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Improved Prediction of Barite Sag Using a Fluid Dynamics Approach

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Abstract

The prediction of barite sag is a difficult undertaking for the drilling industry. Published literature shows that barite sag correlates poorly with a wide variety of predictive parameters and, consequently, fairly accurate prediction of barite sag occurrence remains elusive. However, recent re-examination of experimental results of invert emulsion drilling fluids in axial flow has led to the development of a new predictive correlation having a degree of confidence.

A recent advance in invert emulsion drilling fluid chemistry is the development of invert emulsions having no organophilic clays or organophilic lignite to help suspend barite or other solid weighting material particles. The correlation developed in this paper explains the lack of barite sag incidence with use of this particular fluid in the field.

Introduction

The increasing complexity of wells drilled today to maximize reservoir production has presented several challenges to the drilling industry that were not there twenty years ago. With highly-deviated and extended-reach (ERD) wells becoming more commonplace in nearly every producing field worldwide, common drilling challenges include hole cleaning, hydraulics optimization within the formation pore pressure/formation fracturization window, and maintaining drilling fluid stability from cold temperatures to high-temperature/high-pressure (HTHP) environments.

The occurrence of barite sag in the field can be quite expensive to deal with, because much nonproductive time is spent on the rig circulating and conditioning the drilling fluid during treatments. Left unresolved, the barite sag problem can lead to undesired well-control problems.

One particularly troublesome drilling challenge eluding researchers for years is the accurate prediction of barite sag in deviated wellbores. While nearly all recent research[1-5] has acknowledged barite sag to be principally a dynamic phenomenon, most researchers use either drilling fluid rheological measurements exclusively or static measurements to model the problem. This study focuses on the application of fluid dynamics to assess the occurrence of barite sag in deviated wellbores. Sophisticated hydraulic modeling of fluids in axial flow shows the importance of understanding fluid behavior at the conduit walls, where barite sag first occurs. Correlations of measured barite sag as functions of fluid shear stress and fluid velocity are shown. These correlations are used to help improve prediction of barite sag occurrence in the field and to help minimize nonproductive time spent dealing with the problem on the rig.

The utility of the barite sag correlations developed in this study can be seen in the modeling of field cases of barite sag incidence in new-generation invert emulsion drilling fluids. These new fluids contain no organophilic clays, but instead employ organic polymers dispersed in base fluids to achieve adequate suspension properties. Information from field drilling operations has shown that these new generation fluids are not prone to barite sag occurrence. The barite sag prediction correlation developed in this work is used to document the lack of barite sag occurrences in four field cases involving this particular drilling fluid.

Barite Sag Definition

Barite sag is commonly defined as the slow settling of barite particles (or other solid weighting agent), which results in large fluctuations in drilling fluid density exiting the wellbore. Sometimes fluid densities exiting the wellbore are much higher than the base drilling fluid density, sometimes much lower than the base drilling fluid density. The barite particles usually settle in soft beds easily removed with circulation of the drilling fluid. In high-angle wells, there is commonly some settling of barite in the low side of the hole. This is not commonly thought of as barite sag because density fluctuations are often only 0.012 sg (0.1 lbm/gal). When barite sag occurs, drilling fluid density fluctuations can be as high as 0.36 sg (3 lbm/gal).

Previous Research

Researchers studying the problem generally agree that barite sag occurs under the following conditions:

- In deviated wellbores at angles of 40-75º deviation
- More prone to occur in invert emulsion drilling fluids rather than water-based drilling fluids
- Under dynamic conditions rather than static conditions

- In drilling fluids exhibiting "low" viscosity
- Often associated with running E-logs, slow rotation of the drillpipe, and other low-shear events
- Usually occurs while circulating with annular velocities (AV) less than 0.51 m/s[4] (100 ft/min)

To help prevent and/or predict the occurrence of barite sag, researchers have developed the following recommendations:

- Maintain the drilling fluid's Herschel-Bulkley yield stress (t_0) rheological parameter in the range of 3.4 to 7.2 Pa (7 to 15 lbf/100 ft^2) while drilling and circulating[4,6]
- Avoidance of low circulation rates and/or slow rotation rates of the drillpipe
- Develop testing equipment to measure changes in the center of mass of drilling fluid inside a suspended tube as a function of time[2] and correlate these values with field data
- Maintain drilling fluid viscosity measured at shear rates as low as 0.001 s^{-1} within a specific range[7]
- Use a "barite sag window" in which the drilling fluid viscosity is maintained in a prescribed range between two selected shear rates[7]

