FLOW SITUATIONS OF DRILLING MUDS EFFECTS OF THIXOTROPIC PROPERTY

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ABSTRACT

This paper reports experiments on the flow of bentonite suspensions used as drilling fluid. Thixotropic effects of such fluids depend on structure evolution (rupturing and restoring processes of aggregates). Structure build-up and break down (at rest or under shear) are studied from both rheological and mechanical (flow in a circulating loop), points of view. Different kinetics exist depending on the bentonite kind. Pressure measurements and pulsed ultrasound velocimetry technique are used to get information about the evolution of structure levels with time. An attempt is made to develop a simple structural constitutive model describing all observed phenomena. Experimental flow results are compared with predictions using Rabinowitch equation ; good agreement was obtained.

KEYWORDS : Bentonite (clay) suspension, thixotropy, structural kinetic, constitutive model, ultrasound velocimetry.

I. INTRODUCTION

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 (mud) is pumped down the drillstring (curved layout) and through the nozzles in the drill bit ; and then it flows up the annulus between the drillstring and ground. It has several functions as transport drill cuttings or borehole stabilisation.

Montmorillonite is an expansible 2:1 phyllosilicate (layer sheets structure) clay minerals with permanent layer negative charge. Because the interlayer is open and hydrated, cations may be present within the interlayer to balance negative charges. In contact with water, ions are exchanged and water penetrates between the layers leading to interlayer swelling. Thus, the effective volume fraction taken up by bentonite dispersed in water is much greater than the one calculated simply from the mass of bentonite added to water.

Swelling and interparticule interactions can result in the formation of a three dimensional mechanically rigid network structure that must deform and fail before flow can occur. The strength of the network structure determines the magnitude of the yield stress (which is convenient for suspending cuttings when circulation of the drilling fluid is stopped). This network is related to a large scale organisation with 2 possible microstructures : (i) card house structure or (ii) large pore and locally parallel interaction between adjacent clay platelets [1,2].

The bentonite suspensions are often thixotropic because the breakage and restoring of the network are reversible and not instantaneous, so that fluid properties are governed by different levels of structure.

The rheological behaviour of clay suspensions have been widely studied and specific experimental procedures have been developed to account for yield stress and thixotropic effects and obtain reproducible results [3-5].

Investigations of the pipe flow of thixotropic fluids have been mainly experimental and have often extended to setting up theoretical models by using material parameters (these parameters stem from a complete set of rheometry experiments) [6-8]. Hitherto, few attempts have been made to determine pipe flow structural changes [6,7].

Based on experiments, this paper attempts to present structural evolution kinetics, at rest or under shear, of bentonite suspensions. The laminar flow in axisymetric circular and annular pipes will be considered.

II. MATERIALS AND METHODS

A. MATERIALS

Two commercial bentonites have been used in this study. These clays are denoted respectively A and B.

The identification of the powder nature and of the liquid phase is essential to know the mixture. Bentonite is a mineral powder, which essentially contains smectite clays (mainly montmorillonite) and others secondary minerals, like feldspar, quartz, calcite, iron oxides. Usually, these powders are activated by adding inorganic salts or material polymers. The following parameters were studied : mineralogical composition, chemical composition, physical parameters (size, specific surface, CEC:Cations Exchange Capacity, exchangeable bases).

In this study, no mineralogical pre-treatment were made on account of difficulties to obtain a standard sample and to consider pre-treatment effects.

Mineralogical composition of bentonites was determined by X-ray diffraction (XRD) and differential thermal analysis (DTA). The XRD patterns of bentonites

were obtained with Philips 1729 diffractometer using Cu-Ka1 radiation (wave length1,5406Å). Diffraction patterns were recorded on a microcomputer with a DACO-MP acquisition device. Different types of diffraction patterns were recorded on the bulk sample and on the specific size fraction infra 2µm.

Particle size analysis was performed by sedimentation. The pipet method is a direct procedure, it relies on the Stokes law and permit to determine settling velocity and hydrated particle diameter (Table 1).

Specific surface have been evaluated with the determination of the methylene blue value by means of the stain test. This method is rapid and is used to classify the argillaceous fraction activity and quantity in soils mechanic (Table 1).

