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An improved estimation of shear rate using rotating coaxial-cylinder Fann viscometer: A rheological study of bentonite and fly ash suspensions

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ABSTRACT

Bentonite is commonly used as a drilling fluid additive for viscosity control during drilling of oil wells. Rheological behavior of bentonite suspensions is very complex and it is very difficult to predict accurate shear rates from viscometer readings. This paper deals with the accurate estimation of shear rates of bentonite suspensions using rotating coaxial-cylinder Fann viscometer readings. Rotor rotations and bob deflections are the two important Fann viscometer readings which are used to predict shear rates with the help of generalized viscometer difference equation. Rheological behavior of bentonite suspensions are also compared with classified fly ash suspensions with varying particle size and solid loading. The proposed shear rate equation is quite general and can be applied to any fluid.

1. Introduction

Rheological behavior of bentonite suspensions is known to be non-Newtonian 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 significantly influence the performance of oil well drilling (Gatlin, 1960; Darley and Gray, 1986; Bourgoyne et al., 1991). Fann viscometer is commonly used to measure the rheological properties of drilling fluid and it is a rotational coaxial-cylinder viscometer where drilling fluid is confined into the annular space between two cylinders (i.e., rotor: outer cylinder, and bob: inner cylinder), one of which is in motion (usually rotor). Rotor rotations and bob deflections are the two important Fann viscometer measured readings which are directly used for rheological analysis of the test fluid. The torque exerted on the inner bob wall is measured directly from dial reading (i.e., bob deflection) for given rotor rotation and it is converted easily into shear stress for known viscometer dimensions (Bourgoyne et al., 1991; Guria et al., 2013). However, the major difficulty arises to predict the wall shear rate which is not straightforward, and it has been the subject of research since a long time. The difficulty of estimating shear rate is mainly due to the non-uniform distribution of shear rate in the concentric cylindrical annulus. Moreover, there is no exact method of calculating shear rate distribution using viscometer readings, unless the fluid model is assumed a-priori. For the materials with unknown rheology, one or more approximate methods must be employed for analyzing the viscometer data. The selection and the accuracy of a technique depend on the radius ratio of bob to rotor and the nature of non-Newtonian fluid tested. Details of these techniques for shear rate estimation have been reviewed by Wazer et al. (1963), Steffe (1996), Chhabra and Richardson (2008). Mooney (1931) first proposed an approximate shear rate equation for a coaxial rotating cylinder viscometer considering uniform shear rate distribution in the narrow gap with negligible viscometer curvatures. He also assumed the shear stress to be the arithmetic mean of the stresses at the bob and rotor walls. Krieger and Maron (1952) obtained an exact shear rate equation for a 'narrow-gap' viscometer by incorporating radius ratio of bob to rotor in the final expression. Krieger and Elrod (1953) derived an asymptotic solution for shear rate using the Euler–MacLaurin formula and proposed an infinite series for shear rate which can be rearranged in such a way that the dominant term was similar to the power law behavior (Krieger, 1968). To correct the homogeneous approximation of shear rate, Moore and Davies (1956) have developed shear rate equation at any point between the rotor and bob by defining a generalized radius in between rotor and bob (i.e., $r = r_2^a r_1^{1-a}$ where parameter 'a' reduces to bob radius for $a = 0$ and rotor radius for $a = 1$). Based on this radius, Moore and Davies proposed the rate of shear in the form of infinite series i.e., $\gamma = \frac{\omega}{k} - (2a-1)\frac{d\omega}{d(\ln T)} + \frac{k}{3}(6a^2-6a+1)\frac{d^2\omega}{d(\ln T)^2} - \frac{k^2}{3}(4a^3-6a^2+2a)\frac{d^3\omega}{d(\ln T)^3} + \cdots$, where $k = \ln(r_2/r_1)$ and T = torque exerted on the bob of wall. Moreover,

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Moore–Davies equation can also be simplified to Krieger–Elrod equation for bob and rotor substituting a = 0 and a = 1 respectively. For a = 1, Moore–Davies equation reduces to the shear rate equation which is similar to Mooney's equation except that it gives the rate of shear corresponding to the geometric mean stress instead of the arithmetic mean stress. Apelblat et al. (1975) proposed an approximate shear rate formula for Couette viscometer with a narrow annular gap by considering the truncated Taylor series with the first three terms. Yang and Krieger (1978) obtained the shear rate using series solution procedure for a model fluid having yield stress. More recently, de Hoog and Anderssen (2006) obtained the improved flow curves from Couette rheometer data using the Euler–MacLaurin sum formula (Krieger and Elrod, 1953). For rheological analysis of drilling fluids, Fann viscometer data reduction is usually carried out with the help of rheological models. Details of these rheological models have been described by Bird et al. (1982) and Bourgoyne et al. (1991). To determine the rheological behavior of drilling fluid, simple Newtonian approximation has been made, and the predicted shear rate is related with the rotor rotation *only* which is independent of the fluid type (Darley and Gray, 1986; Bourgoyne et al., 1991). Till date, this procedure is quite common and it is frequently used to determine the rheological behavior of drilling fluids to monitor the oil well drilling operation (Gatlin, 1960; Darley and Gray, 1986; Bourgoyne et al., 1991).

