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Experimental study and predictions of pressure losses of fluids modeled as Herschel–Bulkley in concentric and eccentric annuli in laminar, transitional and turbulent flows

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ABSTRACT

Experimental data is presented for the flow of bentonite–water dispersions, modeled as Herschel–Bulkley fluids, for the pressure loss at different flow rates covering laminar, transitional and turbulent flow regimes, while flowing in concentric and fully eccentric annuli. The concentric experimental data has been compared with predictions from a recently-introduced model which covers the full flow regimes for concentric annulus, while corrections for eccentricity, previously suggested for non-Newtonian fluids, have also been used to compare with eccentric data. Laminar flow data not only from this work but also from work from the literature is very well predicted while transitional and turbulent flow data are predicted with less accuracy, requiring improvements on predicting transition points. The corrections for eccentricity work well and can be used to accurately correct concentric annulus data. Turbulent non-Newtonian flow data exhibit a power law exponent relationship between flow rate and pressure loss smaller than the Newtonian case pointing out directions for future research.

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1. Introduction

Flow of yield-pseudoplastic fluids in annuli is encountered in many situations in a variety of industries and particularly in oil-well drilling. Such fluids require at least three rheological parameters for a near-optimum modeling of their rheological behavior. The non-linear three parameters model proposed by Herschel and Bulkley (1926) has become in recent years the model of choice to simulate the behavior of such fluids, replacing the well-known two-rheological parameter models of Bingham and power-law. The choice has been done not only by the oil-drilling industry (Bailey and Peden, 2000; Becker et al., 2003; Hemphil et al., 1993; Maglione and Ferrario, 1996; Maglione et al., 1999, 2000; Kelessidis et al., 2007; Zamora et al., 2005) but also by many other industries such as food, painting, concrete, waste and mineral processing (Bartosik, 2010; De Larrard et al., 1998; Fordham et al., 1991; Ferraris, 1999).

Analytical studies of laminar flow of Bingham plastic and power-law fluids in concentric annuli have been carried out by Fredrickson and Bird (1958) while a non-analytical solution covering laminar flow of Herschel–Bulkley fluids in concentric annuli has been investigated by Hanks (1979), with Buchtelova (1988) pointing out some errors in the analysis. Bird et al. (1983) provided an overview of solutions for the flow of several yield-pseudoplastic fluids in various conduits. Analytical solution for different yield-pseudoplastic fluids, but not for Herschel–Bulkley fluids, in concentric annuli has been presented by Gucuyener and Mehmetoglu (1992). Fordham et al. (1991) provided a numerical solution together with limited experimental laminar flow data for Herschel–Bulkley fluids. Results of measured and computed velocity profiles for laminar flow of shear thinning fluids Escudier et al. (2002a, 2002b) in concentric and eccentric annuli have also been given.

Experimental data for flow of non-Newtonian fluids, and particularly for Herschel–Bulkley fluids, in concentric or eccentric annuli, covering transitional and turbulent flows are rather scarce. Pipe flow data and analysis, however, are more readily available in the literature. Heywood and Cheng (1984) have reported variations of predictions of different proposed correlations up to ±50% for turbulent flow of Herschel–Bulkley fluids in pipes. Harnett and Kostic (1990) reported that the best approach for turbulent flow of power-law fluids in pipes was through the use of the approach of Metzner and Reed graph (1955). The majority of published data and flow predictions of Herschel–Bulkley fluids in concentric and eccentric annuli concern oil-well drilling (Bode et al., 1989; Cartalos and Dupuis, 1993; McCann et al., 1995; Ribeiro and Podio, 1994; Uner et al., 1989; Wang et al., 2000). This reflected the need in the last few decades of a more accurate modeling of annular pressure losses due to an increasing application of new drilling technologies, such as slim hole and coil tubing, characterized by narrower annuli between drill string and borehole or casing walls compared to standard drilling. However,

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critical information on the most sensitive issues, such as for e.g. full rheograms of the tested fluids are normally missing from these publications. Reed and Pilehvari (1993) presented a fairly complex model covering laminar, transitional and turbulent flows of Herschel–Bulkley fluids flowing in concentric annuli. Subramanian and Azar (2000) have presented experimental data but with limited information on the fluid properties. Hansen et al. (1999) provided experimental and modeling results for flow in annuli with and without rotation of the inner pipe for a series of non-Newtonian fluids. However, the tested Herschel–Bulkley fluids provided data only for laminar flow. Kelessidis et al. (2006) presented a comprehensive solution for Herschel–Bulkley fluid flows in concentric annuli covering laminar flow. Founargiotakis et al. (2008) extended the laminar approach and proposed the Kelessidis et al. model to cover also transitional and turbulent flows. Ogugbue and Shah (2009) have presented data and flow analysis for drag-reducing polymers in concentric and eccentric annuli covering all flow regimes.

