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Low Shear Rate Rheology: Clarifying Muddied Waters

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Abstract

Over the past several years, much has been published upon the role of low / ultra-low shear rate rheology in the oil field literature. Generally, the importance of rheology has been linked to the following areas of study for non-Newtonian drilling fluids in laminar flow: fluid hydraulics / pressure loss prediction, hole cleaning in vertical and deviated wellbores, particle settling velocities, and barite sag development. Typical industry viscometers measure fluid properties in the range from about 5 to over 1000 sec^{-1}. Some have suggested that use of low / ultra-low shear rate (5–1/1–0.001 sec^{-1}) data produces more accurate modeling of field scenarios since many drilling-related events occur in the low to ultra-low shear rate range. In this paper the usefulness of low shear rate data in these areas is discussed.

Introduction

Key to understanding the role of fluid rheology is identifying the appropriate shear rate distribution ranges for each of these areas of study. Since shear rate ranges pertinent to one phenomenon may not be appropriate to another, each should be investigated individually. Complicating shear rate estimations for purely axial flow cases are the effects of drill pipe eccentricity and drill pipe rotation.

In this paper, shear rate ranges for each of these 4 areas of study are discussed for typical drilling scenarios from the field: axial flow with concentric and eccentric drill pipe and axial flow with and without drill pipe rotation. From this information, the reader can better decide whether the low or ultra-low shear rate measurements used in modeling clarify the issues or serve only to "muddy the waters".

Measurement and Use of Low Shear Rate Data

In the oilfield, rheological data is usually obtained using a viscometer that uses Couette flow to measure drilling fluid properties. Other types of instruments and geometries could be used (pipe viscometers, controlled-stress rheometers, cone and plate geometry, etc), but have found only occasional mention in the drilling literature and little if any application in the field. Hence these techniques are not discussed in this paper.

The Fann Model 35 VG meter is the industry standard for measuring fluid rheological properties of non-Newtonian drilling fluids. With this device, shear stresses are measured for fluids having average shear rates in the approximate range 1022 s^{-1} to 5.1 s^{-1}.

Viscometers have been developed to measure drilling fluid properties at shear rates as low as 0.001 sec^{-1}. The main premise behind their development was the thinking that the availability of low-to-ultra low shear data, better results could be obtained in hydraulics, particle settling rates, and hole cleaning calculations. Unfortunately, little field or laboratory data was supplied to substantiate their claims.

Some work has been presented previously on the modeling of low-to-ultra low shear rate data taken from rotational viscometers[2]. When dealing with low-to-ultra low shear rate data, several important considerations should be kept in mind:

- The lower the shear rate used, the % error of the measurement will be greater. Interference from vibration, particularly on floating vessels, can be a constant problem. Gellation of thixotropic drilling fluids exhibiting elevated levels of yield stress can alsoproduce significant measurement errors at ultra-low shear rates.
- Because most drilling fluids are non-Newtonian, their average shear rates across the narrow gap in a rotating viscometer are not equal to 1.703 * RPM (units of s^{-1}); for pseudoplastics, the shear rates are higher in value. These shear rates must be corrected for the degree of non-Newtonian behavior of the drilling fluid as given by the flow index 'n'.
- The low-to-ultra low shear rate data should be fit by a rheological model that is capable of incorporating them in the calculation procedure. The Herschel-Bulkley rheological model has been shown to handle "good" low shear rate data well while the Bingham plastic and power law rheological models do not[2]. Using good modeling techniques, a drilling fluid's behavior from 0.5 to 600 rpm can usually be well mapped.
- Comparisons of the observed data vs the data predicted by the rheological model parameters with decreasing shear rate will show increasing errors. An acceptable error limit should be established so that the rheological modeling process does not become "garbage in – garbage out". Careful

monitoring of the average absolute deviation (AAD) of results is required.
- With the incorporation of lower shear rate data, the value of the rheological modeling parameters will change. For example, when the Herschel-Bulkley rheological model is used to model increasingly low shear rate data, the calculated fluid behavior index 'n' will show change of only 3%. Greater variations in the H-B yield stress (τ_0) and consistency index K values will occur somewhere on the order of 18%, with decreases in the τ_0 value offset by increases of nearly the same magnitude in the fluid's consistency index K values.