The cation exchange capacity was measured by using Jackson's method. The sum of exchangeable bases is then measured during the same test (Table 1).

To determine a swelling capacity, 2 g of bentonite is added progressively into a graduated cylinder filled with 100 ml distilled water during 4 h. The volume of the swollen bentonite (*i.e.* swelling index) is measured after 24 h (Table1).

Table 1: Physical parameters of bentonite A and B.

	hydrated particle size ($\%_{mass}$)				CEC	Surface	Swelling
	infra 2µm	2-20 µm	20-50 µm	sup 50 µm	infra 2 µm	(m^2/g)	cm^3
A	79,98	12,23	0,93	6,86	73,6	639	30
B	95,14	2,96	0,16	1,73	40	410	22

Mineralogical analysis showed that :

1. Bentonite A is a dioctahedral smectite (Na and Ca montmorillonite). Other secondary minerals are found, like quartz, micas and feldspars.
2. Bentonite B is a dioctahedral smectite, with an important quantity of glauconite which is a non-swelling clay mineral, as specific surface and swelling index values indicate. Other secondary minerals, like feldspar and calcite are also found.

The DTA have showed that bentonite B contains polymeric materials (286 °C cellulose peak). Although the CEC value and the capacity swelling are small, the effect of polymeric materials induce specific rheological behaviour.

B. PREPARATION

Suspensions consist in raw bentonites progressively dispersed in distilled water. Two concentrations, 40 and 60 g/l, have been studied.

The rheological study was performed on suspensions stirred for 15 min. by means of a vane rotating at 800 rpm. and then placed on to a roller (50 rpm) for 24 h.

As the circulating loop requires high volume suspensions, the roller stage was discarded. The entire suspension was put in a jug and left at rest for 24 h.

Bentonite A and B had respectively (for each concentrations) a pH of 10 and 10.8.

C. RHEOMETRIC TECHNIQUES

The tests were carried out on a Reologica-Stresstech HR control stress rheometer at a temperature of 20°C. To avoid water evaporation, the upper free surface was covered with a small amount of low viscosity silicon oil. Surrounding atmosphere was trapped in a transparent Plexiglas box.

In order to evaluate characteristic recovery time, the following test was performed.

After breaking down the structure of the sample, shearing it at 500 s^{-1} for 1 h, storage modulus G' and phase angle shift φ are monitoring in time with oscillatory shear. This test involves different stages with suitable strain (ε) and frequency (*f*) values because the extent of the viscoelastic linear domain depends on the structural recovery time. Typically, ε varies from 0.1 to 0.01, and *f* from 0.1 to 0.01 Hz. The rest time elapsing between two measurements was adapted (increasing values) in order to minimise structural impact of the measurement.

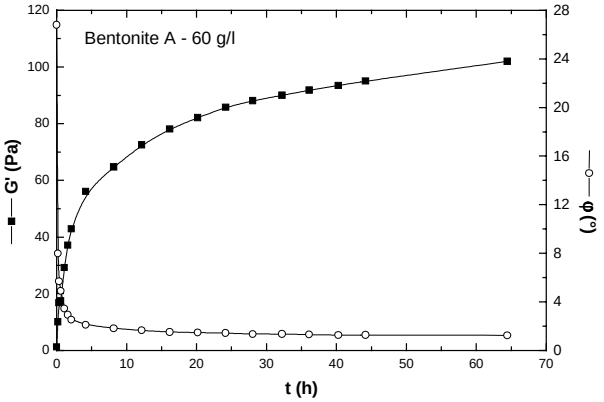


Figure 1 : Structure build-up at rest for bentonite A (60 g/l). Kinetic is fast during the first three hours and afterwards, it becomes slow.

In (Fig. 1), a test of this kind indicates that the recovery appears to occur over a long time scale about several days. Although, G' doesn't reach an equilibrium plateau, end low phase φ values are related to the response of a solid.

Recovery times and final G' values increase with concentrations and are respectively more important for bentonite B than bentonite A.

The variation of G' seems to follow a double exponential growth with two different specific times. One would be associated to small structures with (mutual orientation and bond formation). The other, might be related to more voluminous aggregates.

The transient response of the material subjected to a sudden increase in shear rate, after a long rest (14 h), was studied.

