Experimental study of laminar-turbulent pipe flow of non-Newtonian fluids (bentonite/CMC suspensions as models for drilling mud)

A. Benslimane, P. François, K. Bekkour

Institut de Mécanique des Fluides et des Solides (IMFS), University of Strasbourg
2, rue Boussingault, 67000, Strasbourg

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Abstract : in this work, 5% by weight of bentonite suspension and a blend of 5%/0.1% bentonite/carboxymethyl cellulose (CMC) used as drilling fluid are investigated in terms of their rheology and hydrodynamic behaviour in pipe flows. All fluids exhibit non-Newtonian rheological behaviour which can be well described by the three parameters Herschel-Bulkley model. The axial velocity distribution was determined using ultrasonic pulsed Doppler velocimetry technique. In the laminar regime, the flow parameters can be predicted by integration of the constitutive rheological model used. In the turbulent flow, the Dodge and Metzner model was applied to fit the experimental data. The measurements of the friction factor showed a small amount of drag reduction for the pure bentonite suspension, whereas for the polymer–clay blend the drag reduction was more important.

Keywords: Bentonite, Polymer, Non-Newtonian, Laminar-turbulent, Pipe flow

[Abridged French version on last page]

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, or nuclear waste barrier, and other industrial applications include cosmetics (creams), chemical (paints), food products (wine), etc. A very important application of bentonite clays is their use as drilling fluids which have numerous roles such as stabilizing the borehole by forming a cake, cleaning the hole by evacuating the cuttings, cooling and lubricating the string and the bit. Given the widespread nature of these applications, numerous papers have been published on the rheological characteristics and colloidal properties of bentonite clays. Among others, Lukham and Rossi [1] published an extensive paper on the subject. These gel-like structure fluids are thixotropic, shear-thinning and exhibit a yield stress [2-4]. Their rheological behavior is usually described by the well known Herschel-Bulkley model [2, 5, 6].

Usually, in water-based drilling fluids, polymers are added to reduce filtration, flocculate drilled solids, increase cutting carrying capacity and serve as emulsifiers and lubricants. The addition of polymers to clay suspensions modifies their rheological properties [7-9]. The flow of these fluids is complex and requires a significant amount of investigation to be better understood. However, the number of papers which are concerned with the pipe flow of bentonite clay or fluids having the same rheological properties is small. Only few detailed works involving non-Newtonian pipe flows are reported in the literature. Park et al. [10] presented LDA measurements for laminar-turbulent flow of transparent slurry with yield stress obeying the Herschel-Bulkley law. Escudier and Presti [11] measured pressure drop, mean velocity profiles and *rms* velocity fluctuations by LDA for laponite suspensions in laminar, transitional and turbulent flow regimes. They predicted accurately the laminar pipe flow with the Herschel-Bulkley model. However, the thixotropic effect was not clearly highlighted. Kemblowski and Petera [12] 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, Corsivier et al. [13] investigated the start-up situation of a thixotropic fluid in a pipe and showed, using particle image velocimetry and ultrasonic velocity profile, the effect of thixotropy on the evolution of velocity profiles. 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. [14] for an aqueous solutions of carbopol and by Escudier et al. [15] in a synthetic paper reviewing LDA measurements performed in UK, France and Australia, for many others shear thinning fluids. It was clearly identified that this asymmetry could 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. More recent experimental results obtained by Esmael and Nouar [16] suggested the existence of a robust nonlinear coherent structure, characterized by two weakly modulated counter-rotating longitudinal vortices, and the statistical analysis of the axial velocity fluctuations performed by the same authors showed the existence of a weak turbulence in the transitional regime [17]. In the turbulent flow, it was found that the mean velocity distribution was almost indistinguishable from that of a Newtonian fluid [10, 11]. The turbulence pipe measurements of Pereira and Pinho [18] showed a small amount of drag reduction for the pure laponite suspensions. They reduced significantly the frictional drag by adding small amounts of polymer. These fluids were shear-thinning, thixotropic and exhibited a yield stress.

It is obvious that additional experimental data are needed to understand the pipe flow of bentonite suspensions and the effect of the addition of polymer on their rheological behavior. These materials were widely studied previously in our laboratory from a rheological point of view [2, 8, 19, 20]. The present paper contributes to characterize in detail the pipe flow behavior of bentonite and a blend of bentonite/carboxymethylcellulose. Measurements of pressure drop and mean velocity profiles are presented.

