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Influence of Loss Circulation Materials on the Rheology of Spacers and Cements

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Abstract

A model was developed for modifying individual viscometer torque readings (viscometer dial reading) at each RPM for the influence of loss circulation materials (LCM or LCMs) on the rheology of particle suspensions. This approach provides the convenience of fitting the RPM vs Dial Readings to the viscometric model of choice. The model was developed by testing a significant range of LCMs ranging from: 0.1 to 9.5 mm in size; shape factors ranging 0.06 to 0.95; general shapes of near spheres, ellipsoids, thin flakes, fibers; relative particle textures of very hard, stiff rubber, flexible rubber and plastic; at volume fractions from 0.002 to 0.13. Future work will focus on expanding the volume fraction range.

Introduction

LCM has been used for decades in drilling and cementing of oil wells. However, in recent years, the need for more and larger LCMs keeps increasing due to the type of reservoirs being developed. It is well known that having accurate rheological data for spacers and cement slurries is critical when designing cement jobs. However, obtaining accurate rheological data for LCM laden fluids presents a challenge. The objective of this paper is to present a reliable method and rheological model for spacers and cement slurries containing LCM.

Most oil field viscometers are the bob and sleeve couette type. To have accuracy and sensitivity, the annular gap between the bob and sleeve is traditionally very small when compared to the size of many LCMs that are being used in spacers and cement slurries. Thus, the standard bob and sleeve couette viscometers cannot be used to measure the rheology of spacers and cement slurries with moderate to large LCM sizes. One of the traditional workarounds is to use smaller bobs, thus enlarging the annular gap, to prevent particle jamming. However, this often leads to centrifugal stratification of the LCM particles and may significantly affect accuracy.

Johnson and Morgan (2006) developed a multiple bladed bob and sleeve to overcome the particle jamming issues with LCM particles. The blades were uniquely located on the bob and sleeve so as to provide consistent shear gaps for creating torque while also keeping particulates homogeneously suspended in the fluid. This mixing type viscometer was also found very useful in measuring rheology of foams, such as foam cement and foam fracturing fluids. Harris et al. (2005) used the multiple intermeshing blades of a similar mixing type viscometer to measure the rheology of fracturing fluids with high concentrations of proppant and detect the onset of particle settling.

Thus, a method is needed to transform bob and sleeve rheology data for a spacer or cement slurry without LCM, referred to as the clean fluid, into reliable and accurate rheological data for the same fluid containing a given concentration of a given LCM. Many published works exist on various approaches and mathematical models to achieve this, such as Einstein's (1906) original work describing the effects of solid particles on the viscosity of fluids. Einstein's renown equation was:

$$\eta_p = \eta_0 \ (1 + K f_v) \qquad [1]$$

where: η_p is the apparent viscosity of the fluid with the solid particles; η_0 is the apparent viscosity of the fluid without solid particles, i.e., the clean fluid; f_v is the volume fraction of the solid particles; and K is a coefficient that Einstein reported to be 2.5 for low concentrations of spheres. Vand (1945) reported that Eq. [1] is valid for non-spherical particles where the value of K is a function of shape, rigidity, and Brownian movement. Vand (1945) developed the following relationship for concentrated suspensions:

$$\eta_p = \eta_0 \ (1 - f_v - q(f_v^2))^{-K} \qquad [2]$$

Vand (1945) found for rigid spheres in concentrations from 0 to 0.4, that q was 1.16 and K was 2.5. The value of q is expected to be less if the spheres were made of soft material.

Maron and Pierce (1956) presented the following relationship for concentrations from very low to near particle packing:

$$\eta_p = \eta_0 \ (1 - f_v / f_{vm})^{-2} \qquad [3]$$

where: f_{vm} is the maximum packing concentration.

Mueller et al. (2009) reported on work by several studies by various researchers on attempts to verify Einstein's K value of

2.5, which is sometimes called the “intrinsic viscosity”. Mueller et al. (2009) reported that the values for K from the various studies ranged from 1.5 to 5. As particle concentrations increase above 0.12 (where particle to particle collision impact becomes important) using Eq. [2] can become less accurate for a wide range of particle sizes and shapes.

The legendary work by Krieger and Dougherty (1959) has been foundational for most researchers studying this topic. Their work is best summarized by their model for describing the volumetric effects of solids in suspending fluids, as follows:

$$\eta_r = (1 - f_v/f_{vm})^{-[\eta] f_{vm}} \qquad [4]$$

where: $\eta_r = \eta_p/\eta_0$ the relative viscosity; and [η] is the intrinsic viscosity.