(Fig. 2) shows the influence of the shearing intensity ($\dot{\gamma}$ = 100 and 500 s^{-1}) on the kinetic of structure destruction. Dimensionless shear stress, obtained by dividing all values with the equilibrium one, are presented.

Characteristic time leading to a structural steady flow decreases with shear rate for bentonite B and conversely increases for bentonite A. As far as the present authors are aware, this latter observation has never been reported. This trend may be ascribed to the polymeric materials

which effects must be cancelled at 500 s^{-1}. Existent charges and aggregates size must also play an important role.

The suspensions examined here present time scales of structure breakdown varying from a few minutes to several hours.

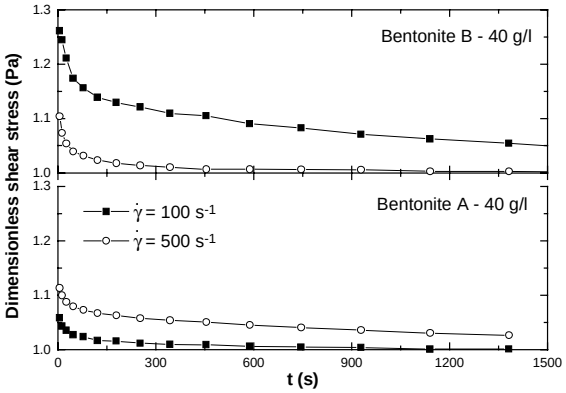


Figure 2 : Start-up flow at a shear rate of 100 and 500 s^{-1}. Bentonite suspensions A and B (40 g/l). Rest time : 14 h

The procedure described in Ref.[4] was used to determine the yield stress value.

The steady flow curve was also obtained with a set of transient flow experiments (not presented here). Each point on the flow curve was determined after stabilisation of the transient response from the previous steady state when a new shear rate (higher or lower value) is applied. Bentonite B flow curve was found to be non monotonic (i.e. existence of a minimum).

As this method requires long experiment duration, a short procedure was developed. Initial state of material was standardised by shearing it at 100 s^{-1} for 300 s. A 600 s period at rest was then realised. At least, successive increasing, and then decreasing, shear stress values were applied (ramp duration about 900 s).

This "quick" flow curve and the steady flow curve are shown in (Fig. 3) for suspension A (40 g/l).

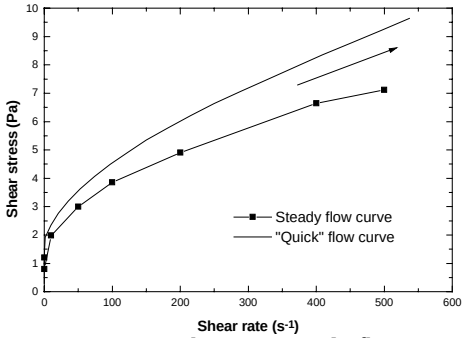


Figure 3 : Comparison between steady flow curve and "quick" flow curve. Suspension A, 40 g/l. The slow structural evolution under shear explains differences at high shear rate.

D. EXPERIMENTAL CIRCULATING LOOP

This equipment is a semi-closed system vertically erected (Fig. 4).

It is designed in such a way that a bentonite suspension can be pumped through one of the 3 sections (Plexiglas) thanks to pneumatic valves. Section 1 and 2 are circular pipes respectively 12 mm and 19 mm in diameter. Section 3 is : (i) circular pipe 32 mm in diameter or (ii) annular pipe with different inner/outer diameter ratio (κ=8/46 or 12/46).

Sections are equipped with 2 miniature semi-conductor pressure transducers (DRUCK PDCR 81) 3 m apart. Pressure measurements obtained after each experiments at zero flow rate define pressure references.

For unidirectional, axisymetric flow in circular pipe, the shear stress (τ_w) at the pipe wall is given by $\tau_w = \frac{D}{4}\cdot\frac{\Delta P}{L}$ with D the inside diameter and $\frac{\Delta P}{L}$ the pressure drop per length unit.

Temperature evolution is followed with a thermometer.

