time for screening fluid.

Results

A newly developed invert emulsion fluid optimized for an active well was used to begin the validation process of the PDSFL (Table 1). Multiple sag characterization methodologies including the fixed sag flow loop, VSST, static sag, and sag window were compared to field and PDSFL results.

Table 1 *- Field Fluid Properties (ºVG Rheology @ 150ºF)*

		Viscometer RPM (R1B1)					
	ρ (ppg)	600	300	200	100	6	3
Fluid A	12.5	69	43	34	23	12	11
Fluid B	13.9	68	41	32	21	11	10
Fluid C	14.9	79	48	37	25	11	10

Additional data was provided through testing performed during PDSFL development. As previously discussed, apart from the flow loops, each of these methods vary considerably in the mechanics used to determine sag. Overall trends were therefore used to qualify the PDSFL except when comparing flow loops.

Comparing the PDSFL to the fixed flow loop was accomplished by directly correlating the sag and recovery values between the loops. A linear relationship with a good fit denotes the equipment functions as designed, while non-linear or large data scatter means the design or execution should be reexamined. Figs. 5 and 6 display the results of all flow loop tests and how the PDSFL correlates to the fixed flow loop.

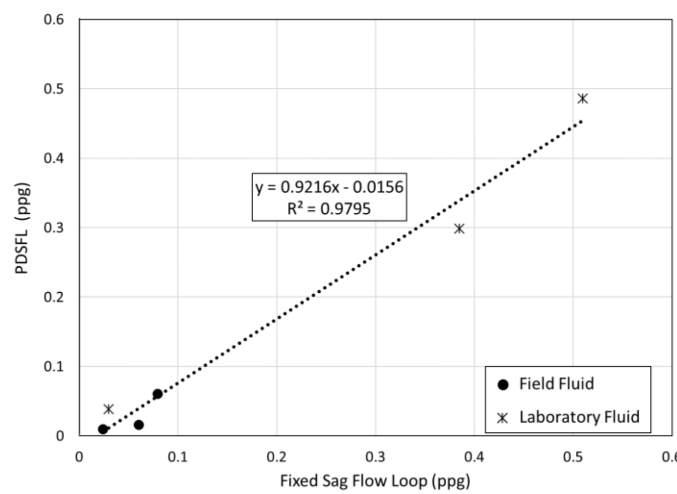

Fig. 5 *– Dynamic Sag Comparison*

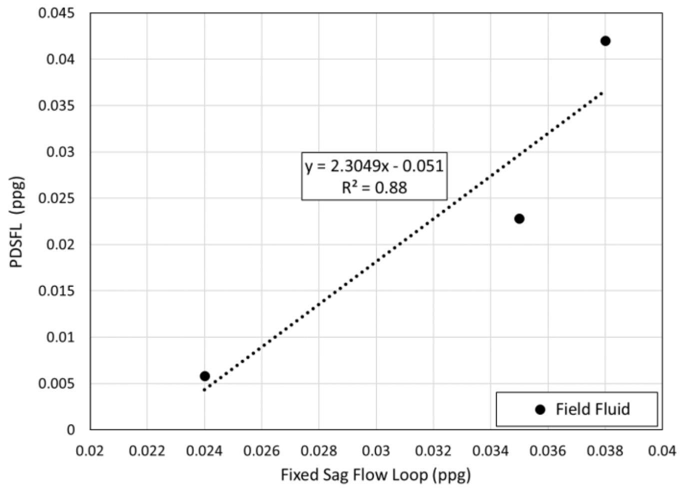

***Fig. 6** – Density Recovery Comparison*

Despite the small sample size, the PDSFL shows that it is an adequate dynamic sag indicator when compared to the fixed flow loop. During initial evaluation of the PDSFL, dynamic sag was the only metric tested. Recovered density values for the laboratory prepared fluid are therefore not available. Field fluid results exhibited a small correlation between the two loops. While this metric is less vital than the dynamic sag measurement, the procedure will be further studied to see if a tangible correlation exists. Selecting fluids with a broader spectrum of sag tendency will aid in displaying data convergence.

Fig. 7 compares sag values obtained from the VSST to both flow loops. Data shows that while the absolute numbers do not differ by an extreme amount, the overall trend provided by the VSST is inconsistent with those obtained via the flow loops.