The aim of this paper is to extend the experimental database of much needed data covering all three flow regimes (laminar, transitional and turbulent), for flow of Herschel–Bulkley fluids in concentric and eccentric annuli, while at the same time testing the predictions of the Kelessidis et al. model with data from this work as well as data from other sources.

2. Theory

The underlying theory of the Kelessidis et al. model for the flow in a concentric annulus of a Herschel–Bulkley fluid, with rheological equation given by

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

has been already presented (Founargiotakis et al., 2008). The approach considers the concentric annulus as a slot, and it has been shown by the authors that this assumption is valid also for very small diameter ratios, close to 0.1. If laminar flow occurs, the flow equation is analytically solved by using the Kelessidis et al. (2006) approach. For transitional or turbulent flow in the Kelessidis et al. model use of the local power-law assumption is made, as follows,

$$\tau_w = K'(\dot{\gamma}_{Nw})^{n'} \tag{2}$$

where the expressions of the local power-law parameters are provided by,

$$n' = \frac{n(1-\xi)(n\xi + n + 1)}{1 + n + 2n\xi + 2n^2\xi^2} \tag{3}$$

and

$$K' = \frac{\tau_y + K\left(\frac{2n'+1}{n3'}\dot{\gamma}_{Nw}\right)^n}{(\dot{\gamma}_{Nw})^{n'}} \tag{4}$$

with

$$\dot{\gamma}_{Nw} = \frac{12V}{d_o - d_i} \tag{5}$$

and

$$\xi = \frac{\tau_y}{\tau_w}. \tag{6}$$

Prediction of frictional pressure losses over the entire flow spectrum spanning laminar, transitional and turbulent flows requires knowledge of the transition limits. These are determined via the use of the modified Reynolds number,

$$Re = \frac{\rho V^{2-n'}(d_2 - d_1)^{n'}}{K'(12)^{n'-1}}. \tag{7}$$

Transition is suggested to occur over a range of two Reynolds numbers which are function of the local power value of n' and these have been taken from Dodge and Metzner (1959) and given by,

$$Re_1 = 3250 - 1150(n') \tag{8}$$

$$Re_2 = 4150 - 1150(n'). \tag{9}$$

Thus, the transition points are not fixed but are functions of rheology, flow rate and conduit diameters. The friction factor for turbulent flow is given by

$$\frac{1}{\sqrt{f}} = \frac{4}{(n')^{0.75}} \log\left[Ref^{1-n'/2}\right] - \frac{0.395}{(n')^{1.2}} \tag{10}$$

while for the transitional regime, an interpolation is performed between the two limits of laminar and turbulent friction factors. The solution requires iteration, where one assumes that flow is laminar, transitional or turbulent, and solves the system, with the ultimate check that the calculated flow rate matches the given flow rate (Founargiotakis et al., 2008).

Determination of frictional pressure losses for drilling fluid flow in pipes and annuli has been standardized for many years under the document API 13D 'Recommended practice on the rheology and hydraulics of oil-well drilling fluids'. This standard has been recently revised (American Petroleum Institute, 2006; Bern et al., 2007) and recommendation has been given for the use of the Herschel–Bulkley model with rheological parameters derived from at least four Couette-type viscometer measurements. The approach uses a fixed transitional Reynolds number, defined as a function of the flow behavior index of the fluid, n, only, rather than the local power law index used in the Kelessidis et al. model. The generalized Reynolds number for the API standard is defined in terms of the shear stress at the wall,

$$Re_G = \frac{\rho V^2}{\tau_w} \tag{11}$$

while the Reynolds number where transition occurs is given by

$$Re_{Gtr} = 3470 - 1370 \cdot n \tag{12}$$

which reduces to Re = 2100 for $n = 1$.

Analytical solutions for the flow of non-Newtonian fluids and particularly for Herschel–Bulkley fluids in eccentric annuli for laminar flow do not exist, let alone for turbulent flow. Hence, resort should be made to correlations. Of the few recommended correlations, those that stand out were proposed by Haciislamoglu and Langlinais (1990) and Haciislamoglu and Cartalos (1994), which are denoted here as Haciislamoglu et al. correlations. The authors have provided corrections to concentric annulus flow predictions from eccentric flow data in terms of eccentricity, e, pipe diameter ratio, d_i/d_o, and flow behavior index, n, derived though for fluids following power-law rheological behavior. The data has been correlated with regard to either the laminar or the turbulent flow regime. The proposed correlation for laminar flow is,

$$C_l = 1.0 - 0.072\left(\frac{e}{n}\right)\left(\frac{d_i}{d_o}\right)^{0.8454} - \frac{3}{2}\left(e^2\sqrt{n}\right)\left(\frac{d_i}{d_o}\right)^{0.1852} + 0.96e^3\sqrt{n}\left(\frac{d_i}{d_o}\right)^{0.2527} \tag{13}$$

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