Fly ash (a mixture of mineral oxides) is a pozzolanic material and is considered as a major environmental pollutant in the ‘recent-past’. Coal fired thermal power plant produces huge amount of fly ash that creates severe waste disposal and environmental problems. In this regard, a good deal of work has been undertaken worldwide for the efficient utilization of fly ash. Utilization of fly ash as a resource material has been studied extensively in many areas such as extraction of valuable minerals, water pollution control, production of ceramic products, composite materials, agriculture, building materials, paint and plastic industries. Many investigators have also been carried out towards effective utilization of fly ash with understanding the potential environmental pollution and health impacts associated with the disposal of fly ash by land filling. More recently, the details of fly ash utilization as resource materials have been reviewed by Ahmaruzzaman (2010). In oil well drilling applications, fly ash is commonly used for the stabilization of drilling fluid wastes to avoid ground water contamination (Deeley et al., 1987; Thompsom, 1994). It is also used as a foamable drilling fluid for deep water offshore drilling operations (Totten et al., 1997). For efficient handling of fly ash suspension in different areas, it is essential to know the actual flow behavior of fly ash suspensions with varying particle size and solid loading.

In this study, an improved shear rate formula has been proposed to predict the accurate rheological behavior of bentonite suspensions for the given dimensions of rotational coaxial-cylinder Fann viscometer. The generalized viscometer difference equation is used to predict wall shear rates of the test fluids with the help of Fann viscometer readings. Classified fly ash suspensions with different particle size and solid loading have also been considered for rheological analysis. The rheological results of fly ash suspensions have also been compared with aqueous bentonite suspensions.

2. Experimental

2.1. Materials

Bentonite powder and fly ash were used for rheological analysis using Fann viscometer. Bentonite powder was used directly for rheological analysis with 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 double distilled water), and it was obtained from SD Fine-Chem Ltd., Mumbai, India. Virgin fly ash was collected from thermal power plant (Rihand, Noida, India: Field No. 08) with specific gravity: 2.0–2.5 and particle size: 1–100 μm. Chemical assay of virgin fly ash was determined using X-ray Fluorescence (Model: PW-1710; Make: Philips) with the following composition (wt.%): SiO_2—59.23, Al_2O_3—32.16, Fe_2O_3—5.03, CaO—0.9 and TiO_2—2.59. Morphological analysis of virgin fly ash was obtained using Scanning Electron Microscope (Model S-440, Make: LEO). The microphotograph of fly ash is shown in Fig. 1 and it reveals that fly ash particles are *almost* spherical and smooth. Zinc chloride with specific gravity: 2.91 and assay: >99.9% was used as a medium to classify the grinded fly ash by float and sink test, and it was also obtained from SD Fine-Chem Ltd., Mumbai, India.

2.2. Classification of fly ash

Virgin fly ash was sieved by using 200 mesh sieve to reject naturally occurring fines and it was grinded using laboratory scale ball mill for 24 h to reduce the particle size. Grinded fly ash was subjected to float and sink test using aqueous zinc chloride solutions with varying specific gravity. Aqueous zinc chloride solutions with 2.0, 1.8 and 1.5 specific gravity were used for classification. Floats were collected from the top which was thoroughly washed with distilled water and finally with methanol to remove residual zinc chloride. Washed floats were centrifuged first and then dried at 100 °C for 48 h to remove residual moisture/methanol content in the fly ash floats. Particle size analysis of dried classified fly ash floats was carried out using laser beam particle size analyzer (Mastersizer S Ver. 2.19, Malvern Instruments Ltd., Malvern, U.K.). Surface mean particle diameters of the classified fly ash floats were found to be 3.21 μm, 2.99 μm and 2.75 μm using aqueous zinc chloride 2.0, 1.8 and 1.5 specific gravity floating medium respectively. Now the classified dried fly ash floats with varying particle size and reduced silica content were used for rheological analysis using Fann viscometer. Here it is mentioned that the classification of grinded fly ash was carried out to reduce the silica content in it. Fly ash with reduced silica content can be used as an additive for drilling fluid with minimum handling problem due to abrasion. Moreover, fly ash floats with low grinding index can easily be grinded to produce nano sized fly ash which may be helpful for the appropriate chemical modification.

2.3. Fann viscometer for rheology

In the present study, Fann viscometer (API RP 13B: Model 35) was used to measure the rheological properties of bentonite and fly ash suspensions. Though the use of Fann viscometer in oil and gas fields is quite old, till date, it has been used as a common instrument to measure

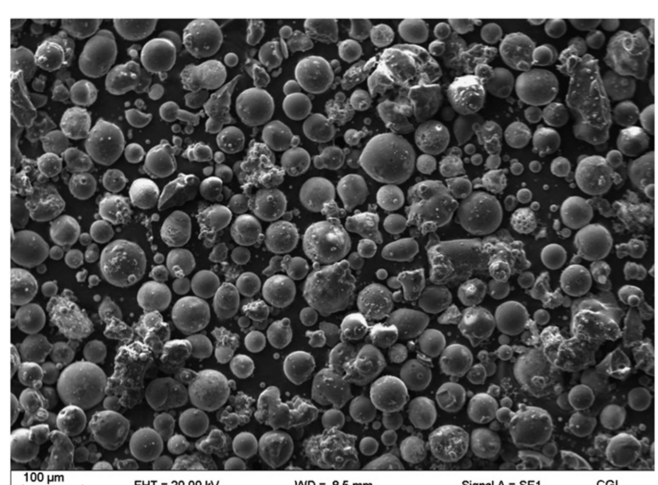

Fig. 1. Scanning electron microscope microphotograph of virgin fly ash.