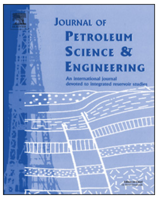
Journal of Petroleum Science and Engineering 139 (2016) 85–93

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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



Laminar and turbulent pipe flow of bentonite suspensions

A. Benslimane [a,*], K. Bekkour [b], P. François [b], H. Bechir [a]

[a] *Laboratoire Mécanique, Matériaux et Energétique (L2ME), Faculté de Technologie, Université de Bejaia, Route Targa Ouzemour, 06000 Bejaia, Algeria*
[b] *Icube, Département de Mécanique. CNRS-Université de Strasbourg. 02, Rue Boussingault, 67000 Strasbourg, France*

ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form
4 December 2015
Accepted 15 December 2015
Available online 20 December 2015

Keywords:
Bentonite
Non-Newtonian
Laminar
Turbulent
Pipe flow

ABSTRACT

The purpose of this paper is to investigate rheology and hydrodynamic behavior of different mass concentration of bentonite suspensions in pipe flow. Bentonite suspensions exhibited shear thinning and yield stress non-Newtonian rheological behavior. Most of the data reported are for the laminar and turbulent flow, data are also included the start-up flow development. The axial velocity distribution was determined using a Ultrasonic Pulsed Doppler Velocimetry technique.

The experimental results show a progressive destructuration of the suspensions in the entrance region due to the segregation of the structural elements of the fluid and tend to a steady state and a fully developed laminar pipe flow. In the majority of cases, axisymmetric flow is observed for both laminar and turbulent flow conditions. Also an asymmetry characterizes the axial velocity profiles in the laminar-turbulent transitional flow.

In the laminar regime, the flow parameters were fitted by using the Herschel–Bulkley model. For the turbulent flow, the Dodge and Metzner model was applied to fit the experimental data.

1. Introduction

Bentonite suspensions are widely used as widespread thickening agents and as key component in various industrial fluid formulations. Among their uses in civil engineering are soil boring, slurry walls, nuclear waste barrier, and other industrial applications including cosmetics (creams), chemical (paints), food products (wine), etc.

In petroleum engineering where horizontal directional drilling (HDD) is a trenchless technology capable of placing pipes and conduits beneath obstacles over extended distances. HDD requires the use of bentonite suspension (commercial sodium montmorillonite clay) in water as drilling fluid. The fluid called mud (bentonite–water) is pumped down the drillstring (curved layout) and through the nozzles in the drill bit. It has several functions such as stabilizing the borehole by forming a cake, cleaning the hole by evacuating the cuttings, cooling and lubricating the string and the bit (Caenn and Chillingar, 1996; Besq et al., 2000).

Drilling mud contains suspended clay particles which are thin, flat and electrically charged platelets. These platelets can interact to form a structure or gel which is responsible for the yield characteristics of the fluid and for its thinning behavior upon breakdown by shear. This is why many papers were published with framework of the mechanical and hydrodynamics characteristics of bentonite suspensions.

Given the widespread nature of these applications, numerous papers have been published on the rheological characteristics and colloidal properties of bentonite clays. Among others, Luckham and Rossi (1999) published an extensive paper on the subject. These gel-like structure fluids are thixotropic, shear thinning and exhibit a yield stress i.e. solid-like below some critical yield stress but flow above this value (Magnin and Piau, 1990; Coussot et al., 1993; Bekkour et al., 2005; Klessidis et al., 2006; Kelessidis et al., 2007; Dolz et al., 2007).

Many rheological models have been suggested to describe the non-linear behavior of these suspensions. The choice of the "best rheological model" that characterizes water-bentonite suspensions is of an extreme importance. The rheological behavior of these used suspensions is usually described by the well-known Herschel–Bulkley model (Bekkour et al., 2005; Kelessidis et al., 2006; Kelessidis et al., 2007; Kelessidis et al., 2011). It is believed that the Herschel–Bulkley model is more accurate than the two-parameter models such as the Bingham and the Casson models, in predicting the rheological behavior of drilling muds (Livescu, 2012; Xia et al., 2015).

However, the number of papers which are concerned with the pipe flow of bentonite clay or fluids that have the same rheological properties is not enough. Only few detailed works involving bentonite suspensions pipe flow are reported in the literature. Otherwise, the flow of such yield-pseudoplastic fluids in various conduits such as pipes, annuli and ducts has been the subject of work of many investigators. Park et al. (1989) presented LDA (Laser

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[*] Corresponding author.
E-mail address: benslimane.ah@gmail.com (A. Benslimane).

http://dx.doi.org/10.1016/j.petrol.2015.12.020
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Doppler Anemometry) measurements for laminar-turbulent flow of transparent slurry with yield stress obeying the Herschel–Bulkley law. Escudier and Presti (1996) measured pressure drop, mean velocity profiles and velocity fluctuations by LDA of laponite suspensions for laminar, transitional and turbulent flow regimes. They predicted accurately the laminar pipe flow with the Herschel–Bulkley model. We note that the thixotropic effect was not clearly highlighted. Kembłowski and Petera (1981) presented an analysis of the thixotropic behavior of paints from the measurement of the pressure drop between the inlet and the outlet of the pipe. Later, Corvisier et al. (2001) investigated the start-up situation of a thixotropic fluid in pipe and showed, using particle image velocimetry and ultrasonic velocity profile, the effect of thixotropy on the evolution of velocity profiles. Also, Poole and Ridley (2007) and Poole and Chhabra (2010) reported in their works the results of a detailed and systematic numerical investigation of developing pipe flow of inelastic non-Newtonian fluids.