The barite sag problem still occurs sporadically in the field, and none of the above tools has satisfactorily solved nor consistently predicted the problem. Interestingly, the one drilling fluid rheological parameter that consistently exhibits the highest correlation with barite sag is the Herschel-Bulkley rheological model yield stress (t_0). However, the r^2 correlation for this parameter[7] is reported to be 0.7-0.8, which shows there is still a great need for further work in this area.

Purpose of This Work

In this work, the study of barite sag is undertaken from a perspective different from previous studies. Rather than looking at the problem from a purely fluid rheological standpoint, this study uses flow dynamics to study the phenomenon of barite sag. No new laboratory studies were undertaken in this work. Instead, data from a published work[7] is used, and the experimental setup and data collection techniques are detailed therein.

The underlying physical principles used in this study of barite sag development include:

- Barite sag occurs in a low shear rate environment.
- Barite sag is most problematic under dynamic conditions.
- Drilling fluid rheological properties play an important part in governing barite sag occurrence.
- In barite sag occurrence, barite particles begin to accumulate at the conduit wall on the low side of the hole in angled wellbores. Hence, the annular area immediately next to the conduit wall is most pertinent for this study.
- In high-deviated drilling situations where barite sag is most prevalent, the drillpipe is usually assumed to lie somewhere toward or directly on the low side of the hole. Therefore, the effect of drill pipe eccentricity on axial flow must be considered.
- A sophisticated hydraulic model designed for use in eccentric annular geometry can be used to map the point velocities and shear rates in the annulus.

Hydraulic Modeling in Eccentric Wellbores

In axial flow in concentric annuli, the calculation of a pressure drop required to shear a pseudoplastic drilling fluid is governed by the following parameters:

- OD of the inner tube and the ID of the conduit
- Drilling fluid's Herschel-Bulkley rheological parameters (n, K, t_0)
- Flow rate
- Shear stress at the wall (t_w).

For fluids in the laminar flow regime, the general equation to calculate t_w is given by:

$t_w = R/2 * dP/dL$…………………………………………………(1)

In eccentric annuli, the calculation of key hydraulic parameters is more complicated, because the gap between the OD of the inner tube and the ID of the conduit change with radial position about the eccentric inner tube. However, with a sophisticated hydraulic model, the annular pressure drop, the point velocities, and the shear rates in all parts of the eccentric annulus can be calculated using numerical methods. This hydraulic model has been used previously in hole cleaning studies in ERD wells.[8,9]

Important to this work, iterations can be run with the hydraulic model to determine:

- The flow rate required to overcome the fluid yield stress and initiate shear at or near the conduit wall.
- The shear rates and shear stresses at and near the conduit wall for a given flow rate.

Recap of the Experimental Design

In previous work,[7] drilling fluids were circulated in a flow loop containing a stationary inner tube to simulate the presence of annular flow. Pertinent details of the experimental procedure have been detailed. The testing matrix was designed with the following key points in mind:

- The inner tube was deliberately set in an eccentric position so that fluids moving in the small gap under the stationary tube would have much lower annular velocities and hence lower shear rates than those above the inner tube.
- Drilling fluids were circulated at a variety of flow rates designed to provide low shear rate environments conducive to barite sag development.

- For each flow rate, drilling fluid densities in the area next to the conduit wall were measured and increases over the base drilling fluid density were interpreted to be dynamic barite sag occurrences.
- Profiles of dynamic barite sag vs. flow rate were determined for each drilling fluid tested.

Recap of Previous Testing Results

In the cited work, the researchers documented a number of points pertinent to this work:

- There is a relationship between dynamic barite sag and average annular velocity of fluid flowing in the eccentric conduit.
- Above an average annular velocity of 0.51 m/s [100 ft/min], dynamic barite sag is low; below this level, dynamic barite sag rises dramatically with decreasing annular velocity.
- Barite sag under static conditions is very low. Given that the static tests were conducted over an interval 32 times longer than that used in the dynamic tests, the measured values of static barite sag can be considered essentially zero in value.