2. Materials and Methods

2.1 Materials and sample preparation

All the products used in this work were provided from VWR Prolabo (VWR, France). The bentonite used for the experiments was composed mainly of calcium montmorillonite, natural clay of the smectite group. In water, several physical states were observed depending on the percentage of available water, such as solid, gel or liquid. One of the most significant properties is the formation of a gel structure with a yield stress and viscoelastic properties at low concentrations [1].

The carboxymethyl cellulose (CMC) is a water-soluble flexible anionic polymer derived from natural cellulose. In water-based drilling fluids, CMC is used to increase the stability and viscosity of the mud as it stabilizes the aqueous clay suspensions due to its high water retention.

All the fluids were prepared using the same procedure. The base bentonite suspension of 5 wt. % mass concentration was obtained by progressive dispersion of the required quantity of bentonite in distilled water. For the mixtures, the CMC (nominal molecular weight of 700 000 g.mol^{-1}) solutions were added to the base bentonite suspension in the adequate proportions, afterwards the bentonite/CMC mixtures were stirred for 24h prior to the experiments.

2.2 Experimental setup and instrumentation

A schematic diagram of the flow loop used to carry out reliable velocity and pressure drop measurements is shown in Figure 1.

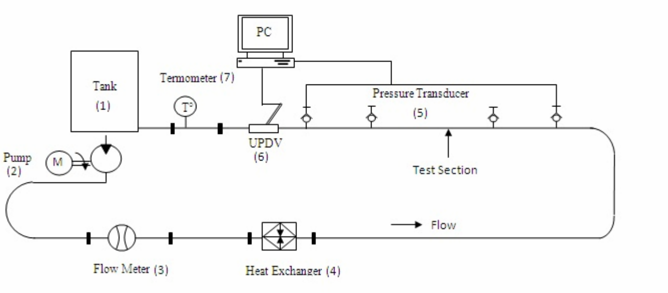

Figure 1. Schematic diagram of pipe flow facility.

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 20 mm inner diameter and 16 m length. The temperature of the test fluid is controlled by a heat exchanger (4) and a thermometer (7) mounted in the downstream of the test section (8) is used to monitor the fluid temperature. The test section is equipped with pressure transducers (5). Two pressure transducers (GS Sensors XPM5), providing absolute pressure points, with a range of 2.5 bars, were used and are located at 9.22 and 11.97 m from the inlet of the experimental setup. Their operating temperature range is from -40°C to 120°C. The pressure transducers are fixed to holes drilled in the pipe with diameters equal to the diameter of transducers. The pressure measurement obtained after each experiment at zero-flow rate was defined as the pressure reference. An electromagnetic flowmeter (model: DS41F, from ABB) (3) is incorporated upstream of the test section to measure the flow rate. The velocity profiles were obtained by ultrasound pulsed Doppler velocimetry (UPDV). The main advantage of this technique is that it is non-intrusive and therefore does not disturb the fluid flow. Contrary to optical methods, it is not limited to optically transparent liquids and can be used in the flow velocity measurement of opaque media.

The UPDV technique is based on pulsed ultrasound echography: sinusoidal ultrasonic burst is successively emitted from the transducer with a constant frequency f_E, during a short time along a measuring line, and then the echo signal that is reflected from targets that maybe present in the path of the ultrasonic beam is detected by the same transducer. PRF is the pulse repetition frequency, inversely proportional to the period of pulse repetition. The transducer is mounted according to the flow direction with an angle of 75°. The angle was fixed at this value in order to increase the range of measurable velocities. The backscattered echo is then demodulated in order to preserve only the modulated frequency or Doppler shift frequency f_D induced by the motion of the particles. The velocity of the particles within the sample volume is proportional to the frequency of the Doppler signal. This is described by:

$$u = \frac{c \cdot f_D}{2 \cdot f_E \cdot \cos\theta} \tag{1}$$

where u is the velocity of the particles, c is the acoustic velocity in water ($c = 1456$ m.s^{-1} at 11°C), f_E is the emission frequency, and θ is the angle between the ultrasonic beam and the flow direction (the Doppler angle).

The velocimeter used in this study is in-house design. Fully developed in the laboratory (IMFS, Strasbourg, France), this velocimeter has a highly configurable system.