Rotation speed of the volumetric pump (MOINEAU MR6ID5) is controlled so that this device is assumed to fix the volumetric flow rate (Q). The latter is measured with a magnetic flowmeter (ROSEMOUNT 8712C). Pump operating range (4-20 l/min) and the 3 circular pipe sections allow to apply a mean shear rate ($\dot{\gamma}_m = 32Q/\pi D^3$) from 20 s^{-1} to 1900 s^{-1}.

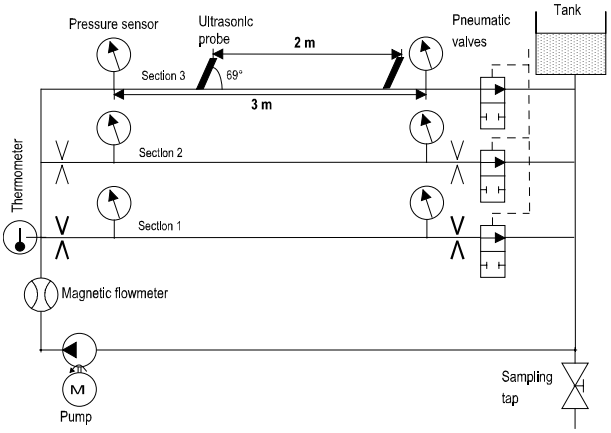


Figure 4 : Experimental circulating loop sketch.

Structural changes during transient flow situations has been investigated by means of pulsed ultrasound doppler velocimeter (Signal Processing-DOP1000). Velocity profiles have been obtained in two different places along the pipe with probes, referred to as upstream probe and downstream probe, respectively. Both, are fixed on the top of the pipe. Velocity information comes from Doppler frequency shifts induced by the movement of particules. The velocity component measured by the velocimeter is the component in the direction of the ultrasonic beam. In our experiments laminar flow situations will be considered. We can then suppose that the real velocity direction is that of the axis pipe. Thus, velocimeter could automatically compute the real velocity value u by using the introduced Doppler angle value (69°). A multiplexer unit, controlled directly by the velocimeter allows to successively measure the velocity profile from different probes (upstream and downstream probe).

Dimensionless velocity profiles $u^*(r^*)$ will be presented afterwards. $u^*=u/u_m$ where u_m is the mean velocity. $r^*=2r/D$ where r is the radial distance from the axis of the

pipe (for annular pipe, D is the inner diameter of the outer pipe). r^*=-1 corresponds to the top of the pipe.

Data sampling and velocimeter piloting are realised with a computer-acquisition board set, and synchronised with the start-up flow.

Moreover, flow curve of the circulating fluid was determined by using short rheometric procedure mentioned above with no rest time in order to keep the structure of the sample as close as possible to the circulating fluid one.

In this paper, only experimental results relative to bentonite A will be examined.

E. MODELS

As has been already pointed out, structure evolution (rupturing and restoring processes of aggregates) are not instantaneous and thus thixotropic effects may occur as result.

The most common approach to thixotropy is phenomenological due to the lack of knowledge of internal structure changes. Different structure levels can be denoted by the single parameter λ varying within the range $0 \le \lambda \le 1$. $\lambda=0$ corresponds to the complete break down of structure, and $\lambda=1$ to the equilibrium gel structure at rest. Within this framework, material is described with a flow behaviour law (E.1) and kinetic expression for the creation (or destruction) rate of the structure (E.2) :

$$\tau = f(\lambda, \dot{\gamma}) \qquad \text{(E.1)}$$

$$\frac{d\lambda}{dt} = g(\lambda, \dot{\gamma}) \qquad \text{(E.2)}$$

(E.1) and (E.2) become after the model proposed by Mollet [7] :

$$\tau = \tau_o \lambda + k\dot{\gamma}^n \quad (k > 0\,; 0 \le n \le 1) \qquad \text{(E.3)}$$

$$\theta(\dot{\gamma})\frac{d\lambda}{dt} = 1 - \lambda - a\dot{\gamma}^m \lambda^\alpha \ (\alpha=1 \text{ or } 2) \qquad \text{(E.4)}$$

$$\text{with } \theta(\dot{\gamma}) = \theta_1 \qquad \text{(E.5)}$$

τ_o, θ_1, a are positive constants.

