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An improved estimation of shear rate for yield stress fluids using rotating concentric cylinder Fann viscometer

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ABSTRACT

This paper deals with the estimation of wall shear rates for yield stress fluids using rotating coaxial-cylinder viscometer readings. The estimation is based on the generalized difference equation for rotating narrow gap coaxial cylinder Fann Viscometer under purely steady, laminar and isothermal tangential fluid flow condition. Rotor rotations and bob deflections are the two important viscometer readings and these are used to predict wall shear rates. The proposed equations are used to calculate shear rates for several Herschel–Bulkley type fluids involving polymer (for example, xanthan gum, poly-anionic cellulose and carbomethoxy cellulose) solutions with varying concentration and bentonite suspension, which are frequently used as drilling fluid additives. Parametric sensitivity is made for stability analysis of the proposed shear rate equations. Finally, the predicted shear rates are compared with the conventional method of estimating the rate of shear for drilling fluids.

1. Introduction

Rheological behavior of polymer solution is very complex and known to behave as a non-Newtonian fluid due to the presence of long chain molecules with different chain lengths. Polymers like xanthan gum, poly-anionic cellulose and carboxy methyl cellulose play an important role to control the rheology of drilling fluids and the drilling efficiency is improved significantly in the presence of these polymer additives (Darley and Gray, 1986; Bourgoyne et al., 1991). Bentonite is one of the key components in drilling fluid that exhibits non-Newtonian behavior due to the presence of fixed ionic charges on the surface of the clay particles. Yield point, apparent viscosity, plastic viscosity and gel points are the important rheological properties of drilling fluid which is continuously monitored during drilling operation. In oil fields, Fann viscometer and Marsh funnel are frequently used to measure the rheological properties of the drilling fluids (Gatlin, 1960; Darley and Gray, 1986; Bourgoyne et al., 1991; Guria et al., 2013). Fann 35 viscometer is a rotational coaxial cylinder viscometer where drilling fluid is placed in the narrow annular space between rotor (i.e., outer cylinder) and bob (i.e., inner cylinder). Usually rotor is in motion which invariably results Couette flow. Dial reading (i.e., bob deflection) is measured for a given rotor rotation and it is converted into the shear stress with reasonable accuracy (Bourgoyne et al., 1991). However, there is no straight forward methodology available in the literature to determine the shear rates *accurately* and it has been a subject of research since long time. The difficulty of measuring shear rates arises due to the non-uniform distribution of fluid flow in the concentric annulus of the rotational viscometer. Numerous studies were carried out in the recent past to determine the shear rate at the wall and the details have been described by Wazer et al. (1963), Middleman (1968), Steffe (1996), Chhabra and Richardson (2008), Kumar and Guria (2013) and Kumar et al. (2014). Kelessidis and Maglione (2006, 2008) adopted series expansion methodology to invert the flow equation of Herschel–Bulkley, Casson and Robertson-Stiff fluids using Couette Viscometer data for finding the shear rates and the corresponding model parameters. To monitor the rheological parameters while drilling of oil wells, simple Newtonian fluid flow approximation was made to estimate the shear rates of drilling fluid using Fann Viscometer reading (Bourgoyne et al., 1991), which helps to determine apparent viscosity, plastic viscosity, Bingham yield point and gel strength of drilling fluids very easily (Gatlin, 1960; Darley and Gray, 1986; Bourgoyne et al., 1991). However, the assumption of Newtonian behavior of drilling fluids in the narrow gap rotating coaxial cylinder viscometer is not valid during rheological analysis (Bailey and Weir, 1998; Joye, 2003; Kelessidis and Maglione, 2006; Kelessidis et al., 2006, 2007, 2010, 2011). More recently, Kumar and Guria (2013) and Kumar et al. (2014) reviewed the estimation of wall shear rates for the rotational viscometer and proposed shear several shear rate equations which were based on the generalized difference equation for the rotating narrow gap coaxial cylinder Fann Viscometer under purely steady, laminar and isothermal tangential fluid flow

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Nomenclature

A, B	roots of Eq. (B.3)
C	root of Eq. (C.3)
D	differential operator ($=\mathrm{d}/\mathrm{d}\tau$)
E–H	roots of Eq. (C.3)
h	bob height (m)
i	integer in Eq. (8) (0–∞) and Table 2 (Krieger–Elrod equation)
I	integral, defined in Eq. (A.4)
k_1	spring constant (N m/scale unit)
K	constant in Herschel–Bulkley type flow equation (rad s^{-1} Pa^{-n})
k	flow consistency parameter (Pa s^n)
m	flow behavior parameter Herschel–Bulkley type flow equation (Eq. (8))
N	rotor rotation, rpm
n	flow behavior index
$O(h^n)$	Taylor series truncation error of the order n, $h=\tau(1-s^2)$
p	variable depends on τ and defined in Eq. (12)
ΣQ^2	sum of the errors square
rpm	revolution per minute (min^{-1})
r	radius (m)
R^2	correlation coefficient
s	radius ratio of bob to rotor ($=r_1/r_2$)
x	dummy variable for τ (Pa)
y	variable, τ–τ_0, (Pa)