The ultrasonic velocimeter was placed at the end of the useful area of the pipe. The experiments were performed with an 8 MHz frequency transducer. It is of ceramic type, with a diameter of 5 mm. Velocity information comes from Doppler frequency shifts induced by the movement of particles.

The velocity component measured by the velocimeter is the component in the direction of the ultrasonic beam. Thus, the velocimeter can automatically compute the real velocity value using the introduced Doppler angle value (θ =75°). Preliminary measurements showed good agreement between the theoretical data and the experimental data parameterized by the electromagnetic flowmeter and confirm those obtained by Jaafar et al. [21] with the same method and equipment. The volumetric flow rate obtained from integration of the measured velocity profile differs by less than 3% when compared to the flow rate obtained from the electromagnetic flowmeter.

The rheological measurements were performed by the use of a controlled stress rheometer, AR2000 (TA Instrument), equipped with cone and plate geometry (acrylic cone, 60 mm diameter, 2° angle). The temperature was kept at 20°C. To avoid water evaporation, the sample was placed in a water-saturated environment. All tests were carefully carried out under the same conditions to allow comparison of the results.

Due to the mechanical degradation of the fluids, the rheological parameters were measured after each experimental test following the same procedure: the sample volume was taken from the loop and tested on the rheometer.

3. Results and discussions

3.1 Viscosimetric measurements

The viscometric data were acquired by applying an increasing shear stress ramp at a constant relatively slow stress rate (0.03 Pa.s^{-1}), selected in accordance with the relaxation time of the materials. The flow curves of the dispersions (pure 5 wt% bentonite suspension, pure 0.1 wt% CMC solutions and polymer-bentonite mixture), i.e. shear stress as a function of the shear rate, are depicted in Figure 2 where the effect of adding CMC on the rheological properties of the pure bentonite suspension is observed.

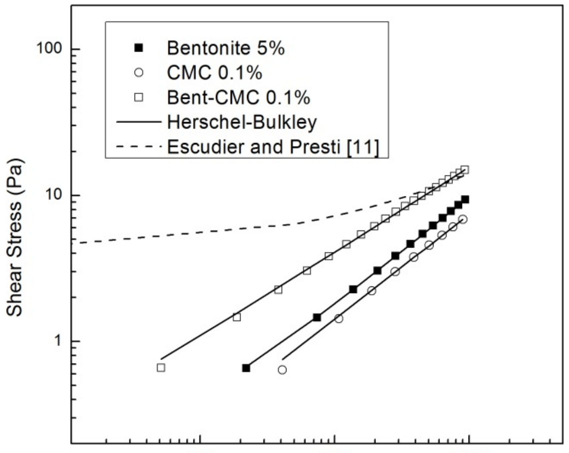

Figure 2. Shear stress vs. shear rate for 5% bentonite, 0.1% CMC and 5%/0.1% bentonite/CMC.

The flow curves were fitted with the Herschel-Bulkley model equation:

$$\tau = \tau_0 + k\dot{\gamma}^n \tag{2}$$

where τ_0 is the yield stress, k is the consistency index and n is the flow index. This model was chosen for its simplicity and efficacy.

It is seen that the viscosity of the bentonite suspension is increased by adding the polymer.

3.2 Flow measurements

3.2.1 Non-Newtonian flow

As the Herschel-Bulkley model was used for the correlation of the experimental data, the velocity distribution, and hence the relation between pressure drop and mean velocity was obtained, in the laminar flow, by integration of the Herschel-Bulkley equation:

$$U = \frac{2}{R}\frac{1}{\tau_w k^{\frac{1}{n}}\left(\frac{1}{n}+1\right)}\left[\frac{R^2}{2}\left(\tau_w-\tau_0\right)^{\frac{1}{n}+1}.\right.$$

$$-\frac{R^2}{\left(\frac{1}{n}+2\right)\tau_w}\left(\tau_w-\tau_0\right)^{\frac{1}{n}+2} \tag{3}$$

$$\left.+\frac{R^2}{\left(\frac{1}{n}+2\right)\left(\frac{1}{n}+3\right)\tau_w^2}\left(\tau_w-\tau_0\right)^{\frac{1}{n}+1}\right]$$

where τ_w is the wall shear stress. For unidirectional, axisymetric flow in pipe, the shear stress τ_w at the pipe wall is given by:

$$\tau_w = \frac{D}{4}\frac{\Delta P}{L} \tag{4}$$

In a turbulent flow regime, Blasius [31] and Dodge and Metzner [22] carried out semi-empirical analysis formulated from experimental data of pipe flow of Newtonian and non-Newtonian fluids and obtained the following expressions, respectively:

$$\frac{f}{2} = 0.0395\ Re'^{0.25} \tag{5}$$

$$\frac{1}{\sqrt{f}} = \frac{4}{\left(n'\right)^{0.75}}\log\left(Re' f^{\left(1-\frac{n'}{2}\right)}\right) - \frac{0.4}{\left(n'\right)^{1.2}} \tag{6}$$

where f is the Fanning friction factor and Re' is the generalized Reynolds number as defined by Metzner-Reed (MRR):

$$Re' = \frac{D^{n'}U^{2-n'}\rho}{K' 8^{n'-1}} \tag{7}$$

where ρ is the liquid density. Koziki et al. [23] determined n' and K' for several rheological models and ducts of arbitrary cross section. Over the range of shear rates where the power-law model ($\tau = k\dot{\gamma}^n$) is applicable, the consistency index K' and the index n' are related to the parameters of the Ostwald-de Waele equation, k and n, by:

$$n' = n \tag{8}$$

$$K' = k\left(\frac{3n+1}{4n}\right)^n \tag{9}$$

Figure 3 presents plots of the shear stress as a function of the pseudo-shear rate ($4Q/\pi R^3 = 8U/D$) for the 5% bentonite suspension and 5% bentonite/0.1%CMC blend in both laminar and turbulent flows.

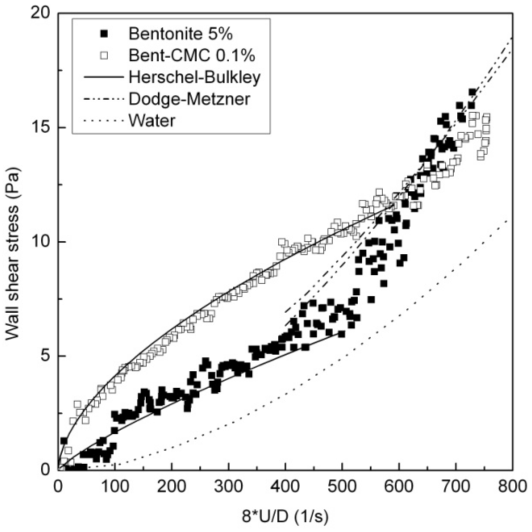

Figure 3. Laminar and turbulent flow of fluids.

The experimental data obtained in laminar and turbulent flows were compared to the theoretical predictions. The rheological parameters of the Herschel-Bulkley equation fitted to the flow curves were used as input parameters for laminar (Eq. (2)) and turbulent flow prediction models (Eq. (4), Newtonian behaviour, and Eq. (5), non-Newtonian behaviour). Comparison of the flow curves depicted in Figure 2 and Figure 3 shows that the data obtained using the AR2000 rheometer are in the same order of magnitude with the data deduced from measured velocity. Also, it can be seen that the experimental data are in close agreement with the Herschel-Bulkley model in the laminar regime (solid line) and Dodge and Metzner model (non-

Newtonian fluids represented by dashed lines) in the turbulent regime (Fig. 3). Note that the Dodge and Metzner flow curves of 5%bentonite with 0% and 0.1%CMC are very close. Even if it is difficult to accurately predict the transition from laminar to turbulent flow regime in actual processing systems, it may be estimated by the abrupt slope change at a given shear rate in the shear stress versus shear rate plot of the 5 wt% bentonite suspension. The calculated critical Reynolds number corresponding to the shear rate at which the slope change was evaluated to be about 2500, in close agreement with values given in the literature [15]. Furthermore, it is interesting to point out that the flow curve presents approximately the same trend when using the Blasius equation for Newtonian fluid (water) and Dodge and Metzner correlation for non-Newtonien fluids (bentonite, bentonite/CMC), demonstrating that at high Reynolds numbers the flow behavior of bentonite suspensions is insensitive to rheological properties, well in accordance with results established by others [11]. As also shown in Figure 2, the addition of CMC to the bentonite suspension yields an increase in viscosity, particularly in the laminar regime. Inversely, in the turbulent regime, the addition of the polymer leads to a decrease in viscosity. This result confirms the main mechanism of drag reduction described by Toms [24]. Indeed, the polymer is strongly on the nearest wall region and the macromolecules tend to act as a lubricant, reducing friction in this region. The macromolecules have the ability to grow in an extensional flow and interact with the turbulent flow, causing a reduction in drag.