Applications of Low-to-Ultra Low Shear Rate Data

The use of low / ultra-low shear rate data has been applied in several areas for conditions of laminar flow:
- Drilling fluid hydraulics (pressure loss, surge, ECD prediction, etc)
- Particle settling velocity prediction
- Annular velocity modeling / hole cleaning
- Barite sag development prediction

For each of these areas, the appropriateness of the use of low- to ultra-low shear rate rheology is discussed. In this discussion, a "typical" SBM drillilng fluid having the shear stress / shear rate profile depicted in Figure 1 serves as the basis for all calculations. The fluid's H-B parameters calculated over 3 shear rate ranges[2] are given in Table 1.

Drilling fluid hydraulics. The effect of incorporating low-to-ultra low shear rate data in hydraulics calculations was evaluated in terms of predicted pressure loss and Equivalent Circulating Density [ECD]. Pressure loss calculations were first calculated at 800 gal/min in a 12.25-in ID hole across a wide range of drill pipe eccentricity. The results given in Figure 2 show that the highest pressure drops occur when the Range 1 fluid rheology is used. Incorporation of lower shear rate data does drop the pressure losses somewhat. Overall, there is a difference of only 8-9% between pressure loss results obtained with Range 1 and Range 3 fluid rheologies. Similar trends are seen at all levels of drill pipe eccentricity. Subsequent calculations at 1000 gal/min gave higher pressure drops, as expected, but the differentials between Range 1 and Range 3 results remained in the range 7-8 %.

The effect of incorporating low shear rate data in ECD calculations was next investigated. To do these calculations, a drilling fluid weighing 10.0 lbm/gal was given. Pump rates of 800 and 1000 gal/min and drill pipe rotation speeds of 0 and 100 rev/min were input items. In order to calculate ECD, a hypothetical high angle ERD well profile given in Table 2 was used. In the calculations the levels of drill pipe eccentricity were held constant for each hole section.

The calculated ECD results for 800 and 1000 gal/min flow rates are depicted in Figure 3, and show that there is very little difference in ECD. Again, as expected, results using Range 1 fluid rheology are slightly higher than the others, but the difference between Range 1 and Range 3 results is 0.25% or less for all cases tested. The differentials in ECD are slightly reduced as average annular velocities and average annular shear rates increase.

Results shown here implicitly concur with recently published material showing that very accurate prediction of ECD in high angle and deepwater drilling is possible with use of standard 6-speed viscometer data[3,4].

Particle settling velocity. The effect of incorporating low-to-ultra low shear rate rheology on particle settling velocity [PSV] calculations was next investigated. Accurate PSV predictions are especially useful in the evaluation of hole cleaning. According to Chien[5] , the velocity at which a drilled cutting settles is dependent upon the drilling fluid viscosity and the particle's settling shear rate. The question arises whether the incorporation of lower shear rate data produces better calcuated results. To answer this question, particle settling velocities were calculated on both static and dynamic bases for a wide range of particle diameters. The fluid properties used in the hydraulics calculations were used in these calcualtions.

Figure 4 shows the results obtained for the static case. There is very little difference in calculated PSV when the 3 ranges in fluid rheology are used – as long as particle diameters remained at 0.25-in or less. Above 0.25-in diameter, differences in results begin to appear. The lowest static PSV are seen when the Range 1 rheology is used, a consequence of the highest yield stress value of rheology Range 1. As fluid yield stress levels decline, static PSV can be expected to increase.

