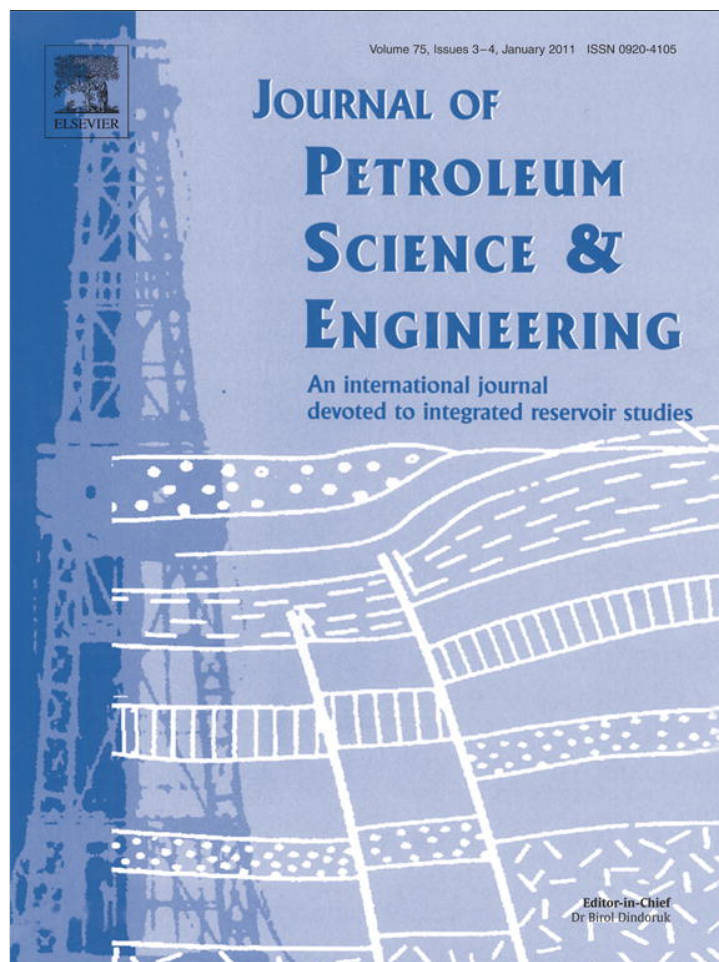


Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



(This is a sample cover image for this issue. The actual cover is not yet available at this time.)

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

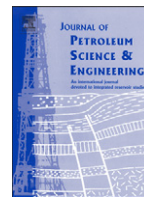
In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

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

Vassilios C. Kelessidis^{a,*}, Panagiotis Dalamarinis^a, Roberto Maglione^b

^a Department of Mineral Resources Engineering, Technical University of Crete, Polytechnic City, 73100 Chania, Greece

^b Consultant, Moncrivello, Vercelli, Italy

ARTICLE INFO

Article history:

Received 20 November 2010

Accepted 10 April 2011

Available online xxxx

Keywords:

annulus flow

water–bentonite dispersions

laminar

turbulent transitional flows drilling fluids

concentric

eccentric

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.

© 2011 Elsevier B.V. All rights reserved.

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 $\pm 50\%$ 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,

* Corresponding author. Tel.: +30 28210 37621; fax: +30 28210 37874.
E-mail address: kelesidi@mred.tuc.gr (V.C. Kelessidis).

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

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

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,

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

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

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

and

$$K' = \frac{\tau_y + K \left(\frac{2n'+1}{n^3} \dot{\gamma}_{Nw} \right)^n}{(\dot{\gamma}_{Nw})^{n'}} \quad (4)$$

with

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

and

$$\xi = \frac{\tau_y}{\tau_w} \quad (6)$$

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,

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

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,

$$Re_1 = 3250 - 1150(n') \quad (8)$$

$$Re_2 = 4150 - 1150(n') \quad (9)$$

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

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

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,

$$Re_G = \frac{\rho V^2}{\tau_w} \quad (11)$$

while the Reynolds number where transition occurs is given by

$$Re_{Gr} = 3470 - 1370 \cdot n \quad (12)$$

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 Hacıslamoglu and Langlinais (1990) and Hacıslamoglu and Cartalos (1994), which are denoted here as Hacıslamoglu 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,

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

while for turbulent flow is,

$$C_i = 1.0 - 0.048 \left(\frac{e}{n} \right) \left(\frac{d_i}{d_o} \right)^{0.8454} - \frac{2}{3} (e^2 \sqrt{n}) \left(\frac{d_i}{d_o} \right)^{0.1852} + 0.285 e^3 \sqrt{n} \left(\frac{d_i}{d_o} \right)^{0.2527} \quad (14)$$

where the correction coefficient C_i for laminar ($i=1$) and turbulent ($i=t$) flows is given by,

$$C_i = \frac{(\Delta p / \Delta L)_{ei}}{(\Delta p / \Delta L)_{ci}} \quad (15)$$

where $(\Delta p / \Delta L)_e$ is the pressure loss for the eccentric annulus and $(\Delta p / \Delta L)_c$ is the pressure loss for the concentric annulus. In order to compare our predictions with data derived from this study as well as with data from other sources, our concentric model predictions were corrected by using the Hacıislamoglu et al. correlations but using the flow behavior index (n) from the Herschel–Bulkley model.