In **Figure 1** (scanned from the cited work), the relationship between annular velocity and dynamic barite sag is depicted. For clarity, a maximum barite sag profile is added to show the general shape of the data. It should be noted that at very low average annular velocities, the maximum curved profile drops sharply as the AV approaches the origin. An important observation from **Figure 1** is that the maximum dynamic barite sag peaks well below 0.51 m/s (100 ft/min) average AV.

Experimental Data Used in This Study

The experimental data used in this study was taken from published work[7]. Key pieces of data include:

- Geometry dimensions of the inner tube and conduit
- Eccentricity level of the inner tube
- Drilling fluid rheological parameters
- Maximum levels of measured dynamic barite sag

The Role of Annular Velocity

The role of average annular velocity in the promotion of dynamic barite sag needs further investigation. At first glance, the jumble of data points in **Figure 1** appears to show nothing more than a general trendline. However, through hydraulic modeling, the data sets become much more meaningful.

The hydraulic model was used to determine pressure drops, shear rates, and shear stresses at the conduit wall using the individual fluid rheological properties reported in the original work. Because all of the simulated annular velocities were well within the laminar flow regime, the pressure drop vs. AV profile is linear for each fluid simulated.

For each annular velocity simulation, the conduit wall shear stress (t_w) levels were calculated for cases in which the annulus was fully sheared. **Figure 2** shows the t_w vs. AV data for the individual fluids. To make the scatter plot easier to understand, the linear profiles for each of the fluids are also marked in **Figure 3** and are sorted by measured levels of dynamic sag. The levels of measured maximum dynamic sag are:

- Low: 0 – 0.12 sg (0 -1 lbm/gal)
- Medium: 0.121 – 0.24 sg (1.01 -2 lbm/gal)
- High: > 0.241 sg (>2 lbm/gal)

From this data, one can see definite differences between the fluids in regard to development of wall shear stress.

Because barite sag is a dynamic phenomenon, the t_w values calculated at an optimum level of annular velocity conducive to barite sag development were then plotted against the published maximum barite sag measurements. Here the optimum velocity is that required to slightly overcome the fluid yield stress. From this exercise, a strong correlation between measured barite sag and drilling fluid behavior was seen, as **Figure 4** shows. The correlation here is quite high, with a degree of confidence r^2 = 0.943, a level much higher than any published correlation parameter.

Usefulness of the Correlation

The correlation between conduit wall shear stress and measured dynamic barite sag can be used to predict the incidence of barite sag in invert emulsion drilling fluids. Drilling fluids, even those with an “adequate” yield stress [t_0] according to the Herschel-Bulkley rheological model, can develop insufficient levels of wall shear stress when they are sheared at low annular velocities. Barite sag can be expected in these cases.

In the past two years, the drilling industry has seen the development of invert emulsion drilling fluids that contain no organophilic clay or organophilic lignite additives.[10] The formulations of these new-generation invert emulsions have been described and their excellent drilling performances documented (reduction of downhole whole mud losses, fragile but firm gel strengths, etc.). Interestingly, after having been used on over 120 deepwater and shelf wells, these fluids have been associated with minimal occurrence of dynamic barite sag while drilling.[10]

After development of the correlation shown in this paper, the dynamic sag potentials of several clay-free invert emulsions fluids from the field were predicted using the same hydraulic modeling as the 10 fluids described in this paper. **Figure 5** shows the calculated results of the field fluids plotted with the original correlation. Here the clay-free invert emulsions generate sufficient conduit wall shear stresses at low annular velocities to give zero to near-zero predictions of dynamic barite sag.

Conclusions

The following conclusions can be made from the findings presented in this paper:

- Sophisticated hydraulic modeling can be used to better understand the development of dynamic barite sag in high-angle wellbores.
- Drilling fluids unable to generate adequate levels of shear stress at the conduit walls while being sheared at low annular velocities are prone to exhibit dynamic barite sag in the field.
- A correlation incorporating a drilling fluid's wall shear stress has been developed to predict the occurrence of dynamic barite sag. This correlation can provide a much higher degree of confidence than any previously published.
- The lack of reports of barite sag incidents from the field where, a new-generation invert emulsion drilling fluid containing no organophilic clays or organophilic lignite has been used, can be understood using the correlation developed in this paper.