Dynamic particle settling velocity calculations were next investigated at 2 pump output levels: 800 gal/min [164 ft/min average annular velocity] and 400 gpm [82 ft/min average annular velocity]. The results are shown in Figure 5. Due to the shear-thinning nature of non-Newtonian drilling fluids, their PSV levels are higher as shear rates in the annulus increase. Figure 5 shows much higher particle settling velocities at 400 and 800 gal/min than those for the static case. Figure 5 also shows that as annular shear rates increase, the difference in results between Range 1 and Range 3 rheology narrows. However, even at 400 gal/min, calculated PSV for a given average particle diameter varies only slightly. Whether Range 1 or Range 2 or Range 3 rheology is used does not appear to affect numerical results significantly.

Annular velocity modeling / hole cleaning. Closely related to drilling fluid hydraulics and particle settling velocity calculations is the subject of hole cleaning. The principal factor controlling hole cleaning is velocity distribution in the annulus. In concentric wellbore, it is fairly straightforward to calculate sector velocities across the annular gap and wall shear stresses. However, in an eccentric wellbore the calculation procedures are more complicated. In order to evaluate the effect of incorporating additional low shear rate data on the annular velocity distribution, calculations were performed, In this evaluation, two pump rates were input in a 12.25-in by 5.5-in annulus, with a 0.5 eccentricity assigned to the drill pipe. Rather than lying in the middle of the annulus, the simulations were designed to reflect an actual drilling situation in high angle drilled. All 3 shear rate ranges were input into the eccentric annulus velocity model to determine their effect on velocity distribution.

Figure 6 shows the results for both the 400 gal/min and 800 gal.min cases. In this graph, the position of each sector is given in terms of degrees from the top of the hole. The profiles for the 400 gal/min and 800 gal/min curve sets are quite similar in form. In each curve set at the same pump rate, the velocities in the top part of the hole have the following stacking arrangement: Range 1 > Range 2 > Range 3. In the lower part of the hole where the annular gap is muchmore narrow, the opposite stacking arrangement in sector velocity occurs: Range 3 > Range 2> Range1. However, the calculated velocity differences are small for the three rheology ranges used in the calculations.

Barite sag prediction. Barite sag occurrence, an infrequent but expensive problem in high-angle drilling situations. Usually linked with use of invert emulsion drilling fluids, barite sag is still poorly understood and difficult to predict. The role of drilling fluid rheology in barite sag incidence has been recognized for some time[6,7,]. In recent years researchers have found that barite sag is a dynamic phenomenon that occurs mainly at low shear rates. Often it is mechanically induced [eg, slow drill pipe rotation, vibration, running wirelines, etc]. The problem for researchers is quantifying the shear rates that induce barite sag.

Recently, experimental work using a flow loop was performed to create an environment that would produce barite sag[8]. In that work, the authors found:

- Barite sag occurrence was a function of drilling fluid low shear rate rheology [shear rates < 4 s^{-1}] and aveage annular velocity [AV < 100 ft/min].
- Barite sag severity increases from 40 degrees to 65 degrees deviation.
- Poor correlation between barite sag and standard 6-speed viscometer measurements; higher correlations were seen when low-to-ultra low shear rate data was incorporated in the rheological modeling procedures.
- Of all the rheological parameters studied, the Herschel-Bulkley yield stress parameter τ_0 had the strongest correlation with dynamic barite sag.
- Drilling fluid density did not correlate with the incidence of dynamic barite sag.

From these studies, it can be determined that more work should be done in the area of barite sag. The role of low shear rate rheology certainly needs further investigation and better modeling of conditions that promote dynamic sag incidence is needed.