3. Experimental materials and methods

Experimental data has been collected in the flow system of the Drilling Engineering and Fluid Mechanics Laboratory of the Technical University of Crete. The system, shown in Fig. 1, consists of a 5 m annulus with an inner pipe with external diameter of 40 mm and an outer pipe with internal diameter of 70 mm. The pipes are made of Plexiglas and the annulus can be concentric or eccentric by moving the inner pipe. The eccentricity tested, defined as the distance between the two pipe centers divided by the gap, was 100%, i.e. with the inner and outer pipes touching each other. A 750 L tank provides the place for fluid mixing and storing, a 7.5 kW centrifugal pump regulated by an inverter provides the flow, while the flow rate, density and temperature of the fluid are monitored with a Coriolis mass flow meter. A serpentine inside the tank circulates cold water from an A/C unit to keep the fluid temperature constant. Pressure data is collected at 3 m from the entrance and 1 m from the exit with a differential pressure transducer over a total length of 90 cm, eliminating thus entrance or exit effects. A specially-designed system allowed both for calibration of the transducer and for ensuring that the pressure lines were full of the fluid. The Herschel–Bulkley fluid is prepared by adding Wyoming bentonite in tap water at fixed concentration to achieve the desired rheology. Mixing is performed in the tank with a 4-bladed agitator, using also the flow system itself as agitation and as a mixing device. After initial mixing, the fluid was left for 16 h for complete bentonite hydration.

For each concentric or eccentric annulus flow test a fresh batch of fluid was prepared. The rheology of the fluids was determined with a

Grace Instruments Couette-type concentric cylinder viscometer with samples taken before the start of testing and at the end of each test, with measurements performed following API 13D Standard approach (API, 2006; Kelessidis et al., 2007). Normally, the measurements done before and after each test were almost identical, as the series of tests did not last longer than 30 min and the cooling system kept the temperature constant at 24 °C.

4. Results and discussion

4.1. Water flow and rheological measurements

A standard run with water has been done both for the concentric and the fully eccentric annuli before testing with the Herschel–Bulkley fluid. Flow conditions of the runs were turbulent as the minimum Reynolds computed was 10,629 at the minimum imposed by the flow system of 0.35 m/s. Results of the experimental runs together with the predictions for the concentric case from the Kelessidis et al. model, which was run with $n=1.0$, $\tau_y=0.0$ Pa and $K=0.001$ Pas, are shown in Fig. 2. We see that concentric predictions match the data fairly well and that they are off by a maximum factor of +10% with respect to concentric data. In the graph, predictions by using the Fanning friction factor for rough conduits defined by Haaland (1983) as,

$$\frac{1}{\sqrt{f}} = -3.6 \log \left(\left\{ \frac{\varepsilon}{3.7d_h} \right\}^{1.11} + \frac{6.9}{Re} \right) \quad (16)$$

are also shown, where use is made of the hydraulic diameter, d_h . The best match, seen also by the data fit, could be derived when assuming a roughness, ε , of 0.024 mm. Thus, this exercise identified a small roughness for the Plexiglas pipes, which though cannot be taken into account for the non-Newtonian predictions, neither for the concentric nor for the eccentric case, as no such correlations or models are presently available. Hence, annular pipes will be considered smooth, probably introducing a very small error.

The bentonite–water dispersions were prepared with 1.85% bentonite concentration, based on previous model runs which indicated that the particular fluid experiences all three flow regimes, laminar, transitional and turbulent flow regimes, when using the available pump rate ranges of the flow system. Of course such concentration is not very typical of bentonite concentration used in drilling fluid formulation; however it was the estimated concentration that would give turbulent flow in our flow system. Rheological data for both cases, the concentric and the fully eccentric annulus runs, as determined via the Couette-viscometer, for the 1.85% bentonite dispersions together with the Herschel–Bulkley model fit for both samples, are shown in Fig. 3. As

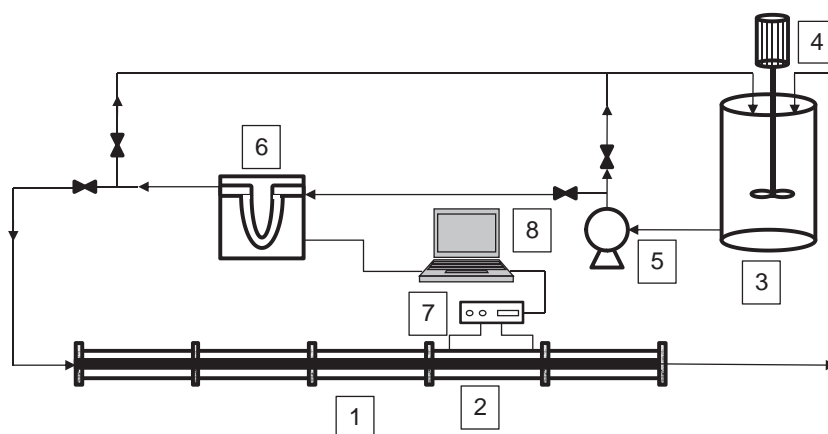


Fig. 1. Schematic of the experimental flow loop. 1) Annulus, 2) measurement section, 3) tank, 4) agitator, 5) slurry pump, 6) mass flow meter, 7) pressure transducer, and 8) lab computer.