Nomenclature

AV	=	annular velocity (m/s)
dP/dL	=	pressure drop per unit length (Pa/m)
HB	=	Herschel-Bulkley rheological model
ID	=	inner diameter of conduit or channel (m)
OD	=	outer diameter of tube (m)
R	=	radius of conduit or channel (m)
t_0	=	yield stress, HB rheological model (Pa)
t_w	=	wall shear stress (Pa)

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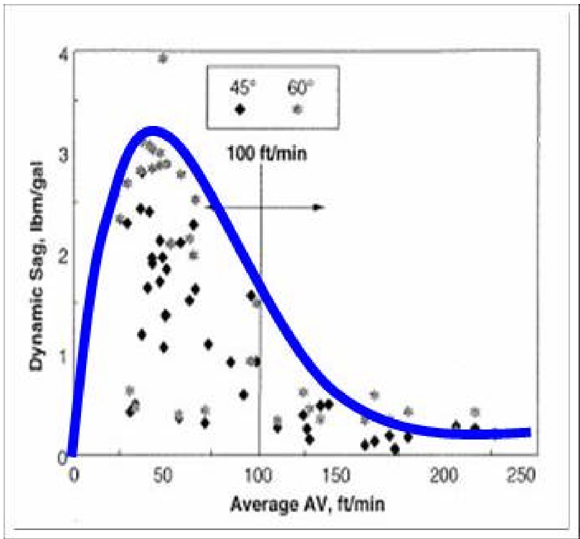

Figure 1: Average annular velocity vs measured dynamic barite sag (data scanned from Ref. 7).

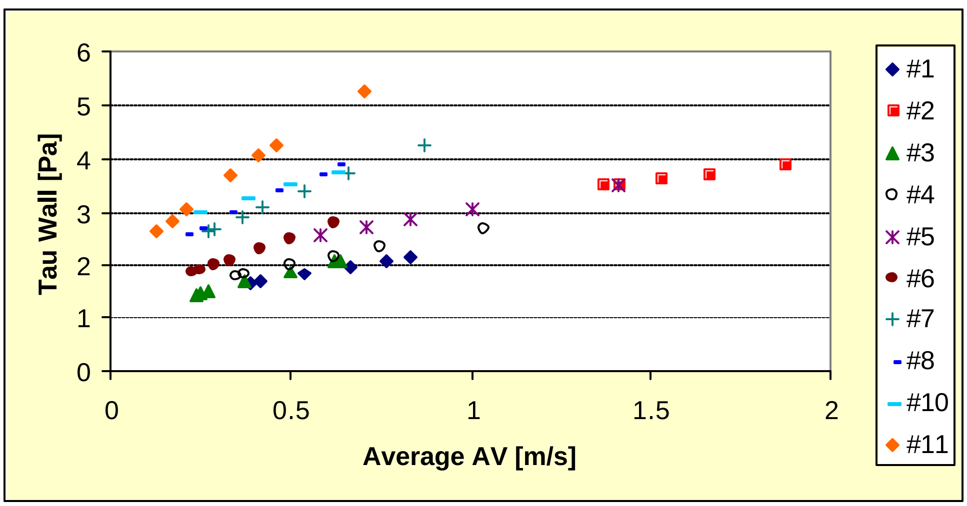

Figure 2: Average annular velocity vs. shear stress at the conduit wall by fluid number.

