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Optimal determination of rheological parameters for Herschel–Bulkley drilling fluids and impact on pressure drop, velocity profiles and penetration rates during drilling

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Abstract

Drilling fluids containing bentonite and bentonite–lignite as additives exhibit non-Newtonian rheological behavior which can be described well by the three parameter Herschel–Bulkley rheological model. It is shown that determination of these parameters using standard techniques can sometimes provide non-optimal and even unrealistic solutions which could be detrimental to the estimation of hydraulic parameters during drilling. An optimal procedure is proposed whereby the best value of the yield stress is estimated using the Golden Section search methodology while the fluid consistency and fluid behavior indices are determined with linear regression on the transformed rheometric data. The technique yields in many cases results which are as accurate as these obtained by non-linear regression but also gives positive yield stress in cases where numerical schemes give negative yield stress values. It is shown that the impact of the values of the model parameters can be significant for pressure drop estimation but less significant for velocity profile estimation for flow of these fluids in drill pipes and concentric annuli. It is demonstrated that very small differences among the values of the model parameters determined by different techniques can lead to substantial differences in most operational hydraulic parameters in oil-well drilling, particularly pressure drop and apparent viscosity of the fluid at the drilling bit affecting penetration rates, signifying thus the importance of making the best simulation of the rheological behavior of drilling fluids.

Keywords: Drilling fluids; Rheology; Herschel–Bulkley; Pressure drop; Velocity profile; Penetration rates

1. Introduction

In oil-well drilling, bentonite is added in drilling fluids for viscosity control, to aid the transfer of cuttings from the bottom of the well to the surface, and for filtration control to prevent filtration of drilling fluids into the pores of productive formations. It is long known that above around 120 °C and in conditions of high salinity, bentonite slurries begin to thicken catastrophically (Gray and Darley, 1980; Bleler, 1990; Elward-Berry and Darby, 1992). Attempts to describe and to predict the gelling tendencies of bentonite suspensions have not yet resulted in a concise method which could predict rheological and filtration properties, given the amount of added bentonite and its physical characteristics. The flocculation of bentonite suspensions at high temperatures could be resolved with the addition of

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thinners to reduce the rheology of the mixture but many thinners degrade over the same temperature range. A thinner with high thermal stability is lignite (Clark, 1994; Briscoe et al., 1994; Miano and Rabaioli, 1994) and recent evidence (Mihalakis et al., 2004; Kelessidis et al., 2005) demonstrated the stabilizing effect of Greek lignite in terms of rheological and filtration control of bentonite slurries. Their measurements also showed that the three parameter Herschel–Bulkley model describes well the rheology of these bentonite–lignite water suspensions.

Various rheological models have been proposed to describe the rheological behavior of bentonite mixtures, particularly for drilling applications. The two parameter Bingham plastic model (Bingham, 1922) or the power law model (Govier and Aziz, 1972; Bourgoyne et al., 1991) are used most often because of their simplicity and the fair agreement of predictions with the rheograms. The power law model, although useful as a first correction to Newtonian behavior, it may lead to substantial errors if the fluid exhibits yield stress. Other two parameter models like the Casson model (Casson, 1959; Hanks, 1989) or the Prandl–Eyring model (Govier and Aziz, 1972) have not found wide acceptance. Three constant parameter models have been proposed by Herschel and Bulkley (1926), by Graves and Collins (1978), by Gucuyener (1983) and by Robertson and Stiff (1976). More complex four parameters models (Shulman, 1968; Mnatsakanov et al., 1991) or even five parameter models (Maglione et al., 1996) have also been proposed. Detailed description of the various rheological models proposed and derivation of the appropriate flow equations have been given by Bird et al. (1982) and by Maglione and Romagnoli (1999).

The more complex rheological models are deemed more accurate in predicting the behavior of drilling fluids than the two parameter models that are widely accepted at present. However, there is not wide acceptance and wide application of the more complex models because of the difficulty in finding analytical solutions for the differential equations of motion and because of the complexity of the calculations for the derivation of the appropriate hydraulic parameters such as Reynolds number, flow velocity profiles, circular and annular pressure drops and criteria for transition from laminar to turbulent flow. Simulation of rotational viscometer data of non-Newtonian fluids appears to be better when a larger number of rheological parameters is used but in this case, the hydraulic parameters can be obtained only by numerical methods for most of the more complex rheological models. As of today, a compromise between the accuracy in the calculations and the simplicity of the use is required and the best way to achieve this is with the use of the Herschel–Bulkley rheological model. The three parameter Herschel–Bulkley model has not been used widely until very recently, although it was not only proposed almost at the same time as the Bingham plastic model but it also describes most drilling fluid rheological data much better (Fordham et al., 1991; Hemphil et al., 1993; Maglione and Ferrario, 1996; Kelessidis et al., 2005). The reason for the nonfrequent use is that derivation of the model's three parameters is complex (Nguyen and Boger, 1987; Hemphil et al., 1993). Furthermore, analytical solutions for laminar flow in pipe and annuli are not possible, requiring either graphical or trial-and-error solutions (Hanks, 1979; Govier and Aziz, 1972; Fordham et al., 1991). The advent of personal computers and their online use in the field, however, made trial-and-error solutions trivial tasks, hence, more and more investigators opt to use Herschel–Bulkley rheological models in fluid mechanics computations of drilling fluids (Maglione et al., 1999a; Maglione et al., 2000; Becker et al., 2003). A search in the Society of Petroleum Engineers electronic library of scientific articles, covering the period of 1975–2003, resulted in 319 articles having as keywords 'power law', 131 articles with keywords 'Bingham', 51 articles with keywords 'Herschel–Bulkley', and 16 articles with keywords 'Casson'.

Viscometric data reduction procedures applicable to various rheological models have been proposed by many investigators, addressing also some of the inherent problems associated with data reduction (Krieger, 1968; Darby, 1985; Borgia and Spera, 1990; Yeow et al., 2000). The standard procedure for the estimation of the three rheological parameters for Herschel–Bulkley liquids, with rheological equation,

$$\tau = \tau_y + K\gamma^n \tag{1}$$

where τ, τ_y are the shear stress and the yield stress respectively, K, n are the fluid consistency and fluid behavior indices respectively and γ is the shear rate, is through non-linear regression of the viscometric data from concentric cylinder geometry. This is normally done using a numerical package, minimizing the sum of error squares and judging the goodness of fit through the value of the correlation coefficient R_c^2 from the linearized form of Eq. (1), as in Eq. (2),

$$\ln(\tau - \tau_y) = \ln K + n\ln(\gamma) \tag{2}$$

However, non-linear fit to various data in this laboratory with a numerical package sometimes has