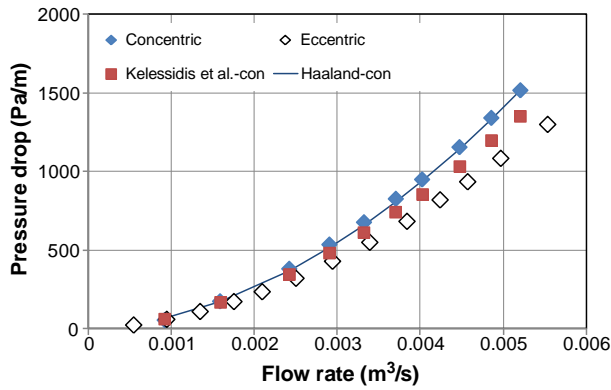


Fig. 2. Pressure loss data for water, for concentric and 100% eccentric annuli, and comparison with Kelessidis et al. predictions for concentric case (run for Newtonian data) and with the Haaland predictions (Haaland, 1983) for the concentric case.

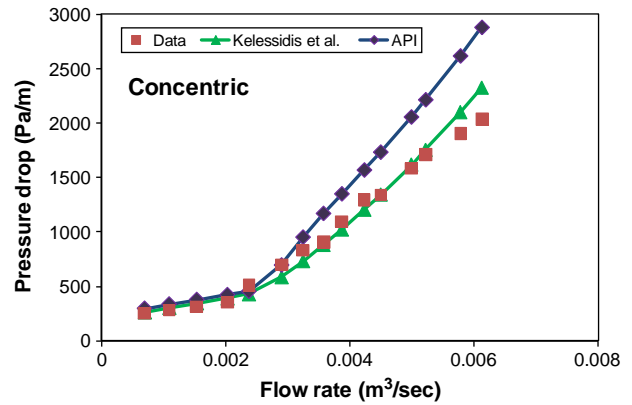


Fig. 4. Comparison of pressure loss data in 0.070-by-0.040 m concentric annulus versus predictions both with Kelessidis et al. model and the API model for 1.85% bentonite suspension.

different batches were prepared for each condition, concentric and eccentric cases, and preparation of large quantities of bentonite dispersions cannot fully be replicated, the rheograms for each case are not exactly identical, but this did not affect the overall process evaluation since the rheological equations were determined for each case. The Herschel–Bulkley model fitted data extremely well for both cases giving, for the concentric annulus, the following equation,

$$\tau = 1.073 + 0.0088(\dot{\gamma})^{0.8798} \quad (17)$$

with a sum of square errors of 0.09 Pa² and a correlation coefficient of $R_c^2 = 0.9999$. For the eccentric annulus sample, the rheological data were fitted by,

$$\tau = 0.886 + 0.0130(\dot{\gamma})^{0.8343} \quad (18)$$

with a sum of square errors of 0.02 Pa² and a correlation coefficient of $R_c^2 = 0.9984$.

4.2. Pressure losses for the concentric annulus

Results for concentric annulus pressure losses of the bentonite dispersion are presented in Fig. 4 together with predictions of the Kelessidis et al. model and the recently-revised API model. As one can see from the figure the data covers the full spectrum, laminar, transitional and turbulent flows, evidenced from the change of the slope of the experimental curve. The API model follows well the

laminar flow data and seems to predict well the transition to turbulent flow, which is assumed to take place at a value of a critical Reynolds number computed by Eq. (12). The API model over predicts the transitional and turbulent flow data, with the discrepancy growing progressively larger at higher flow rates. The Kelessidis et al. model predicts very well the laminar flow data as well as the start of the transition from laminar flow. The turbulent flow data are not accurately predicted as in the laminar case, but never-the-less they show good correspondence, much better than the API model. The maximum negative deviation (–16%) occurs in the transition and in the first predicted turbulent flow points (at a flow rate of 0.024 and 0.029 m³/s, respectively), and maximum positive deviation (14%) can be found in the last turbulent point. This in turn reflects in a slightly different power-law exponent between experimental data and predictions in a pressure loss representation of turbulent flow data of the form,

$$\frac{\Delta p}{\Delta L} = aQ^m. \quad (19)$$

Attempts to fit the experimental data in the form of Eq. (19) gave, in SI units,

$$\frac{\Delta p}{\Delta L} = 2.8446 \cdot 10^6 Q^{1.417} \quad (20)$$

with a correlation coefficient of 0.9930, while the correlation for the prediction results is given by,

$$\frac{\Delta p}{\Delta L} = 2.2797 \cdot 10^7 Q^{1.803} \quad (21)$$

with correlation coefficient of 0.9998. Thus, the multiplier constants differ by a factor of 10 and the experimental data shows a smaller power-exponent, of 1.417 compared to that of the predictions of 1.803 which is closer to the value normally obtained for turbulent flow of Newtonian liquids. It is interesting thus to determine the power-law pressure loss equation for the concentric water data, shown in Fig. 2. Data regression gives,

