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Viscous behavior and wall slip of barite-weighted water-based drilling fluids containing a high particle fraction

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ABSTRACT

Accurate rheological measurements of barite-weighted ultrahigh density water-based drilling fluids with a rotational viscometer may be hindered by the wall slip effect. This paper describes a correction method that is based on the principle of flow curves gap dependence. A two-stage Tikhonov regularization numerical strategy was developed to obtain the true viscous behavior and wall slip of barite-weighted drilling fluids containing a high particle fraction. The proposed approach does not depend on the narrow gap assumption or the prescribed form of rheological models. The results show that barite-weighted ultrahigh density drilling fluids start to slip after reaching a small value of critical shear stress, and the wall slip velocity increases linearly as a function of shear. There are significant discrepancies between the slip-corrected rheological models and the apparent models. Curve fitting results show that the slip-corrected flow curves are linear as would be expected for Bingham plastic fluids, while the uncorrected apparent flow curves are nonlinear as one would expect for yield power law fluids. Failing to correct for the wall slip effect would result in seriously underestimating the bulk viscosity of barite-weighted ultrahigh density water-based drilling fluids.

1. Introduction

Ultrahigh density drilling fluids have been widely used to balance the abnormal ultrahigh formation pressure in the oil and gas industry. Their rheological properties affect several aspects of the drilling process, such as the borehole cleaning, hydraulic power optimization of the jet flow, and pressure loss calculation of the annulus hydraulic (Dokhani et al., 2016; Erge et al., 2015; Kelessidis et al., 2006; Mahto and Sharma, 2004).

Concentric cylinder viscometers of robust design are often used in the oil and gas industry to collect rheological data of drilling fluids (Guzek et al., 2015; Mahmoud et al., 2017; Sisodia et al., 2015). The equations used in the procedure that relates stress field to the flow field are based on the no-slip boundary assumption, which is the assumption that the velocity of a fluid at a solid boundary is zero. This is valid for Newtonian fluids under normal flow conditions, but there is a growing body of evidence indicating that some rheologically complex non-Newtonian fluids (e.g., gels, foams, polymeric liquids, emulsions, and suspensions) may exhibit a phenomenon called wall slip that occurs at solid-fluid boundaries (Ahuja and Singh, 2009; Barnes, 1995; Brunn et al., 1996; Churchill, 2011; Kalyon, 2005; Pilehvari and Clark, 1985; Sadeghy, 2001; Wang and Pu, 2011). As a result of the wall slip effect, fluid viscosity measurements are affected enough to yield significant errors.

Mooney (1931) first proposed a correction method for wall slip Couette viscometer. His method required experimental data from three measuring sets of precisely diameters. Using Mooney's method, several researches in the cementing industry have shown that the flow curves for a given cement slurry is not always independent of the annular gap size, and the effect of wall slip could be accounted for (Denis and Guillot, 1987; Haimoni, 1987; Lapasin et al., 1983; Mannheimer, 1983; Tattersall, 1973). Guillot (1990) pointed out that in the absence of a proven method of allowing for wall slippage, the coaxial cylinder viscometer data should not be used when trying to determine the rheological parameters of cement slurry. Yoshimura and Prud'homme (1988a; 1988b) derived a method that only needs data from two different viscometers with the same radius ratio. Kiljański (1989) presented a method that also only required data from two measuring sets and no radius ratio restriction, but this method assumes that the fluid is a power law fluid and is restricted to viscometers with a narrow annular gap. Wein and Tovchigrechko (1992) described a method that can cope with data from different Couette viscometers under presence of apparent wall slip, and this method has no explicit restrictions on the cylinder radius. More recently, Yeow et al. (2004) developed a general method for obtaining

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the shear rate function and the slip velocity function simultaneously from Couette viscometry data based on Tikhonov regularization. This method benefits from the advantages that it is not restricted to narrow the gap condition and does not require that the material function be prescribed.

Despite the fact that barite-weighted ultrahigh density drilling fluids are suspensions, which are known to be vulnerable to wall slip, to date, there has been little investigation into the effects of wall slip on the collection of viscosity data for ultrahigh density drilling fluids. Therefore, knowledge of the effects of wall slip on viscosity readings is still limited.

The objective of this study is to investigate the viscous properties and wall slip behaviors of barite-weighted ultrahigh density water-based drilling fluids. First, we collected the two-measurement experimental data of the tested ultrahigh density drilling fluids using two measuring settings with different annular gaps. Second, a two-stage Tikhonov regularization numerical strategy was developed and programmed into MATLAB software. Then, by applying this numerical strategy to the experimental data, both the slip velocity and the true rheological models were extracted simultaneously. Finally, the computation results of the slip-corrected rheological models and the uncorrected models were compared. Furthermore, the empirical correlations of wall slip velocity with shear stress are also presented in this paper.

2. Experimental

The test drilling fluid for this work was prepared using base drilling fluid and barite powder. The base drilling fluid was formulated by blending an aqueous suspension of bentonite (Xiazijie, Xinjiang, China), zwitterionic viscosifier (FA-367), sulfonated filtrate reducers (SMP, SMC and SPNH from Chengdu, China), inorganic additives (NaOH and KCl), and an organic salt weighting agent (OS-300 from Karamay, China). Table 1 shows the details of the drilling fluid formulation.

Table 1
Formulation of the drilling fluid.