Another interesting feature observed is that, when the polymer is added to bentonite suspension, the transition to the turbulent flow shifts towards higher shear rates values: for the bentonite suspension, the transition is observed at 450-550 s^{-1} and, for the mixture, the transition appears at 600-700 s^{-1}.

3.2.2 Friction factor

The fanning friction factor is defined as the ratio of viscous forces in a pipe over kinetic energy per unit volume:

$$f = \frac{2\tau_w}{\rho U^2} \qquad (10)$$

where τ_w is the wall shear stress as defined in Eq. (5). The wall Reynolds number is expressed as:

$$Re_w = \frac{\rho U D}{\eta_w} \qquad (11)$$

where the wall viscosity η_w is the ratio of wall shear stress over wall shear rate, i.e. $\eta_w = \tau_w / \dot{\gamma}_w$. In this equation, the wall shear rate $\dot{\gamma}_w$ is extracted from the velocity profile.

Then, to investigate the drag reduction effect of CMC on bentonite suspensions, the Dodge and Metzner correlation (Eq. (7)) was rearranged to be written in terms of friction factor and wall Reynolds number as follows:

$$\frac{1}{\sqrt{f}} = 0.8685\, n^{0.25} \ln\left(\frac{2n}{3n+1} Re_w \sqrt{f}\right) + \frac{2.4082}{n^{0.75}}(1-n) - \frac{0.2}{n^{1.2}} \qquad (12)$$

Friction factors as a function of wall Reynolds numbers are plotted in Figure 4 for the bentonite suspension and bentonite/CMC blend.

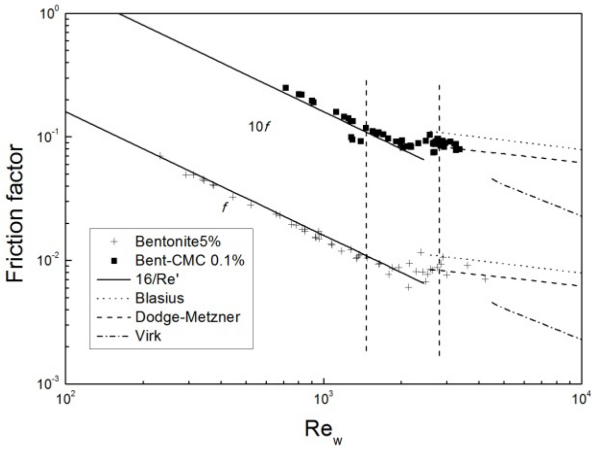

Figure 4. Friction factor as a function of the Reynolds number Re_w.

It can be observed that the experimental data are well correlated with the theoretical equation ($f = 16/Re'$) in the laminar regime. In the turbulent regime, the Blasius equation and the Dodge and Metzner correlation were used to model the flow behavior of the fluids. For the two fluids used, good agreement is observed between the experimental measurements and the Dodge and Metzner correlation (dashed lines), whilst the Blasius equation (dotted lines) overestimates the experimental measurements. This was expected since the Blasius equation is appropriate for Newtonian flows. Moreover, the drag reduction was evaluated by the use of the following definition:

$$DR(\%) = \frac{f - f_N}{f_N} \times 100 \qquad (13)$$

with all parameters obtained at the same wall Reynolds number: f is the value of the measured friction factor for any fluid and f_N is the corresponding Newtonian coefficient at the same Reynolds number. Note that f_N is calculated from the power-law Blasius relationship. The application of the above-mentioned definition results in maximum of drag reduction values of about 18% and 24% for bentonite suspension and bentonite-polymer blend, respectively. This indicates that the addition of polymer gives the pure bentonite suspension higher drag reduction properties. Indeed, it is well accepted that reduction in drag is associated with the viscoelastic character of additive solutions and that the interaction of additive structures with the fluid turbulence near the pipe wall plays a major role [25]. These values are to be compared to the maximum drag reduction asymptote (MDRA) of Virk [26], also shown in Figure 4, and expressed as:

$$\frac{1}{\sqrt{f}} = 19.0\,\log\left(Re\sqrt{f}\right) - 32.4 \qquad (14)$$

3.2.3 Velocity profiles

3.2.3.1. Laminar flow

For Herschel-Bulkley fluids, in laminar flow and no slip boundary condition, the velocity distribution between the plug and the wall of the tube where the fluid is subject to shear is given by the following expression:

$$u(r) = \frac{R}{\tau_w k^{\frac{1}{n}}}\,\frac{1}{\frac{1}{n}+1}\left[\left(\tau_w - \tau_0\right)^{\frac{1}{n}+1} - \left(\frac{\tau_w r}{R} - \tau_0\right)^{\frac{1}{n}+1}\right] \qquad (15)$$

for $R_C < r < R$, where $\tau \geq \tau_0$, R_C being the critical radius, which defines the outer boundary of the plug.

The maximum velocity in the pipe, which is the plug velocity in the center section of the pipe (for $r < R_C$) where there is no shearing flow because the shear stress is below the yield stress ($\tau < \tau_0$), is expressed as:

$$u_c = \frac{R}{\tau_p k^{\frac{1}{n}}}\,\frac{1}{\frac{1}{n}+1}\left[\ \tau_p - \tau_0\ \right]^{\frac{1}{n}+1} \qquad (16)$$

Figure 5 illustrates typical measured velocity profiles for 5wt% bentonite suspension and bentonite/CMC mixture in fully developed laminar flow. The profiles were measured at L=700 D (14 m from the inlet of the pipe). According to Froishteter and Vinogradov [27], the entrance length L_e after which the laminar flow of a Herschel–Bulkley fluid is considered established is given by:

$$\frac{Le}{R\,Re_g} = \frac{0.23}{n^{0.31}} - 0.4a \qquad (17)$$

where a is the ratio of the yield stress to the wall shear stress and Re_g is the Reynolds number defined by $Re_g = \rho U^{2-n} R^n / K$. Eq. (17) is used to ensure that our measurements concern a fully developed flow.

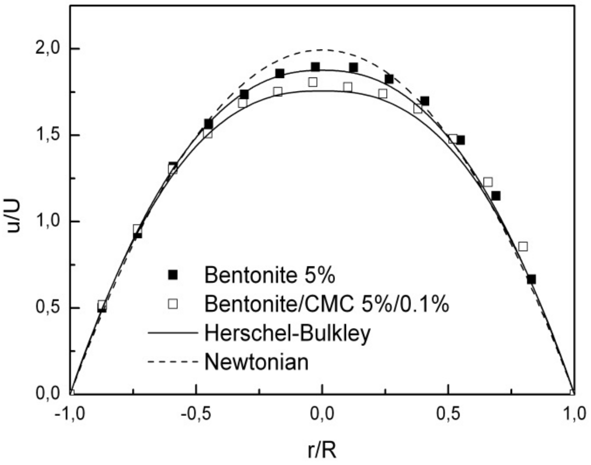

Figure 5: Laminar velocity profiles.
(Pure bentonite: $Re_w = 360$, Mixture : $Re_w = 390$)

The velocity profile for Newtonian fluid is shown as reference. Moreover, one can observe that the experimental velocity profiles are in good agreement with the theoretical profiles which were plotted by the use of the Herchel-Bulkley model. It is worth noting that the maximum difference between measured and calculated axial velocity does not exceed 3%, showing the accuracy of both velocity and viscometric measurements.

3.2.3.2. Transitional flow

The experimental profiles were measured at L = 700 D (14 m from the inlet of the pipe) and azimuthal position $\varphi = \pi/2$ where $\varphi = 0$ is the horizontal plane. In the transitional flow, the experimental velocity profiles present an asymmetry (Fig. 6) when comparing with the average velocity profile (solid line). Since it was observed over a decade ago [11], the existence of this phenomenon is now incontrovertible for viscoelastic, shear-thinning and yield stress fluids, and has been well documented [14-16, 28, 29]. Esmael and co-workers [16, 17] suggested the existence of a robust coherent structure, characterized by two weakly modulated counter-rotating longitudinal vortices, mediating the transition from laminar to turbulent flow. For the same authors, the reorganization of the flow is probably related to the strong stratification in viscosity between the central area and the near wall area.

Concerning the pure bentonite suspension, the asymmetry appeared at $Re_w \approx 1150$. This value is close to the results given in the literature by Escudier and Presti [11] where asymmetry was observed for a flow of Laponite at $Re_w = 1275$.