(E.3) is the Herschell-Bulkley relation modified by incorporating the effect of changes in the structure on the yield stress value ($\tau_o \lambda$). A fully broken structure is assumed to exhibit no yield point. k and n values are the consistency and the flow index, respectively.

At this point, mention must be done about the more sophisticated model proposed by Coussot *et al.* [3]. It describes thixotropic fluids with yield stress. The most remarkable feature of this theoretical model is that it contains no mathematical criterion to predict existence of a yield stress, contrary to (E.3).

The first and second terms on the right hand side of (E.4) represent the process of structure build-up and breakdown. Analytical solutions exist for $\alpha=1$ or 2. Billingham and Ferguson [9] extended kinetic equation (like (E.4)) to include structure diffusion. The diffusity term may itself be a function of λ and of $\dot{\gamma}$. Positive diffusity ensures that structure diffuses from regions where λ is large (e.g. plug flow region in pipe) to regions where λ is small (e.g. pipe wall).

$\theta(\dot{\gamma})$ is a characteristic relaxation time which reflects viscoelastic phenomena in rupturing and restoring aggregates. Constant θ value result in structure destruction kinetic increasing with shear rate. Experiments revealed that it's not always true, mainly for bentonite A In a more general context, θ must depend on λ and $\dot{\gamma}$ (e.g. [3]). To account for the specific kinetic previously mentioned, we proposed :

$$\theta(\dot{\gamma}) = \theta_1\left(1 + b\dot{\gamma}^p\right) \text{ with } b,\ p > 0$$

(E.4) corresponds to a breaking down kinetic only if $p \le m$. A breaking down kinetic slowing down with increasing shear rate implies :

- $p = m$, for $\alpha=1$
- $\frac{m}{2} < p < m$, for $\alpha=2$

Eight parameters have to be deduced from rheometric measurement. The different fitting procedures linked to specific rheometric experiment (structure build up, steady flow curve determination, transient flow for a given shear rate with a initial fully developed or broken structure…) were carried out. At the moment, we can not place great emphasis on the 8 fitted values whose magnitude order varies enormously.

For engineering purposes, a more simple model will be considered. Thus, steady state flow in pipe predictions will be performed using Rabinowitsch equation and Hershel-Bulkley behaviour law. The Latter parameters have been determined with a least-squares fit on the flow curve of the circulating fluid.

III. RESULTS AND DISCUSSION

A. Breaking down/restoring of structure under flow

For this experiment, the fluid has been at rest for a long time (17 h) and the structure would normally be in a standardised state (nearly fully build-up structure). Flow was then started-up with a fixed pump speed and for a given section. The gelled fluid was therefore displaced and broken by the pump and the shearing along the loop device. Pressure establishment was observed for 3 h. Then, a high shearing flow (1900 s^{-1}) was performed for 1 h to damage fluid structure seriously. Lastly, both same speed pump and section as initial ones were again fixed in order to make fluid undergo build-up.