Morgan et al. (2002) conducted an extensive study of the rheology of highly concentrated particle-liquid systems. Their work used a mixing type viscometer to measure the rheological impact on Newtonian and Power Law fluids of wide range of particles for volume fractions from 0.05 to 0.50. Particle sizes ranged from 260 to 1020 microns, while specific gravities ranged from 1.13 to 3.6. In the same study, particle sphericity ranged from 0.7 to 0.95. Morgan et al. (2002) presented the following relationship to account for concentration effects:

$$K_{sp} = A_1\,C + A_2\,C^{B2} + A_3\,C^{B3} \qquad [5]$$

where: A_1 was determined to be 2.5; A_2 was determined to be 6.25; B_2 was found to be 1.62; A_3 was a function of average particle size, K_o (the Power Law Consistency Coefficient of the clean fluid without particles); the Power Law shear thinning index and sphericity; and B_3 was found to be 7.5; and where $K_{sp} = (K_c - K_o)/K_o$ with K_c being the Power Law Consistency Coefficient of the slurry with particles.

Cayeux and Leulseged (2019) developed empirical relationships for describing effects of various sizes and shapes of sand particles on the Herschel-Bulkley parameters of a KCl/Polymer water-based mud.

Vergote et al. (2023) studied the effects of concentration and particle morphology of slag suspensions. Their work measured the effects of volume fractions ranging from about 0.01 to 0.16 for shear rates of 2.5 and 24.5 1/sec. Kulkarni et al. (2016) compared the results of measured effects of large LCM particles (D,50 > 400 microns) on rheology of drilling fluids using bob and sleeve viscometers with three different gaps annular gap sizes. The results were used to demonstrate the importance of having accurate rheology data of muds with LCM in order to effectively manage ECD (equivalent circulating density).

Purpose of This Work

The purpose of this work was to develop an effective model for transforming normal rheological data for clean spacer and cement fluids to accurate rheological data of the same fluids containing LCM. The model needed to accommodate various combinations of LCM particles of different densities, shapes, and sizes in concentrations from 0 to 0.15 and sizes from 100 to 4000 microns.

Methods

Two types of spacers and two cement slurry types were used as the carriers or suspending fluids for a wide range of LCM types, sizes, densities, and shapes. Table 1 summarizes the side-by-side testing approach for this work.

Table 1. Side-by-Side Viscometer Test Method

Preparation of the clean spacer of cement slurry-conventional method
Collection of RPM vs Dial (torque) data for the clean fluid
Add the given volume fraction of LCM and mix
Collection of RPM vs Dial (torque) data for fluid with LCM

The test method in Table 1 was used to collect viscometer RPM vs. Dial readings for the clean fluids without and then with various amounts of LCM added. This approach was used to test 45 different combinations of the spacers, slurries, and LCMs summarized in Table 2.

Table 2. Summary of Experimental Combinations

Fluid types: Two spacers and two cement slurries
Number of LCM types: 9
Number of LCM combinations: 3
LCM generalized shape: spheres; ellipsoids; flakes, fibers
LCM material texture: very hard; hard; stiff rubber; flexible rubber/plastic
Specific gravity of LCMs: 1.07 to 2.68
Shape factor of LCMs: 0.065 to 0.95
D-50 of LCMs: 0.4 to 2.4 mm
Range of all particle sizes: 0.1 to 9.5 mm
Range of aspect ratios: 1 to 75
Volume fraction of LCMs: 0.0021 to 0.134
Yield stress of clean fluids: 0.43 to 7.0 Pa
Shear thinning index of clean fluids: 0.31 to 1.0

The viscometer described in Johnson and Morgan (2005) was used to collect the RPM vs Dial readings for the spacer and slurry fluids without LCM and then with LCM. The unique intermeshing teeth geometry was selected for three reasons: 1) it allowed for D-50 sizes up to 4 mm microns without jamming; 2) it is a proven method when compared with the standard R1/B1 bob and sleeve viscometer conventionally used in the oil industry; and its flow regime ensured particle dispersion was maintained homogeneous.

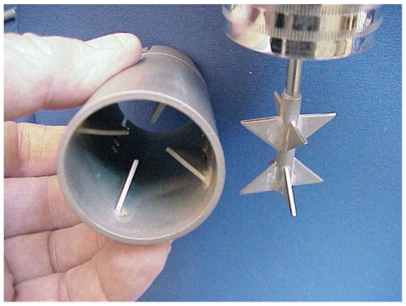

Figure 1. Photo of actual viscometer with intermeshing teeth that was adapted to a conventional bob and sleeve viscometer.