Components	Name	Amount (wt. %)
Bentonite (particle)	Xiazijie bentonite	2.5
Viscosifier (polymer)	FA-367	0.3
Fluid loss additive Ⅰ (polymer)	SMP	2
Fluid loss additive Ⅱ (polymer)	SMC	3
Fluid loss additive Ⅲ (polymer)	SPNH	3
pH control additive (inorganic)	NaOH	0.5
Shale stabilizer (inorganic)	KCl	3
Organic salt weighting agent	OS-300	30-90 (as required)
Barite powder (particle)	API Barite	as required

Three drilling fluid samples were prepared with densities of 1.8 g/cm^3 (15.02 ppg), 2.3 g/cm^3 (19.19 ppg), and 2.8 g/cm^3 (23.36 ppg). The barite powder used in this study had a mean particle diameter of 24.86 μm, and 90% of the barite powder particles were smaller than 56.26 μm. Fig. 1 shows the particle size distribution.

To allow for the wall slip effect of barite-weighted ultrahigh density water-based drilling fluids, a classic two-measurement method was done with a robust designed concentric cylinder rotational viscometer (Fann model 35SA). For one given drilling fluid sample, two measurements were carried out with annular gaps of 1.17 mm and 1.65 mm and a corresponding combination of cup and bob with inner/outer diameters 36.83 mm/34.49 mm and 37.30 mm/34.00 mm, respectively.

The outer cylinder of the rotational viscometer used in this work was operated under the speed-controlled model and rotated at the known constant speeds of 600, 300, 200, 100, 6 and 3 RPM. The torque on the inner cylinder was measured with a torque transducer, and the dial readings were recorded. Each test was repeated at least two times for accuracy.

3. Mathematics

3.1. Basic equations

Allowing for the wall slip effect, a velocity profile of the drilling fluid in the annular gap of the rotational viscometer is shown in Fig. 2.

The relationship between the rotational speed ω and the wall shear stress τ can be expressed by the basic equation of Couette viscometry (Yeow et al., 2000; Yoshimura and Prud'homme, 1988a; Yoshimura and Prud'homme, 1988b):

$$\omega = (\omega_{sc} + \omega_{sb}) + \frac{1}{2}\int_{\tau_c \mathrm{or} \tau_y}^{\tau_b} \frac{\dot{\gamma}(\tau)}{\tau} \mathrm{d}\tau \quad (1)$$

where, $\omega_{sc} = v_{sc}/R_c$ and $\omega_{sb} = v_{sb}/R_b$ represent the slip contributions to the angular velocity at the cup and bob wall, and τ_c and τ_b represent shear stresses at the cup and bob walls, respectively. $\dot{\gamma}(\tau)$ represents the constitute rheological function of the drilling fluid. For fluids without yield stress the lower limit of integral in $\omega = (\omega_{sc} + \omega_{sb}) + \frac{1}{2}\int_{\tau_c \mathrm{or} \tau_y}^{\tau_b} \frac{\dot{\gamma}(\tau)}{\tau} \mathrm{d}\tau$ Eq. (1) is τ_c. For fluids with yield stress the lower limit is τ_c or τ_y, whichever is larger (Yeow et al., 2000).

If there is no slip at the solid walls, the angular slip velocities equal zero, and Eq. (1) is reduced to

$$\omega = \frac{1}{2}\int_{\tau_c \mathrm{or} \tau_y}^{\tau_b} \frac{\dot{\gamma}(\tau)}{\tau} \mathrm{d}\tau \quad (2)$$

which is the basic equation for the classical case of the no-slip boundary condition (Krieger, 1968; Yeow et al., 2000).

Mathematically, both the basic Eq. (1) for the slip boundary condition and Eq. (2) for the no-slip boundary condition are Volterra integral equations of the first kind, which are well-known as ill-posed equations (De Hoog and Anderssen, 2006; Kirsch, 2011).

3.2. Solution equation

In the field of rheology, the Tikhonov regularization method has been widely used to solve the ill-posed problems of Couette, capillary and parallel disk viscometries (De Hoog and Anderssen, 2006; Nguyen et al., 1999; Weese, 1993; Yeow et al., 2000, 2004; Zahirovic et al., 2009). It has been proved to be reliable for determining the shear stress vs. shear rate plots from experimental data.

To apply the Tikhonov regularization, the basic equation was firstly discretized and rewritten as follows. (Details of the derivation are given in Appendix A).

$$\boldsymbol{\omega}_c = \boldsymbol{C}\boldsymbol{D} \quad (3)$$

where the subscript c is used to denote the computed angular velocity, the matrix $\boldsymbol{C}$ is a composite coefficient matrix (see Eqs. (A.4) and (A.6) in Appendix A), and $\boldsymbol{D}$ represents the composite column vector of all the unknown angular slip velocities and shear rates (see Eqs. (A.5) and (A.7)).

By applying Tikhonov regularization, the resulting approximate $\boldsymbol{D}$ is given by the following equation. (Details of the derivation are given in Appendix B.).

$$\boldsymbol{D} = \left(\boldsymbol{C}^{\mathrm{T}}\boldsymbol{C} + \lambda\boldsymbol{M}^{\mathrm{T}}\boldsymbol{M}\right)^{-1}\boldsymbol{C}^{\mathrm{T}}\boldsymbol{\omega}_c \quad (4)$$

$\boldsymbol{M}$ represents a composite tri-diagonal matrix (see Eq. (B.3)), and λ represents a regularization parameter. In this study, generalized cross validation (GCV) was adopted to guide the choice of λ (Wahba, 1990; Yeow et al., 2000). The slip velocities, $\boldsymbol{v}_{slip}$, at the walls of the inner cup and the outer bob were obtained from the relationship between the angular slip velocity, $\boldsymbol{\omega}_{slip}$, and the radius, R.

It is worth pointing out that the proposed approach in this study differs from the method described in the work of Yeow et al. (2004). First, the fractional deviation may be unrealistic for a wide range of rotation speeds. Therefore, rather than fractional deviation used in Yeow's work, we used the absolute deviation to quantify the precision