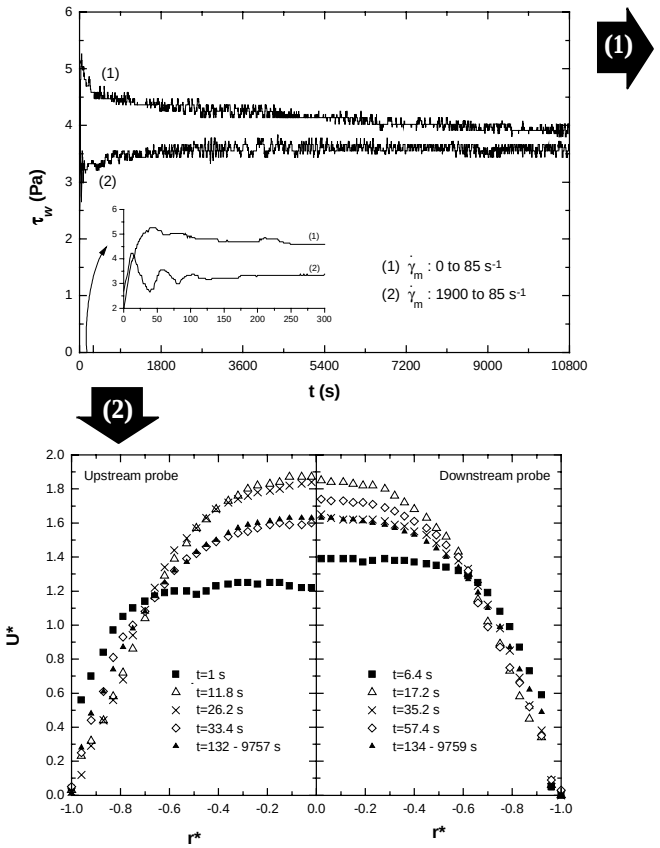


Figure 5 : Shear stress at the pipe wall and velocity profiles evolution during a breaking down (1) and restoring (2) flow. Pipe 32 mm in diameter. $\dot{\gamma}_m$ =85 s^{-1}.

(Fig. 5) presents experiment data in a diagram shear stress at the pipe wall versus time for both breaking down (1) and restoring (2) flow at 85 s^{-1} (section 3).

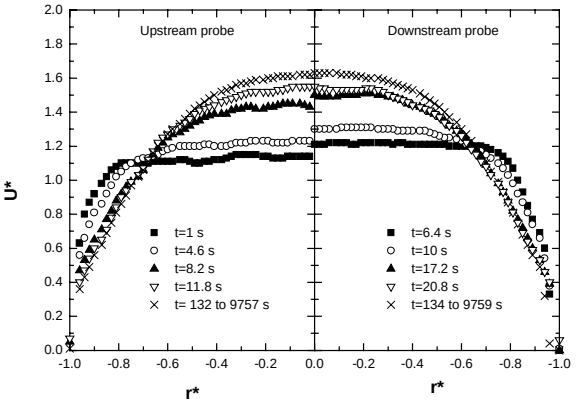
This graph is compared with velocity profiles evolution for the upstream probe and for the downstream probe. Only half top region of the profile is shown owing to profile symmetry. Same symbol is used for the same volume of fluid. So, we can follow the same fluid during the movement and observe the state of structure with regard to the velocity profiles.

We can observe for the breaking down curve (1) that τ_w first increases during 45 s and then decreases monotonically. For this experiment, flow rate stabilisation requires 7 s.

Three stages can be described in velocity profiles evolution.

Solid squares and open circles profiles correspond to a fluid with a fully developed structure circulating in section 3. Differences between upstream and downstream regions reveal the break down process along the pipe. As flow rate is establishing, the plug region and shear rate at the pipe wall decrease.

Solid up triangles and open down triangles are relative to fluid incoming from the pump. The gelled fluid is collectively and quickly displaced. Therefore, the velocity profiles exhibit a sharp jump and become more rounded. Destruction of the structure along the pipe is less important so that upstream and downstream profiles become quite similar



The second passage through the pump implies weak evolution, such axial velocity increasing. Afterwards (cross symbol), no evolutions are observed although successive passages through the pump contrary to the values of τ_w.

Restoring curve (2) displays a more complex behaviour.

We must bear in mind that during high shearing process, section 1 is the operating section. Accordingly, fluid in section 3 have been subjected to a structure build-up stage. Therefore, the first increasing part of τ_w (t=0-13 s) may be explained by the displacement of a fluid with a semi-developed structure. Structure levels evolve slightly (solid squares profiles) so that flow rate establishment implies an increase of τ_w in section 3.

Then, replacement with a low structural level fluid (as indicated by the open up triangles profiles) implies a sharp decreasing part (t=13-39 s). During this stage, "oscillating" profiles can be observed (crosses and diamonds profiles). Interfacial instabilities between the incoming fluid and outgoing fluid may account for such fluctuations. This digitation phenomenon has been reported by Toure [5].

From t=39 s to t=140 s, τ_w evolution is probably due to a progressive mixing of the outgoing fluid and the incoming fluid. Three successive loops are efficient to smear out the structural levels of these two kinds of fluids.

At last, τ_w increases monotonically (t=140-10800 s).