Conclusions

The following conclusions can be drawn from this study involving invert emulsion drilling fluids:

- Use of low-to-ultra low shear rate data in oilwell drilling fluid should be handled with care, not only in the measurments but also in their inclusion in rheological modeling.
- The incorporation of low-to-ultra low shear rate data in the calculation of the Herschel-Bulkley rheological model parameters will produce changes in their values.
- With the incorporation of decreasing low-to-ultra low shear rate data compared to use of standard 6-speed viscometer data in the calculations :
  1. Decreases in pressure loss calculations can be expected [8-9%]. These differentials decrease with increasing annular velocity and average annular shear rates.
  2. These decreases in pressure loss calculations produce little if any noticeable change in ECD calculated for the example well of intermediate depth.
  3. Calculations of static particle settling velocity show little change for particles less than 0.25-in average particle diameter. For larger particles up to 0.5-in average diameter, increases in static particle settling velocity of up to 10 ft/min only were seen.
  4. Under dynamic conditions, differentials in calculations of particle settling velocity were small. As was seen with pressure loss calculations, the calculated differences became smaller as average annular velocity and average annular shear rates increased.
  5. Sector velocities in the eccentric annulus showed little change for a given pump rate.
- More study of the role of low-to-ultra low shear rates in the promotion of dynamic barite sag should be done. A review of the literautre clearly shows the promise this study could have on significantly improving the ability to predict sag occurrence.

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Nomenclature
AAD = average absolute deviation
ECD = equivalent circulating density
H-B = Herschel-Bulkley rheological model
SBM = synthetic based drilling fluid

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Table 1 – SBM Rheological Data

Viscometer RPM	Dial Reading Ramge 1	Dial Reading Range 2	Dial Reading Range 3
600 rpm	110	110	110
300 rpm	65	65	65
200 rpm	49	49	49
100 rpm	31	31	31
6 rpm	11	11	11
3 rpm	10.5	10.5	10.5
0.9 rpm	-	5.5	5.5
0.5 rpm	-	-	5.2
H-B 'n'	0.851	0.822	0.808
H-B K [lbf/100 sq ft s^n]	0.294	0.362	0.401
H-B τ_0 [lbf/100 sq ft]	9.8	8.08	7.23

Table 2: Hypothetical Well Profile for ECD Calculations

Section No.	Hole ID [in]	Meausred Depth [ft]	TVD [ft]	Angle [degrees]
1	12.615	5000	5000	0
2	12.25	5400	5200	60
3	12.25	11400	8200	60

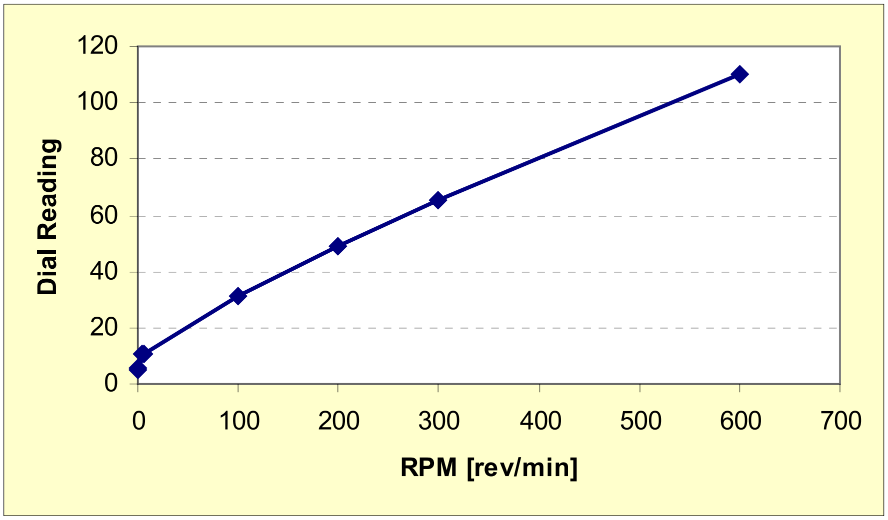

Figure 1: Rheogram of SBM .