A standard calibration method was used to verify the K1 and K2 values for the viscometer in Figure 1, where Shear Rate (SR) was computed as SR = K1*RPM and Shear Stress (SS) was computed as SS = K2*Dial reading (SS has units of Pa).

Model Development

As summarized in the literature review above, there have been various models developed over several decades to predict the rheological impact of adding LCM and other particles to carrier fluids. Most of the work referenced above focused on developing multipliers for various viscometric parameters, such as Newtonian viscosity, apparent viscosity, power law consistency coefficients, and Herschel-Bulkley coefficients. The more parameters in a chosen viscometric model, the more difficult the challenge of developing reliable and accurate models for predicting the effects of adding LCM particles to carrier fluids, such as spacers and cement slurries.

Becker et al. (2003) introduced a four parameter viscometric model, called the Generalized Herschel-Bulkley (GHB) model and found significant improvement in predicting hydraulic friction across a wide range of oil well fluids. For example, the GHB model provided improved accuracy for predicting yield points of foamed cements versus the use of Bingham Plastic and Herschel-Bulkley. However, the GHB viscometric model developed by Becker et al.(2003) is universal in that collapses to a wide range of traditional viscometric models including: Newtonian; Power Law; Bingham Plastic; Herschel-Bulkley; Casson and Heinz.

However, given the need to predict the impact of adding LCM to GHB type fluids, the authors elected to develop a model that would be used as a multiplier to each viscometer Dial Reading at each RPM. The model form selected was a "Product Solution" type as follows:

$$\frac{DR_{rpm,lcm}}{DR_{rpm}} = [Conc.][Shape][Size][Shear\ Thinning] \ldots$$

$$\ldots .[Yield\ Stress][Density\ Ratio] \qquad [6]$$

Where: $DR_{rpm,lcm}$ = viscometer dial reading at given RPM and concentration of lcm; DR_{rpm} = viscometer dial reading at same rpm for clean fluid without LCM; [Conc.] = multiplier for volume concentration effects; [Shape] = multiplier for particle shape effects; [Size] = multiplier for size effects; [Shear Thinning] = multiplier for shear thinning effects of clean carrier fluid; [Yield Stress] = multiplier for effects of yield point of clean carrier fluid; and [Density Ratio] = multiplier for effects of differences in particle specific gravity and specific gravity of the clean carrier fluid.

Each of the "modular multiplier functions" were selected such that each meets the boundary condition of not being zero. Additionally, each "modular multiplier function" is dimensionless except for the [Size] module which has the units of mm. These "modular multiplier functions" are defined as follows:

$$[\text{Conc}] = K_{oo} + K_{fv}(f_v^{\alpha_{fv}}) \qquad [7]$$

$$[\text{Shape}] = SF^{\alpha_{sf}} \qquad [8]$$

$$[\text{Size}] = (1 + D_{50})^{\alpha_{d50}} \qquad [9]$$

$$[\text{Shear Thinning}] = \left(\frac{3n}{2n+1}\right)^{\alpha_n} \qquad [10]$$

$$[\text{Yield Stress}] = \left(1 + \frac{\tau_o}{K_2\, DR_{rpm}}\right)^{\alpha_{ss}} \qquad [11]$$

$$[\text{Density Ratio}] = (1+NDR) \qquad [12]$$

$$\text{NDR} = \ absolute\ v.\left(\frac{SG_f - SG_{lcm}}{SG_f}\right)^{\alpha_{SG}} \qquad [13]$$

Results

The customized mixing type viscometer presented in Figure 1 was used to collect RPM vs Dial Reading data for the clean carrier fluids and then with the same carrier fluids contained given concentration of LCMs and combinations of multiple LCMs for the test defined in Tables 1 and 2. When combinations of different LCM types were used, mass averages were used to determine the values of SF, D_{50}, and SG_{lcm}.

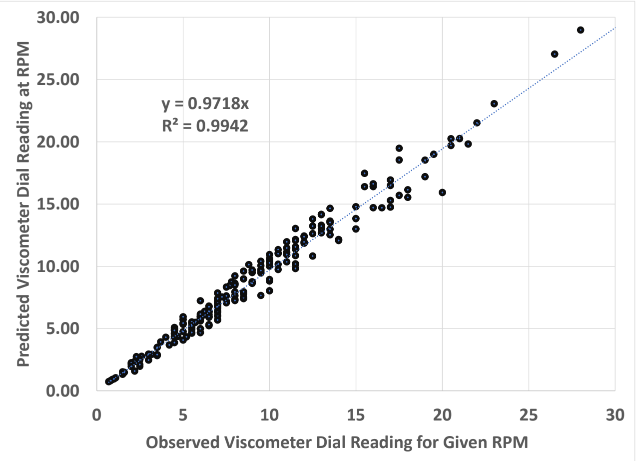

Figure 2 is a plot of X = Observed viscometer dial readings ($DR_{rpm,lcm}$) with the LCM in the carrier fluid vs Y = Predicted viscometer readings with LCM using Eq. [6] through Eq.[12].