In transitional flow, the measured profiles develop an unexplained asymmetry until the flow undergoes transition to turbulence. This asymmetry was reported by Peixinho et al. (2005) for an aqueous solution of carbopol and by Escudier et al. (2005), in a synthetic paper reviewing LDA measurements performed in UK, France and Australia and for many others shear thinning fluids. This asymmetry seems be a consequence of a fluid-dynamics mechanism rather than imperfections in the flow facilities. The former being not yet identified whilst helicity is suspected. Recently, Esmael and Nouar (2008) suggested the existence of a robust nonlinear coherent structure characterized by two weakly modulated counterrotating longitudinal vortices. The statistical analysis of the axial velocity fluctuations performed by the same authors (2010) showed the existence of a weak turbulence in the transitional regime. In the turbulent flow, it was found that the mean velocity distribution was almost indistinguishable from that of a Newtonian fluid (Park et al., 1989; Escudier and Presti, 1996). The turbulence pipe measurements of Pereira and Pinho (2002) showed a small amount of drag reduction for the pure laponite suspensions. They reduced significantly the frictional drag by adding small amounts of polymer, where the fluids were shear-thinning, thixotropic and exhibited a yield stress. Dodge and Metzner (1959) reported this variation of friction factor with Reynolds number of shear thinning fluids, but the mechanism of reduction on the skin-friction coefficient was discovered by Toms (1948). It has been experimentally demonstrated that the existence of maximum drag reduction that may be attained, known as the “Virk's asymptote” (Virk et al., 1967; Virk, 1975). Numerous research efforts have focused on the mechanism of drag reduction.

Livescu (2012) in a review paper focuses mainly on mathematical modeling studies concerning the well and pipeline flow drilling muds and crude oils. After describing how non-Newtonian phenomenon in general and particularly thixotropy is understood inside and outside of the petroleum industry community, several mathematical models available in the literature were examined in his paper.

It is obvious that additional experimental data are needed to understand the rheology and pipe flow of bentonite suspensions to better predict velocity profiles and pressure losses in a transport of such materials. These materials were extensively studied previously in our laboratory from a rheological point of view (Bekkour et al., 2005; Ben Azouz et al., 2010; Bekkour and Kherfellah, 2002). The aim of this paper is to characterize in detail the pipe flow behavior of 3.5, 5 and 8% wt bentonite suspensions. Experimental measurements of pressure drop and mean velocity profiles are presented in laminar, transitional and turbulent flow.

2. Fluid rheology

2.1. Materials and sample preparation

Commercial French bentonite has been used in this study. The bentonite used for the experiments was composed mainly of calcium montmorillonite, natural clay of the smectite group with powerful viscosifying effect.

Given that the way of preparation has a great influence on the final state of the suspensions, and thus on the rheological behavior, all fluids were prepared using the same procedure to ensure fully reproducibility. Three bentonite suspensions with mass concentrations of 3.5, 5 and 8 wt% were obtained by progressive dispersion of the required quantity of bentonite in distilled water at room temperature. Sufficient time ($\geq$24 h) of continuous magnetic stirring was allowed to achieve complete homogenization. Afterwards the bentonite suspensions were stirred for 24 h prior to the experiments.

The rheological measurements were performed by the use of a controlled stress rheometer, AR2000 from TA Instrument, equipped with cone and plate geometry (acrylic cone, 60 mm diameter, 2° angle). The temperature was kept constant at 20.0 ± 0.1 °C thanks to the Peltier system. To prevent water evaporation, the samples were placed in a water-saturated environment. All tests were carefully conducted under equal conditions to allow for comparison of the results.

2.2. Viscosimetric measurement

The viscometric data were acquired by applying an increasing shear stress ramp at a constant stress rate of 0.03 Pa s^{-1}.

The flow curves of the dispersions, i.e. shear stress as a function of the shear rate, are depicted in Fig. 1 where the effect of mass concentration on the rheological properties of the bentonite suspensions is observed.

The Herschel–Bulkley model (Eq. 1) was used to fit the experimental curve:

$$\tau = \tau_0 + k\dot{\gamma}^n \qquad (1)$$

Where τ (Pa) is the shear stress, $\dot{\gamma}$ (s^{-1}) is the shear rate, τ_0 is the yield stress, k (Pa s^n) is the flow consistency index and n (-) is the flow behavior index. This model was chosen for its simplicity and ability to quantify the presence of yield stress.

The shear viscosity data are shown in Fig. 1 together with curves that predicted by the model, as appropriate. The model parameters are listed in Table 1:

The suspensions exhibit a strong shear-thinning behavior without the Newtonian plateau at low shear rates, which is typical of fluids possessing a yield stress. The shapes of bentonite suspensions are similar to those reported in previous works by Ben Azouz et al. (2010). Moreover, it was shown that the viscosity of the bentonite suspensions increases by increasing the mass concentration.

3. Flow measurements

3.1. Experimental setup and instrumentation

A schematic diagram of the flow loop used to carry out reliable velocity and pressure drop measurements is shown in Fig. 2.

Flow is provided by a volumetric pump (PCM-Moineau, France) (2) fed directly from a 50 l capacity tank (1). This pump was selected because it minimizes the amount of mechanical degradation. The flow pipe consists of an assembled Plexiglas® tube of