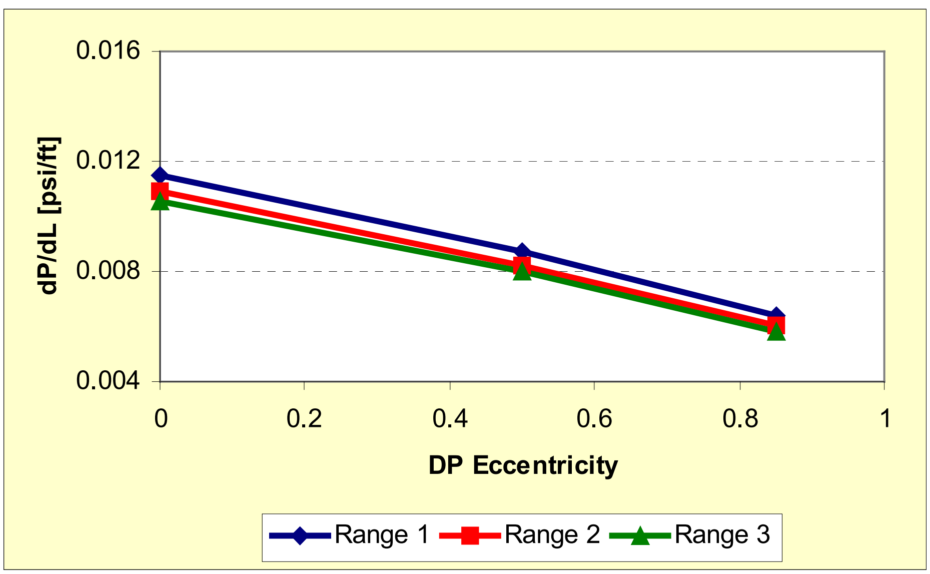

Figure 2: Pressure Loss vs drill pipe eccentricity and rheology range at 800 gal/min.

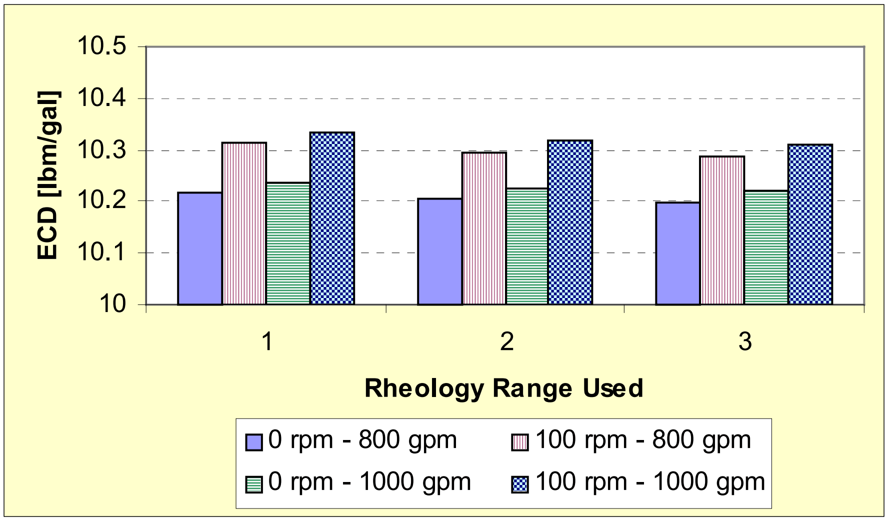

Figure 3: Calculated ECD by pump rate and drill pipe rpm.