$$\frac{\Delta p}{\Delta L} = 1.905 \cdot 10^7 Q^{1.795} \quad (22)$$

with a correlation coefficient of 0.9999. Similarly, the predictions of Kelessidis et al. model gave for the concentric water flow data the equation of,

$$\frac{\Delta p}{\Delta L} = 1.508 \cdot 10^7 Q^{1.773} \quad (23)$$

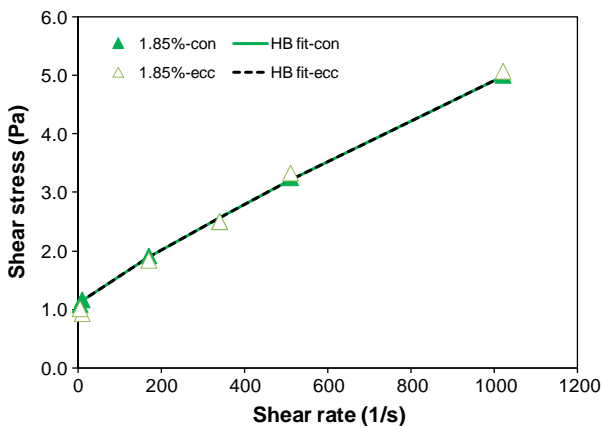


Fig. 3. Rheograms of 1.85% bentonite dispersions utilized when gathering data both for concentric and 100% eccentric annulus flow runs.

with correlation coefficients equal to 0.9999 for both cases. Thus for the Newtonian case, both model predictions and data give a power-exponent value close to 1.8, which is approximately the value for turbulent flow of Newtonian fluids in conduits. For the non-Newtonian fluid, however, the experimental data gives the value of 1.417, indicating that our model, as well as other models and in particular the API model, predicts for turbulent flow a faster rise of pressure loss with increase in flow rate rather than what data indicates and this should be properly taken into account in the future in order to have better match of predictions with measurements.

The Fanning friction factor can be readily calculated by,

$$\frac{\Delta p}{\Delta L} = \left(\frac{2f\rho V^2}{d_h} \right) \quad (24)$$

where $d_h = d_o - d_i = 0.03$ m is the hydraulic diameter.

Computations of the friction factor versus Reynolds number both for the experimental data and predictions, computed by the Kelessidis et al. model, are shown in Fig. 5. The results show that transition to turbulent flow occurs in a range between $Re_1 = 2800$ and $Re_2 = 4000$ with the Kelessidis et al. model appropriately predicting the first transition point, however failing to predict the end of transitional flow, given by design the value of $Re_2 = 2800 + 900 = 3700$, resulting thus in an error for the transitional and turbulent flows. The laminar flow portion is very well represented by the equation,

$$f = \frac{24}{Re} \quad (25)$$

4.3. Pressure losses for the eccentric annulus

The experimental results for the pressure losses of the Herschel–Bulkley fluid in 100% eccentric annulus are shown in Fig. 6, where the predictions of the Kelessidis et al. model as well as the API model are also shown, both corrected by the Hacıislamoglu et al. correlations, given by Eqs. (13) and (14) for laminar and turbulent flows, respectively. It should be mentioned that for the transitional regime use is made of the turbulent correction equation because the corrections do not include a transitional regime. The Kelessidis et al. model, which works for concentric annulus, after the correction follows quite accurately the experimental data for the whole flow range rates tested, while API model predictions deviate quite significantly, in a similar way to the concentric annulus cases. The fully eccentric annulus results, combined with the concentric annulus results analyzed before,

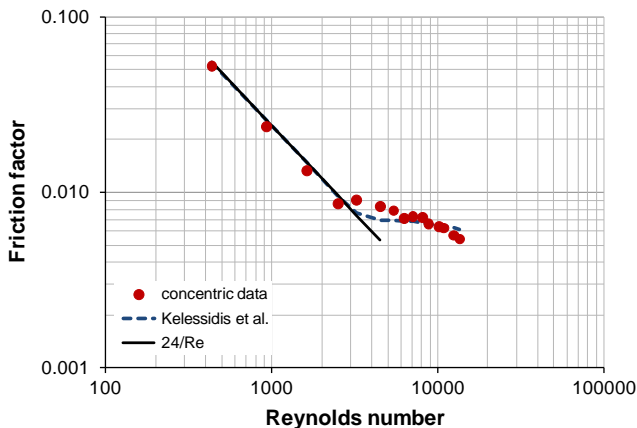


Fig. 5. Friction factor plot for concentric annulus and comparison with predictions from the Kelessidis et al. model.