Greek symbols

β	defined in Eq. (7)
γ	shear rate (s^{-1})
Γ	gamma function
μ	apparent viscosity (cP)
ρ	fluid density (kg m^{-3})
τ	shear stress (Pa)
τ_0	yield stress (Pa)
θ	bob dial reading (deg.)
ω	angular velocity (rad s^{-1})

Subscripts

r	radial
w	wall
θ	θ-directional axis
1	bob
2	rotor

condition. However, the studies of Kumar and Guria (2013) and Kumar et al. (2014) were limited to Newtonian and power law type fluids *only*. In reality, most of the drilling fluids behave like Herschel–Bulkley fluid with a finite yield stress value. In this case, it is difficult to apply the shear rate equations of Kumar and Guria (2013) and Kumar et al. (2014) for the calculation of rheological properties using drilling fluids.

In the present study, the works of Kumar and Guria (2013) and Kumar et al. (2014) were extended and the shear rates were calculated for the fluids with yield stress using rotational coaxial cylinder Fann Viscometer. The generalized difference equation of rotating coaxial cylinder viscometer was used to determine the rate of shear under purely steady, laminar and isothermal tangential flow condition of the fluids which behave as Herschel–Bulkley fluids. Several drilling fluid polymer additives (for example; xanthan gum, poly-anionic cellulose and carbomethoxy cellulose) with varying concentration and bentonite suspension were considered for rheological analysis. The efficiency of the proposed equations has also been compared with the existing shear rate equations (Krieger and Elrod, 1953; Middleman, 1968; Apelblat et al., 1975; Bourgoyne et al., 1991; Kumar and Guria, 2013; Kumar et al., 2014).

2. Experimental

In the present study, Fann 35 Viscometer (API RP 13B: Model 35) was used for rheological analysis of aqueous solution of xanthan gum (XG), poly-anionic cellulose (PAC), carboxy methyl cellulose (CMC) and bentonite suspension separately at room temperature (i.e., 305 K). The detail dimensions of above Fann 35 Viscometer were described by Bourgoyne et al. (1991). For consistent Fann 35 Viscometer readings, experiments were also repeated for several times with fresh suspensions. Aqueous polymer solutions and bentonite suspension used for rheological analysis using Fann 35 viscometer were prepared as per API standard procedure. Aqueous food grade XG solution with 0.28% and 0.85% concentrations was prepared using de-mineralized water by vigorous mixing and subsequent cooling. PAC solution of 0.28%, 0.75% and 1.0% concentration was prepared by adding PAC (specific gravity: 1.5) to the de-mineralized water with 4.0% sodium chloride solution under stirring. Similarly, 0.28% CMC solution was prepared by adding high viscosity grade CMC to the de-mineralized water with 4.0% sodium chloride solution under stirring at room temperature. Bentonite mud at higher concentration exhibits Herschel–Bulkley fluid behavior with high yield stress. Bentonite powder was directly used for rheological analysis with the following specifications: surface mean particle diameter-3.0 μm, loss on drying-3.0% and suspension pH-10.0 (suspension was prepared by dispersing 4.0 g of dried bentonite in 200 cm^3 de-mineralized water). Aqueous 6.0% bentonite suspension was prepared using standard Hamilton Beach high-speed mixer (Model 550). In this study, de-mineralized water with pH ~ 9.0 was used to prepare aqueous polymer solutions and bentonite suspension and pH of de-mineralized was adjusted by adding 2.0% aqueous sodium hydroxide solution.

3. Wall shear rate estimation

The generalized θ-component equation of motion for the coaxial rotational cylinder viscometer under purely steady, laminar and isothermal tangential fluid flow condition is given by the following differential equation (Bird et al., 2002; Kumar and Guria, 2013; Kumar et al., 2014):

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}(r^2\tau)=0 \tag{1}$$

The above equation is applicable to the fluids of any kind with Newtonian as well as non-Newtonian behavior. For the materials with yield stress, entire material in the rotational viscometer may not be sheared fully. The un-sheared part in the viscometer will move as a plug flow (i.e., solid flow) and the sheared part will behave as fluid flow. The existence of plug flow in the viscometer will be observed for the materials with sufficiently high yield stress, whereas plug zone will vanish for low yield stress materials,