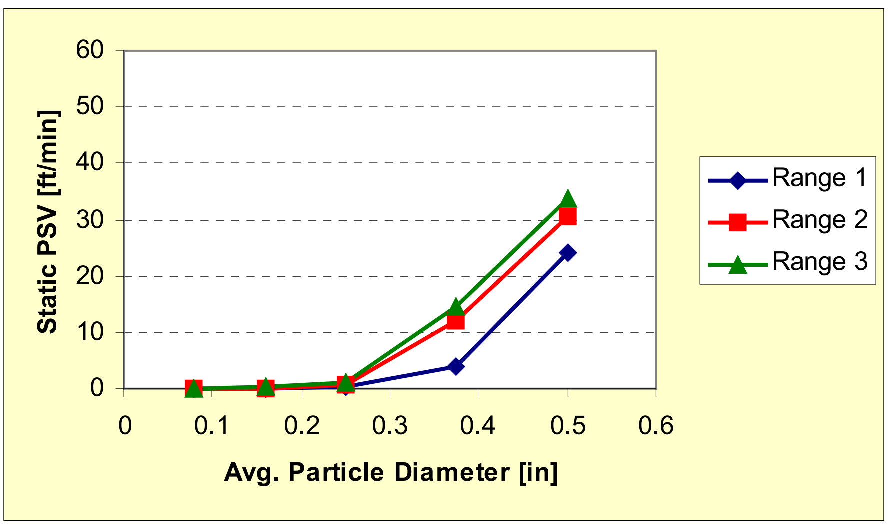

Figure 4: Static PSV by particle diameter and rheology range.

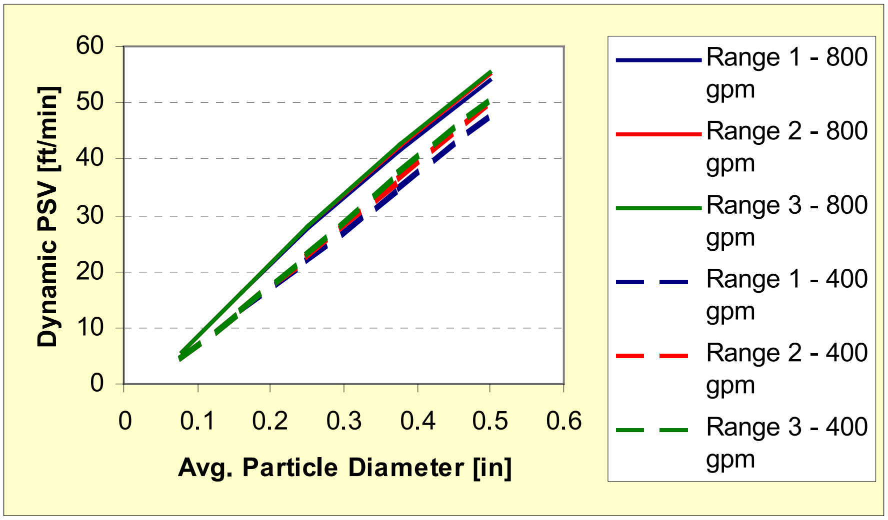

Figure 5: Dynamic PSV by particle diameter, rheology range, and pump output.

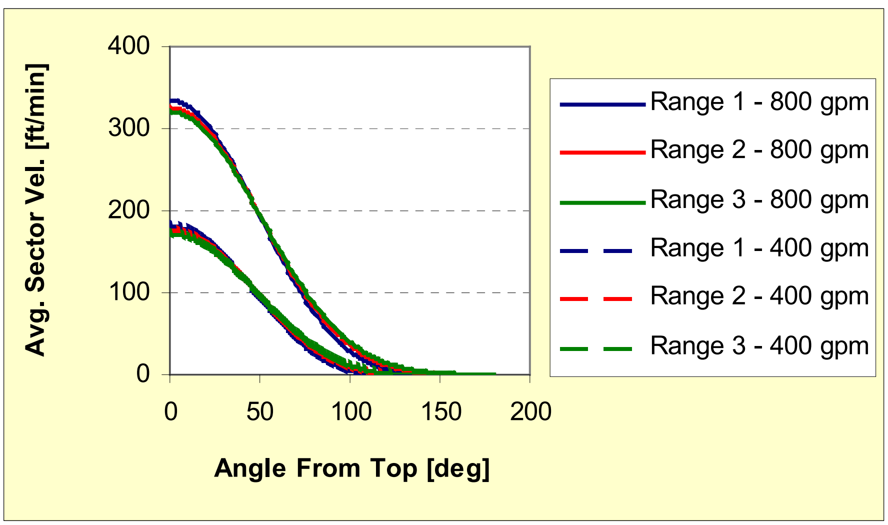

Figure 6: Average sector velocity vs angle from top of annulus, rheology range, and pump output.