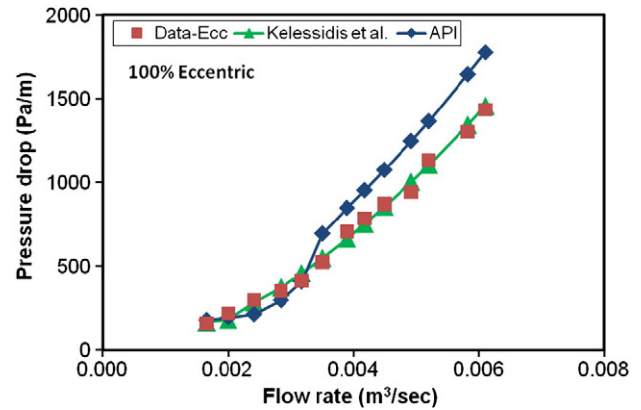


Fig. 6. Comparison of pressure loss data versus predictions for 1.85% bentonite suspension in 100% eccentric annuli. Predictions of Kelessidis et al. and API models have been corrected for eccentricity by the Hacıislamoglu et al. correlations.

show that concentric annulus predictions by the Kelessidis et al. model fairly accurately represent experimental data. It is interesting to note that, although a one-to-one comparison cannot be exactly made between the concentric and the eccentric annulus case because the two fluids were slightly different and the data point were not taken exactly at the same flow rates, never-the-less, one can observe that the 100% eccentric annulus presents pressure loss data which range between 55% and 70% of the concentric case, starting from low to high flow rates. This should be compared to the value of approximately 80% of the water eccentric data compared to the concentric case, which then would indicate that when non-Newtonian fluids flow in eccentric annuli, the reduction of pressure drop compared to concentric case is greater than for the case of Newtonian fluids.

One can compute the friction factor for the eccentric case, in a way similar to that followed for the concentric case by using Eq. (24) and attempting then to generate a similar plot to Fig. 5 for the eccentric case. Of course, first one needs to define a Reynolds number expression for the eccentric case. However, there is no consensus among the research community on how one can define a non-ambiguous eccentric annulus Reynolds number. Based on this, we opted for representing the friction factor, related to the eccentric annulus data, versus the computed Reynolds for the concentric annulus case, but using flow and fluid properties data for the eccentric case. The Reynolds number used was the one computed by the Kelessidis et al. model as reported by Eq. (7). Such computations are shown in Fig. 7. Model predictions match the trend and shape of the experimental data with a delay in Reynolds number transition. Of

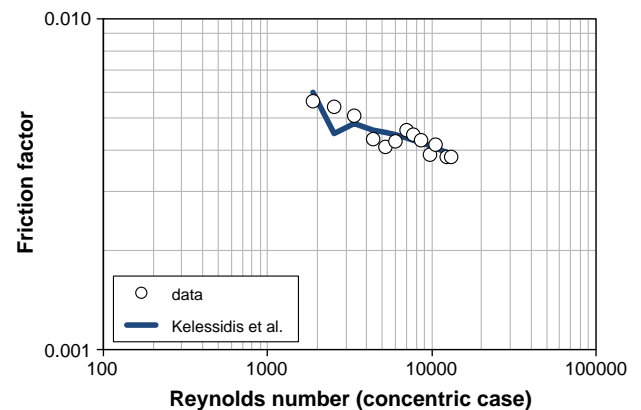


Fig. 7. Friction factor plot for 100% eccentric annulus and comparison with predictions from the Kelessidis et al. model corrected for eccentricity by Hacıislamoglu correlations.

course one cannot define overall transitions to turbulent flow for the eccentric annulus. However, the data indicate that there is a change in friction factor behavior between Reynolds numbers, computed for the concentric case of 3300 and 3800. Thus further investigation is needed with appropriately defined parameters to compute properly the Reynolds number for the eccentric annulus.

5. Discussion

The above analysis has shown that concentric annulus and 100% eccentric annulus experimental data have been correctly predicted by using the Kelessidis et al. model, when the eccentric case was corrected by the Hacıislamoglu et al. correlations. The model has been also used to compare predictions with very limited available data from other investigators which cover all three flow regimes. The laminar flow data of Fordham et al. (1991) and the laminar, transitional and turbulent flow data of Pilehvari and Serth (2009) have been used and the input data are shown in Table 1. Using input data we can compute the friction factor and the Reynolds number according to Kelessidis et al. model. The results are compared, together with the results from this work, in Fig. 8. One can see the very good match with all experimental data, which cover a large Reynolds number range extending over four log-cycles.

It should be further noticed that the coefficient 24 in Eq. (25) is the coefficient for the Fanning friction factor derived for laminar flow between parallel plates, and this is then expected as the laminar flow solution of the Kelessidis et al. model has been derived by assuming that the annulus can be represented by two parallel plates with results valid even for very small inner pipe diameter (minimum value tested with good results was for a diameter ratio, $d_i/d_o = 0.1$) Kelessidis et al. (2006). The fact that the data, not only from this work but also those from other laminar flow work (for e.g. data from Fordham et al., 1991) are very well matched by the predictions of Eq. (25), indicates that for any diameter ratio annulus, more proper representation for the Fanning friction factor for non-Newtonian fluids is $(24/Re)$ rather than $(16/Re)$, which was normally used by previous investigators to define friction factor attempting to extend pipe flow correlations to annular flow data (for e.g. Bhattacharya and Tiu, 1974).