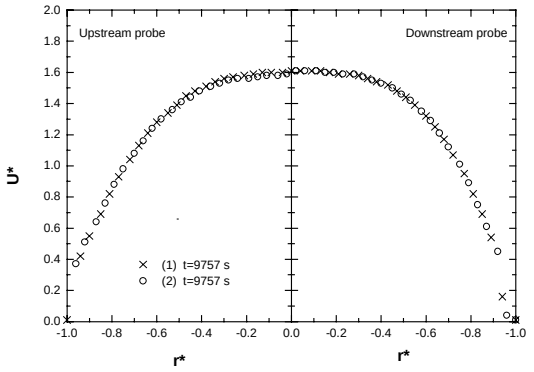


Figure 6 : Equilibrium velocity profiles during breaking down (1) and restoring structure (2) flows.

Both experiment seem to lead to the same steady state. Curves (1) and (2) converge to the same equilibrium value (3.6 Pa). Velocity measurements put forth the same equilibrium profile (Fig. 6). Both structure rupturing and structure restoring are totally reversible processes.

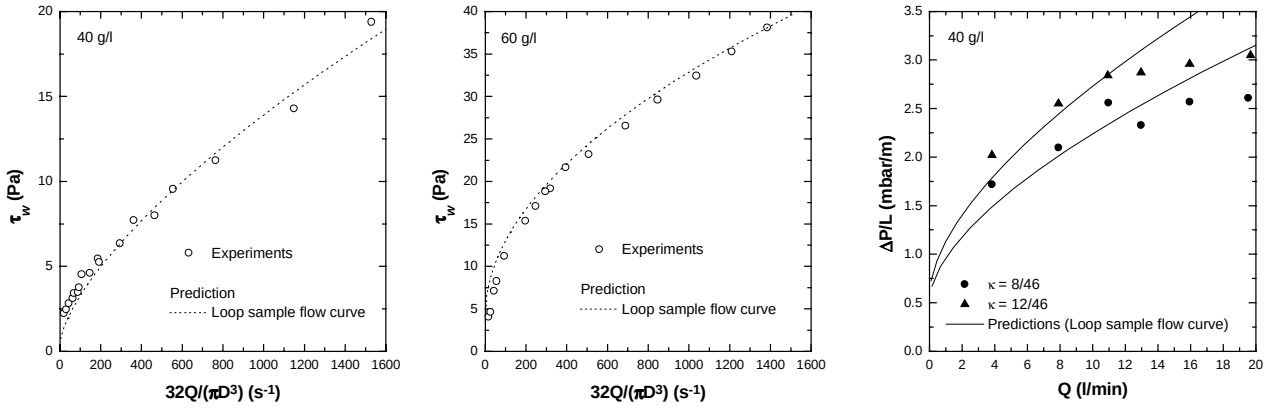
B. FLOW CURVE

The flow curves were achieved with a fluid which has been at rest for 17 h, as follows. For circular pipes, flow rate values and operating section were chosen in order to apply increasing mean shear rate values from 20 s^{-1} to 1900 s^{-1}. For annular pipes, section 3 was fixed, so that increasing mean shear rate values were similar to increasing flow rate values.

Ten loops were systematically realised for each flow rate value.

Fig. 7 a and b present experiment data in a diagram shear stress at pipe wall versus mean shear rate for 40 and 60 g/l concentrations. Results are in fair agreement with predictions (Rabinowitsch equation with Herschel Bulkley model) even if these are not steady flow curves. Limits appears when the flow become turbulent (Fig. 7a, $\dot{\gamma}_m$ =1530 s^{-1}).

Pressure drop (by length unit) evolutions with flow rate are shown in Fig. 7c for annular pipes and a 40 g/l concentration. Predictions do not match experiment data in high flow rate region. At the moment, no inferences on the effect of κ on pressure drop evolution can be drawn.



a) b) c)

Figure 7 : Flow curves for suspensions of bentonite in circular pipes [a):40 g/l, b):60 g/l] and annular pipes [c):40 g/l].

IV. CONCLUSION

This work examined structural changes during laminar pipe flow of bentonite suspensions. These materials present breaking down and restoring kinetics with long specific time.

Using Rabinowitsch equation with the Hershel-Bulkley model , predictions between pressure drop and flowrate are obtained. These are reliable and sufficient for engineering purposes.

Nevertheless, this model is unable to completely describe behaviour of bentonite suspensions. Only structural constitutive model can account for structural changes at rest or under shear. Very specific rheometrics and fitting procedures have to be found in order to determine realistic parameters values.

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