When fitting the parameters in Equations [6] through Eq [12], the best results were obtained by setting K_{oo} = 1.0 and K_{fv} = 2.5, based on convention. Then the remaining best fit parameter values were determined as follows:

α_{fv} = 0.816,
α_{sf} = -0.080
α_{d50} = 0.035,
α_n = 0.19,
α_{SS} = 0.081, and
α_{SG} = 0.19.

Considering that the maximum range of volume concentration for this study was < 0.14, these results confirm the finding of Ouchiyama and Tanaka (1980) that the minimum concentration of uniformed spheres before particles collide is 0.127. The small value of α_{d50} is also related to the fact that concentrations were < 0.14.

The model presented above with the best fit parameters, resulted in 88% of all predicted viscometer dial readings being > 85% accurate as compared to the measured values. The average of the absolute error for all data was 7.5%.

Further studies will focus on broadening the range of rheological properties, mainly yield stress and shear thinning indices. Additional work will focus on measuring the accuracy of the format of Eq. [6] through Eq. [12] for volume concentrations > 0.14.

Conclusions

This work examines the effects of particle suspensions on various viscometric model parameters and provides a simple method to predict the increase in the individual dial readings (torque) at each RPM by measuring the rheology of the clean suspending fluid. Given the predicted RPM vs DIAL readings for the effects of the particles and their properties, the viscometric model of choice can be used to fit the RPM vs $DR_{,rpm,lcm}$ data. The authors recommend using the Generalized Herschel-Bulkley (GHB) viscometric model presented by Becker et al. 2003 because of its versatility. The GHB model is preferred because it can be used in various numerical modeling methods to solve the equations of motion, while also reducing to multiple viscometric models such as: Newtonian; Power Law; Bingham Plastic; Herschel-Bulkley; Casson; and others.

The robustness of the particle suspension model presented in this work (Eq.[6] through Eq. [12]) is proven by the fit in Figure 2 for a wide range of particle sizes, shapes, textures (hardness), and concentrations.

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Nomenclature

A_1 = Dimensionless coefficient in Eq. [5]
A_2 = Dimensionless coefficient in Eq. [5]
A_3 = Dimensionless coefficient in Eq. [5]
B2 = Dimensionless coefficient in Eq. [5]
B3 = Dimensionless coefficient in Eq. [5]
C = Volume concentration of particles in Eq. [5]
D_{50} = Mass average diameter of particles
$DR_{rpm,lcm}$ = Viscometer dial reading at given RPM and concentration of lcm
DR_{rpm} = Viscometer dial reading at given RPM for clean fluid without LCM
f_v = Volume fraction of particles
f_{vm} = Maximum packing volume fraction
K = Dimensionless coefficient in Eq. [1] and [2]
$K1$ = Coefficient for computing shear rate of viscometer
$K2$ = Coefficient for computing shear stress of viscometer
K_c = Consistency coefficient of Power Law fluid with LCM
K_o = Consistency coefficient of Power Law fluid without LCM
$K_{sp} = (K_c - K_o)/K_o$
K_{oo} = Dimensionless coefficient in Eq. [7], [Conc.]
K_{fv} = Dimensionless coefficient in Eq. [7], [Conc.]
n = Shear thinning index of Generalized Herschel-Bulkley fluid
NDR = Normalized Density Ratio in Eq. [12, 13]
q = Dimensionless coefficient in Eq. [2]
SF = Dimensionless shape factor in Eq. [8]
SG_f = Specific gravity of suspending fluid
SG_{lcm} = Specific gravity of LCM particle
α_{d50} = Exponent in Eq.[9], D_{50} must be in units of mm
α_{fv} = Dimensionless exponent in Eq. [7]
α_n = Dimensionless exponent in Eq. [10]
α_{sf} = Dimensionless exponent in Eq. [8]
α_{SG} = Dimensionless exponent in Eq. [12]
α_{ss} = Dimensionless exponent in Eq. [11]
η_0 = Apparent viscosity of suspending fluid without LCM
η_p = Apparent viscosity of suspending fluid with LCM
$\eta_r = \eta_p/\eta_0$
τ_o = Yield point of suspending fluid without LCM

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