Turbulent flow friction factor is slightly over predicted and not following the trend of the experimental data, as discussed above (Fig. 5). Transitional friction factor is underestimated by the model, indicating that the log–log interpolation scheme between the laminar and the turbulent friction factor, which is used by the Kelessidis et al. model, also often used by other investigators, is not appropriate and another interpolation scheme should be devised or a better correlation should be proposed.

The bentonite concentration used was fairly low so that we could cover all three flow regimes for the flow system used in this study. Of course in normal drilling situations bentonite concentrations may be higher giving higher yield stress and flow consistency values and

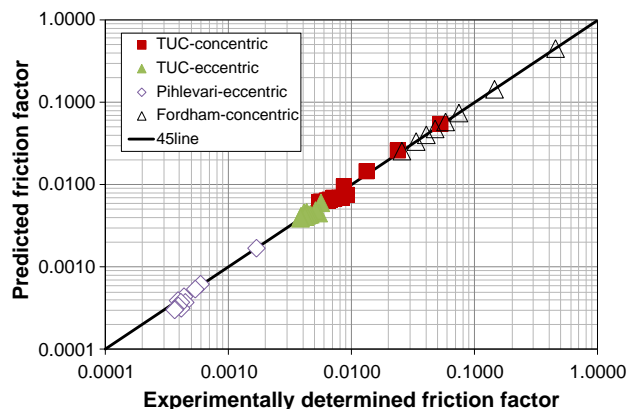


Fig. 8. Comparison of concentric and eccentric friction factors experimentally derived and computed by Kelessidis et al. model, from various sources.

lower flow behavior indices which would then result in an increase in the pressure drop for the cases in laminar flow and in a decrease in the pressure drop for the cases of turbulent flow, in both concentric and eccentric annuli, for the same annulus configuration. In the field operations, however, it will all depend on the combinations of the flow parameters and the conduit geometry and not just on the annulus configuration, but the applicability of the Kelessidis et al. model, as shown in this work, would be sufficient to cover such situations.

The annulus has been considered smooth with a very small pipe roughness, as computed before. Surface roughness is not considered in the computations of pressure loss estimation for drilling but also other operations and none of the available models takes it into account, neither for concentric nor for eccentric annuli. One would expect that, according to what is reported for non-Newtonian fluid flow in pipe configuration, surface roughness will increase pressure drop, especially in the transitional and turbulent flows in concentric and eccentric annuli, the magnitude of which should be evaluated both experimentally and theoretically.

6. Conclusions

Experimental data have been presented for the pressure losses of water–bentonite dispersions modeled as Herschel–Bulkley fluids, in concentric and 100% eccentric annuli, spanning the full spectrum of flow regimes, laminar, transitional and turbulent flows, contributing thus to the public database of such data as they are scarce, particularly for transitional and turbulent flows.

The experimental data have been compared with the predictions of a recently presented model for such flows in concentric annulus from the same laboratory (the Kelessidis et al. model) which also covers the full spectrum of flows and solves both the pressure losses

Table 1
Experimental data from other investigators used in Fig. 8.

Data from Pilehvari and Serth (2009) 100% eccentric annulus	Velocity (m/s)	Measured pressure loss (Pa)	Re	Data from Fordham et al. (1991) 100% eccentric annulus	Velocity (m/s)	Measured pressure loss (Pa)	Re
$d_i = 6.03$ cm	2.54	340	475	$d_i = 4.0$ cm	0.06	1450	12
$d_o = 12.76$ cm	5.08	476	1281	$d_o = 5.0$ cm	0.14	1800	54
$\tau = 1.05 + 0.42\gamma_w^{0.63}$	5.59	521	1480	$\tau = 1.59 + 0.143\gamma_w^{0.54}$	0.28	2300	171
	6.48	567	1826		0.42	2660	332
	6.99	589	2034		0.50	2820	426
	7.24	725	2140		0.57	3030	528
	8.13	848	2522		0.63	3180	627
	8.90	1006	2866		0.71	3320	755
	9.91	1192	3343		0.84	3600	996
	11.44	1496	4038				
	12.25	1700	4518				

and the applicable flow regimes. The concentric data is matched fairly well by predictions, with the observed differences attributed to the prediction of the transition points. The eccentric data is also very well matched with the predictions, when corrected with the use of the Hacıslamoglu et al. correlations for eccentricity.

The Kelessidis et al. model, which uses the local power-law approximation for turbulent flow, assumes that transition occurs over a range of modified Reynolds numbers which depend on the flow situation and they are not known a-priori. The experimental data shows that this is true, both for the concentric and the eccentric case, but some additional parameters may also contribute, thus resulting in the not-so-perfect match of predictions with measurements. Research should thus focus on even better definitions of transition points from laminar to transitional and from transitional to turbulent flow as well as for the correlation used for the transitional friction factor.

Model predictions from the recently-revised API correlations were at odds with the measurements, both for concentric and eccentric annuli (corrected also with the Hacıslamoglu et al. correlation), with API model predicting much higher pressure drop than data indicates in the transitional and turbulent flow regimes.