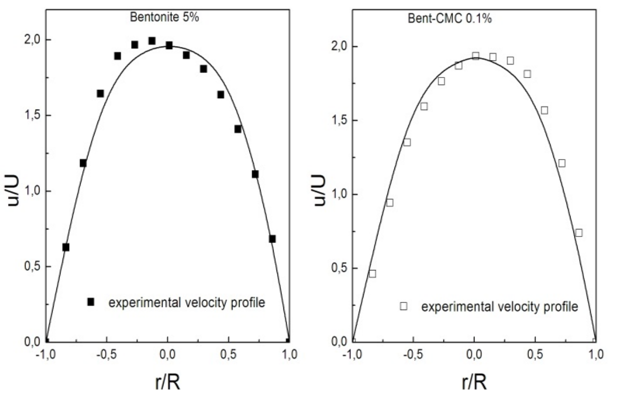

Figure 6. Transitional velocity profiles
(Pure bentonite $Re_w = 1150$, Mixture $Re_w = 1300$)

Figure 7 presents the plot of u_c/U as a function of Re_w in the transitional regime for both fluids. The theoretical solution is shown by the continuous line. It can be observed that the experimental data are in good agreement with the theoretical solution in the laminar flow. In the turbulent flow, the ratio is close to values given in the literature [10, 30]. Furthermore, it can also be seen that the laminar-turbulent transition velocity increases with the addition of polymer to the clay suspension.

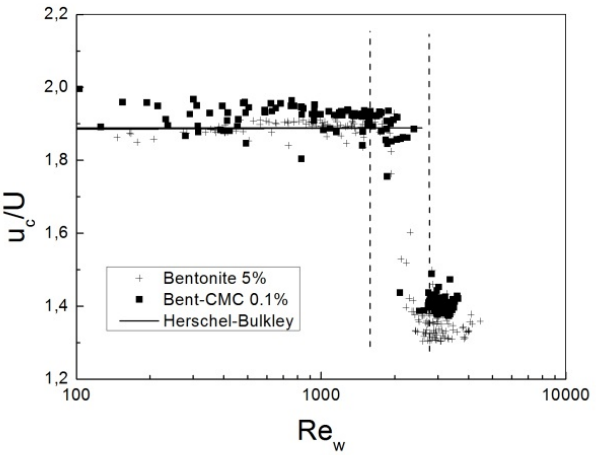

Figure 7. Normalized centerline u_c/U vs. Re_w.

3.2.3.3. *Turbulent flow*

Figure 8 shows mean profiles for 5wt% bentonite suspension and 5%bentonite/0.1%CMC mixture in wall variables $u^+ = u/u^*$ and $y^+ = \rho u^* y/\eta_w$, with $u^* = \sqrt{\tau_w/\rho} = U\sqrt{f/2}$ being the friction velocity. Semi-theoretical prediction equations for the velocity profile of Newtonian fluids in turbulent flows are well established: the normalized velocity profile is correlated in the laminar sub-layer (for $0 < y^+ < 5$), with the linear relation $u^+ = y^+$ and in the turbulent core (for $y^+ \geq 30$) with the logarithmic relationship $u^+ = 2.5 \ln y^+ + 5.5$. The Newtonian laminar sub-layer is shown by the full line and the Dodge-Metzner correlation is represented by dished lines and given by the following equation:

$$u^+ = 5.657 n^{0.25} \log y^+ - \frac{0.566}{n^{1.2}} + \frac{3.475}{n^{0.75}}\left[1.96 + 0.816n - 1.628n \log\left(3 + \frac{1}{n}\right)\right] \quad (17)$$

The centerline of the pipe corresponds to $y_c^+ = 95$ for the clay suspension and $y_c^+ = 70$ for the blend.