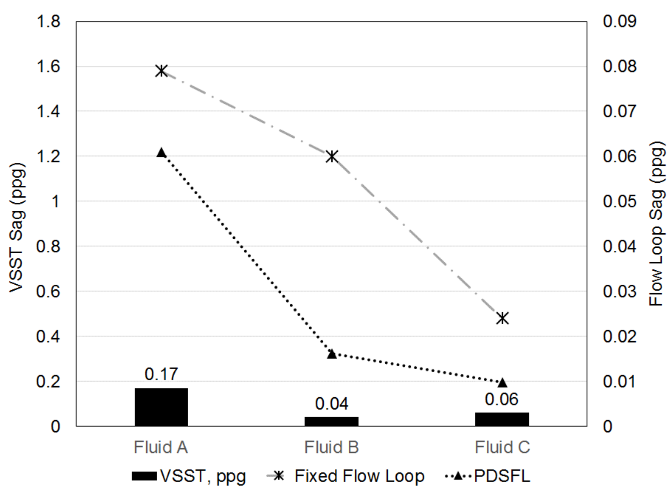

***Fig. 7** – VSST vs Flow Loops*

Fig. 8 shows the sag window values for all three field fluids. All of them are above the upper limit and should therefore not experience a great deal of barite sag. This is supported by flow loop, VSST, and field results.

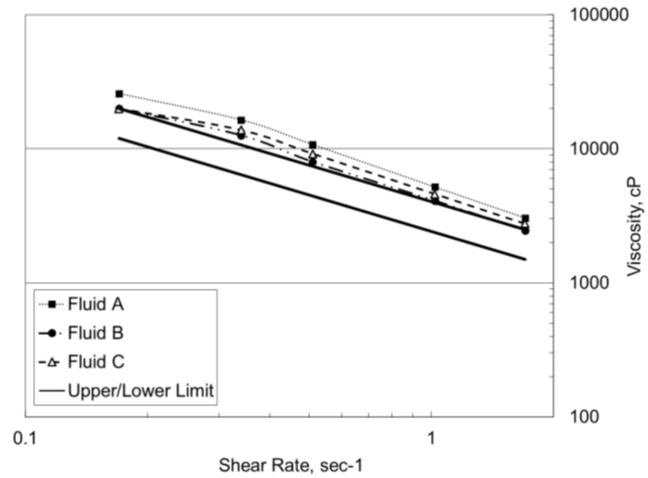

***Fig. 8** – Sag Window*

The graph additionally shows that sag window results did not agree with trends provided by either the flow loops or VSST. Fluid A shows the least sag potential, while VSST and flow loop testing results in the highest sag numbers.

Static sag and electrical stability tests were also performed after static aging at 210°F for 7 days. Table 2 shows that while the static sag results do not correlate with any of the previous tests, only minimal sag occurred.

***Table 2** - Field Fluid Properties*

	Static Sag (ppg)	ES @ 120°F (Volt)	HTHP @ 250°F (mL)
Fluid A	0.96	784	4.8
Fluid B	1.41	834	3
Fluid C	1.51	780	1.8

Lack of agreement between static sag testing and other methods does not diminish the usefulness of this test as static aging has been shown to be strongly correlated to ultra-low shear rheology[1].

Table 3 displays mud weight measurements performed in the field after leaving the fluid under static conditions in the well for the denoted time. While the various laboratory methods described herein did not coincide in absolute numbers or trends, all of them demonstrated that the field fluid exhibits minimum sag potential. This is reinforced by field results which showed that negligible sag occurred in the well.

***Table 3** - Field Fluid Density Variation*

	Static Period (Days)	Initial MW (ppg)	MW @ Gumbo Box After Static Period (ppg)
Fluid A	6	12.5	12.5 – 12.6
Fluid B	3	13.8	13.8 – 13.9
Fluid C	5	14.7	14.7 – 14.9

These results show that testing for barite sag potential may not provide an exact measurement of fluid properties such as temperature or density. A highly variable field environment also makes correlation with laboratory measurements difficult. Flow loop testing, capable of providing dynamic conditions, may therefore be the most suitable method to determine sag potential.

Conclusions

- A new device for testing the sag potential of a drilling fluid has been developed.
- The PDSFL was compared to conventional laboratory sag tests and an industry accepted flow loop tester using field-sourced drilling fluid.
- Dynamic sag results from the new device were consistent with fixed flow loop results.
- Density recovery procedures of the PDSFL require further refinement.
- For this series, conventional laboratory tests did not trend with dynamic sag flow loop results, but did show a minimal sag potential of the fluid.
- The work of improving correlations provided by the PDSFL is ongoing. Testing involves fluids with varying chemistry, density, rheology, and sag potential.

Acknowledgments

The authors thank the management of M-I SWACO for supporting this work and for permission to publish this paper. We thank Yiyan Chen for providing data recorded during project development, and the numerous M-I SWACO scientists and engineers that performed laboratory testing.

Nomenclature

VSST = *Viscometer Sag Shoe Test*
PDSFL = *Portable Dynamic Sag Flow Loop*
PLC = *Programmable Logic Controller*
VFD = *Variable Frequency Drive*
ppg = *Pound Per Gallon (lb/gal)*

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