Nomenclature

a	coefficient ($\text{Pa}^{1/m}, \text{s}/\text{m}^{3+1/m}$)
C_i	correction coefficient for eccentric annulus data
d_i	diameter of inner tube of annulus (m)
d_o	diameter of outer tube of annulus (m)
d_h	hydraulic diameter (m)
$\Delta p/\Delta L$	pressure drop gradient (Pa/m)
e	pipe eccentricity
f	Fanning friction factor
K	flow consistency index ($\text{Pa}\cdot\text{s}^n$)
K'	flow consistency index for local power-law parameters ($\text{Pa}\cdot\text{s}^n$)
L	length (m)
m	power exponent
n	flow behavior index
n'	flow behavior index for local power-law parameters
Q	flow rate (m^3/s)
Re	Reynolds number
Re_G	generalized Reynolds number
Re_{Gtr}	transitional generalized Reynolds number for annulus
V	mean velocity (m/s)

Greek symbols

$\dot{\gamma}$	shear rate (s^{-1})
$\dot{\gamma}_{Nw}$	Newtonian shear rate on the wall (s^{-1})
$\dot{\gamma}_w$	wall shear rate (s^{-1})
μ_w	viscosity at the wall ($\text{Pa}\cdot\text{s}$)
ξ	dimensionless shear stress for annulus
ρ	fluid density (kg/m^3)
τ	shear stress (Pa)
τ_y	yield stress for Herschel–Bulkley fluid (Pa)
τ_w	wall shear stress (Pa)

References

American Petroleum Institute. API Spec. 13D, 2006. Recommended Practice on the Rheology and Hydraulics of Oil-well Drilling Fluids, Fifth Edition.

Bailey, W.J., Peden, J.M., 2000. A generalized and consistent pressure drop and flow regime transition model for drilling hydraulics. *SPE Drilling & Completion*, 15.

Bartosik, B., 2010. Application of rheological models in prediction of turbulent slurry flow. *Flow Turbul. Combust.* 84, 277.

Becker, T.E., Morgan, R.G., Chin, W.C., Griffith, J.E., 2003. Improved rheology model and hydraulic analysis for tomorrow's wellbore fluid applications. Paper SPE 84215. *Proceedings of SPE Productions and Operations Symposium*, Oklahoma City (USA).

Bern, P.A., Morton, E.K., Zamora, M., May, R., Moran, D., Hemphill, T., Robinson, L., Cooper, I., Shah, S., Flores, D.V., 2007. Modernization of the API recommended practice on rheology and hydraulics: creating easy access to integrated wellbore fluids engineering. *SPE Drilling & Completion*, 197.

Bhattacharya, S., Tiu, C., 1974. Developing pressure profiles for non-Newtonian flow in an annular duct. *AIChE J.* 20, 154.

Bird, R.B., Dai, G.C., Yarusso, B.J., 1983. The rheology and flow of viscoplastic materials. *Rev. Chem. Eng.* 1, 1.

Bode, D.J., Noffke, R.B., Nickens, H.V., 1989. Well-control methods and practices in small-diameter wellbore. Paper SPE 19526. *Proceedings of the SPE Annual Technical Conference and Exhibition*, San Antonio (USA).

Buchtelova, M., 1988. Comments on "The axial laminar flow of yield-pseudoplastic fluids in a concentric annulus". *Ind. Eng. Chem. Res.* 27, 1557.

Cartalos, U., Dupuis, D., 1993. An analysis accounting for the combined effect of drillstring rotation and eccentricity on pressure losses in slimhole drilling. Paper SPE/IADC 25769. *Proceeding of the Drilling Conference*, Amsterdam (NL).

De Larrard, F., Ferraris, C.F., Sedran, T., 1998. Concrete: a Herschel–Bulkley material. *Mater. Struct.* 31, 494.

Dodge, D.W., Metzner, A.B., 1959. Turbulent flow in non-Newtonian systems. *AIChE J.* 5, 189.

Escudier, M.P., Oliveira, P.J., Pinho, F.T., 2002a. Fully developed laminar flow of purely viscous non-Newtonian liquids through annuli, including the effects of eccentricity and inner-cylinder rotation. *Int. J. Heat Fluid Fl.* 23, 52.

Escudier, M.P., Oliveira, P.J., Pinho, F.T., 2002b. Fully developed laminar flow of non-Newtonian liquids through annuli: comparison of numerical calculations with experiments. *Exp. Fluids* 33, 101.

Ferraris, C., 1999. Measurement of the rheological properties of high performance concrete: state of the art report. *J. Res. Natl. Inst. Stan.* 104, 461.

Fordham, E.J., Bittleston, S.H., Tehrani, M.A., 1991. Viscoplastic flow in centered annuli, pipes and slots. *Ind. Eng. Chem. Res.* 29, 517.

Founargiotakis, K., Kelessidis, V.C., Maglione, R., 2008. Laminar, transitional and turbulent flow of Herschel–Bulkley fluids in concentric annulus. *Can. J. Chem. Eng.* 86, 676.

Fredrickson, A.G., Bird, R.B., 1958. Flow of non-Newtonian fluids in annuli. *Ind. Eng. Chem.* 50, 347.

Gucuyener, H.I., Mehmetoglu, T., 1992. Flow of yield-pseudoplastic fluids through a concentric annulus. *AIChE J.* 38, 1139.