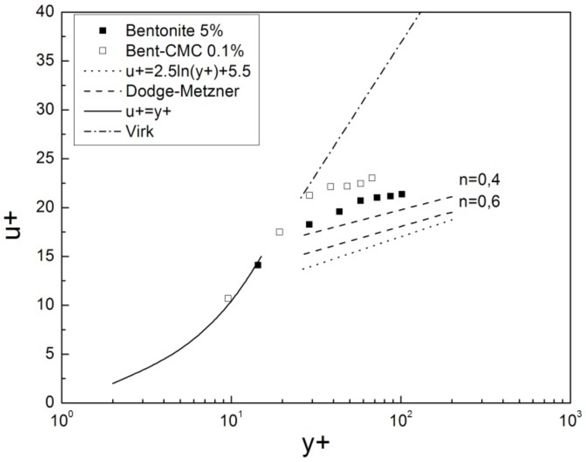

Figure 8. Turbulent velocity profiles

For both fluids, the normalized velocity profile agrees with the linear relation: $u^+ = y^+$ for $0 < y^+ < 5$. The experimental data are not correlated by the Newtonian equation. This result is similar to the observations made in the study of the drag reduction (see Fig. 4), where the experimental data were deviated from the Newtonian equation. It can be observable that there is a lack of experimental data for $y^+ < 10$. This is due to the fact that it is difficult to carry out experimental measurements in the near wall region.

A deviation is also observed when the Dodge and Metzner correlation is used to fitting the experimental data for bentonite suspension as well as for bentonite/polymer mixture. The drag reduction obtained by addition of CMC is to be pointed out, as the experimental data tend to approach the Virk MDRA [26], which is given by the following equation:

$$u^+ = 11.7 \ln\left(y^+\right) - 17 \quad (18)$$

4. Conclusions

A detailed experimental investigation of laminar, transitional and turbulent pipe flow of bentonite suspensions (5 wt%) and bentonite/CMC blend (5 wt% and 0.1 wt% of bentonite and CMC, respectively) was conducted using UPDV measurement techniques. The advantage of this technique is that it is not limited to optically transparent liquids.

In the laminar flow, the experimental velocity profiles and friction factors were found to be in satisfactorily agreement with the theoretical equations based upon the Herschel-Bulkley model.

In the transition regime, the measurements showed asymmetry in the velocity profiles, as expected for shear-thinning fluids and in accordance with published works by other authors.

In the turbulent flow, the friction factors are well described by the Dodge and Metzner correlation. Furthermore, in the case of bentonite suspensions, probably due to their shear-thinning behavior, small drag reduction effects were found whilst the clay-polymer blends exhibited well more pronounced effects.

Nomenclature

D	pipe diameter (m)
f	friction factor
f_N	friction factor for Newtonian fluid
k	constant in Herschel-Bulkley model (Pa.s^n)
K'	generalized consistency (Pa.s$^{n'}$)
n	power law exponent in Herschel-Bulkley
n'	generalized index flow behavior
r	radial location within pipe (m)
R_c	radius of constant velocity plastic plug (m)
R	pipe radius (m)
Re	Reynolds number
Re'	generalized Reynolds number
Re_w	wall Reynolds number
u	axial velocity (m.s^{-1})
u_c	centreline axial velocity (m.s^{-1})
u^+	dimensionless velocity = $u/\sqrt{\tau_w/\rho}$
y	distance from the wall
y^+	dimensionless distance from the wall
y_c^+	centreline dimensionless distance from the wall
$\dot{\gamma}$	shear rate (s^{-1})
ρ	fluid density (kg.m^{-3})
η	fluid viscosity (kg.m^{-1}.s^{-1})
η_w	viscosity of the fluid at the pipe wall (kg.m^{-1}.s^{-1})
τ	shear stress (Pa)
τ_0	yield stress (Pa)
τ_w	wall shear stress (Pa)

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[Abridged French version]

Etude expérimentale d'écoulements laminaires-turbulents de fluides non-newtoniens en conduite (suspensions bentonite/CMC comme modèle de boue de forage)

L'objectif de notre travail est d'apporter un supplément de connaissances quant au comportement mécanique en écoulement des boues de forage. Les fluides utilisés sont une suspension de bentonite de concentration massique de 5% et un mélange de 5%/0,1% bentonite/carboxymethyl cellulose de sodium (CMC). Il a été établi que le comportement rhéologique de l'argile et du mélange peut être caractérisé par un modèle à trois paramètres de type Herschel-Bulkley. Les profils de vitesse instantanés sont mesurés à l'aide d'un vélocimètre ultrasonore pulsé à effet Doppler. En régime laminaire, les paramètres d'écoulement sont en accord avec les résultats analytiques obtenus à partir du modèle de Herschel-Bulkley. En régime turbulent, les équations de Dodge et Metzner modélisent de manière satisfaisante le comportement de nos fluides. Les mesures en écoulement turbulent ont montré une faible réduction de frottement pour la suspension de bentonite, tandis que pour le mélange argile-polymère la réduction de frottement est plus importante.