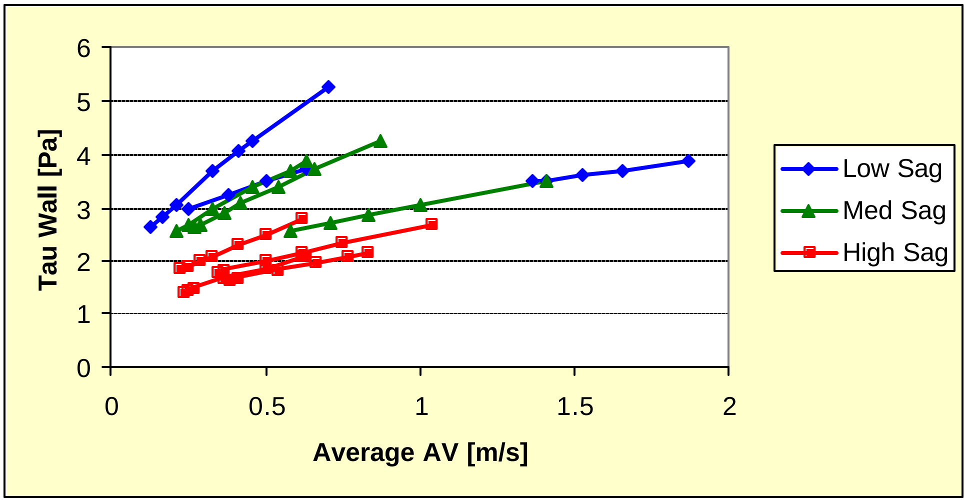

Figure 3: Average annular velocity vs. shear stress at the wall (data sorted by level of measured dynamic sag).

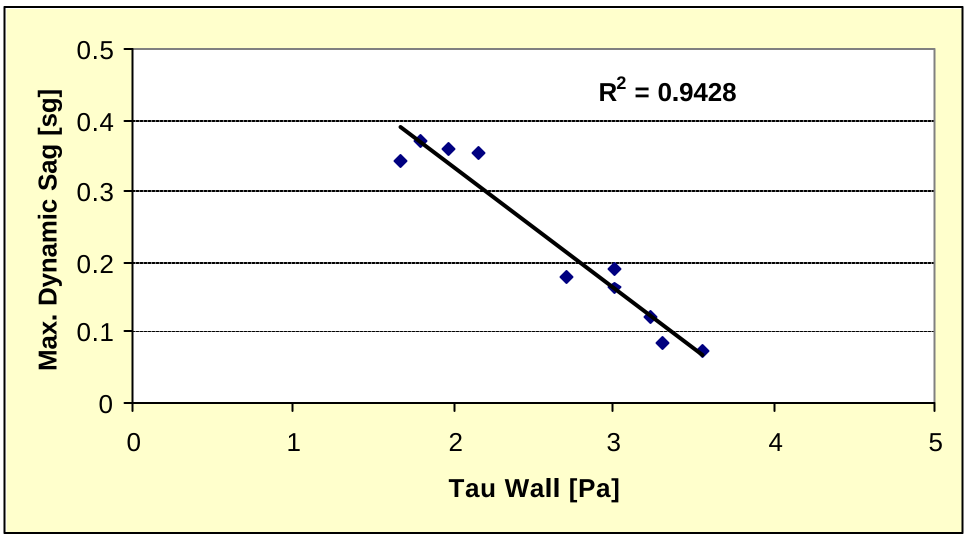

Figure 4: Shear stress at the wall vs. maximum predicted dynamic sag at an optimized average AV.

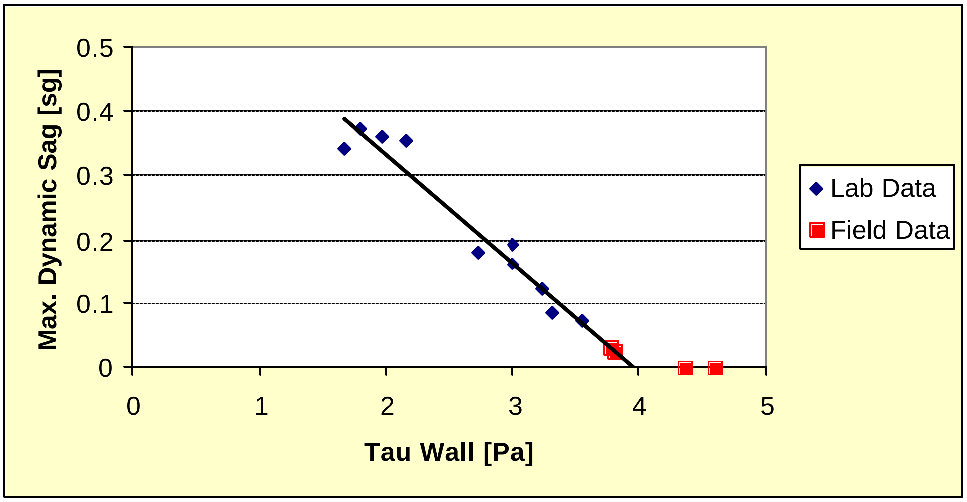

Figure 5: Dynamic barite sag predictions for selected new-generation invert emulsion field fluids.