Haaland, S.E., 1983. Simple and explicit formulas for the friction factor in turbulent flow. *ASME Journal of Fluids Engineering* 103, 89.

Hacıslamoglu, M., Cartalos, U., 1994. Practical pressure loss predictions in realistic annular geometries. Paper SPE 28304. *Proceedings of 69th SPE Annual Technical Conference and Exhibition*, New Orleans (USA).

Hacıslamoglu, M., Langlinais, J., 1990. Non-Newtonian flow in eccentric annuli. *J. Energy Resources Technology* 112, 163.

Hanks, R.W., 1979. The axial flow of yield-pseudoplastic fluids in a concentric annulus. *Ind. Eng. Chem. Proc. DD.* 18, 488.

Hansen, S.A., Rommetveit, R., Sterri, N., Aas, B., Merlo, A., 1999. A new hydraulic model for slim hole drilling applications. Paper SPE 57579. *Proceedings of SPE/IADC Middle East Drilling Technology Conference*, Abu Dhabi.

Harnett, J.P., Kostic, M., 1990. Turbulent friction factor correlations for power law fluids in circular and non-circular channel. *Int. Commun. Heat Mass* 17, 59.

Hemphill, T., Campos, W., Tehrani, M.A., 1993. Yield power-law model mode accurately predicts mud rheology. *Oil Gas J.* 91, 45.

Herschel, W.H., Bulkley, R., 1926. Konsistenzmessungen von Gummi-Benzollösungen. *Kolloid Z.* 39, 291.

Heywood, N.I., Cheng, D.Ch., 1984. Comparison of methods for predicting head loss in turbulent pipe flow of non-Newtonian fluids. *T. I. Meas. Control* 6, 33.

Kelessidis, V.C., Maglione, R., Tsamantaki, C., Aspirtakis, Y., 2006. Optimal determination of rheological parameters for Herschel–Bulkley drilling fluids and impact on pressure drop, velocity profiles and penetration rates during drilling. *J. Petrol. Sci. Eng.* 53, 203.

Kelessidis, V.C., Christidis, G., Makri, P., Hadjistamou, C., Tsamantaki, C., Mihalakis, A., Papanicolaou, C., Foscolos, A., 2007. Gelation of water–bentonite suspensions at high temperatures and rheological control with lignite addition. *Appl. Clay Sci.* 36, 221.

Maglione, R., Ferrario, G., 1996. Equations determine flow states for yield-pseudoplastic drilling fluids. *Oil Gas J.* 94, 63.

Maglione, R., Guarneri, A., Ferrari, G., 1999. Rheological and hydraulic parameter integration improves operations. *Oil Gas J.* 97, 44.

Maglione, R., Robotti, G., Romagnoli, R., 2000. In-situ rheological characterization of drilling mud. *SPE Journal* 5, 377.

McCann, R.C., Quigley, M.S., Zamora, M., Slater, K.S., 1995. Effects of high-speed pipe rotation on pressures in narrow annuli. *June SPE Drilling & Completion*.

Metzner, A.B., Reed, J.C., 1955. Flow of non-Newtonian fluids – correlations of the laminar, transition and turbulent-flow regions. *AIChE J.* 1, 434.

Ogugbue, C.C., Shah, S.N., 2009. Friction pressure correlations for oilfield polymeric solutions in eccentric annulus, Paper OMAE 2009-80044. *Proceedings of ASME 28th International Conference on Ocean, Offshore and Arctic Engineering*, Honolulu (USA).

Pilehvari, A., Serth, R., 2009. Generalized hydraulic calculation method for axial flow of non-Newtonian fluids in eccentric annuli. Paper SPE 111514. *December SPE Drilling & Completion*, 553.

Reed, T.D., Pilehvari, A.A., 1993. A new model for laminar, transitional and turbulent flow of drilling muds. Paper SPE 25456. *Proceedings of Productions Operations Symposium*, Oklahoma City (USA).

Ribeiro, P.R., Podio, A.L., 1994. The effect of rotational speed and eccentricity on annular flows with application to slim hole drilling hydraulics. Paper SPE 26958.

- Proceedings of the III Latin American/Caribbean Petroleum Engineering Conference, Buenos Aires (Argentina).*
- Subramanian, R., Azar, J.J., 2000. Experimental study on friction pressure drop for non-Newtonian drilling fluids in pipes. Paper SPE 64647. *Proceedings of SPE International Conference and Exhibition, Beijing (China).*
- Uner, D., Ozgen, C., Tosun, I., 1989. Flow of a power-law fluid in an eccentric annulus. September SPE Drilling Engineering.
- Wang, H., Su, Y., Bai, Y., Gao, Z., Zhang, F., 2000. Experimental study of slim hole annular pressure loss and its field application. Paper SPE 59265. *Proceedings of the SPE/IADC Drilling Conference, New Orleans (USA).*
- Zamora, M., Roy, S., Slatte, K., 2005. Comparing a basic set of drilling fluid pressure-loss relationships to flow-loop and field data. Paper AADE-05-NTCE-27. *Proceedings of AADE National Technical Conference and Exhibition, Houston (USA).*