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RHEOLOGY AND BULK FLOW CHARACTERISTICS OF A THIXOTROPIC FLUID IN TURBULENT PIPE FLOW

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ABSTRACT

In this work, aqueous suspensions of 1% and 1.5% by weight Laponite and a blend of 0.5%/ 0.07% Laponite/ CMC are investigated in terms of their rheology and their hydrodynamic behaviour in a pipe flow.

The viscometric viscosity was measured for all fluids, but due to the fluid thixotropy a flow-equilibrium procedure was adopted. All fluids were viscoplastic and the measurement of the yield stress was carried out by direct and indirect methods. The yield stress values were of 0.93, 2.13 and 3.4 Pa for the 1% Laponite, 0.5/0.07% Laponite/CMC blend and 1.5% Laponite suspensions, respectively. The oscillatory tests shows that the 1% Laponite suspension is inelastic but the other two suspensions exhibit some elasticity.

All solutions exhibited drag reduction with the difference between the total and shear-thinning drag reductions ($DR - DR_\nu$) of the order of 10% to 20% for both pure laponite suspensions but increasing to 25 to 30% for the laponite-polymer blend. For the pure clay suspensions, and based also on evidence from the literature, it was speculated that $DR - DR_\nu$ could be due to a strong decrease of the viscosity associated with a turbulence-induced destruction of the internal structure plus a second mechanism more akin to that found with drag reducing polymer solutions.

KEYWORDS: thixotropy, turbulent pipe flow, laponite suspension, laponite-CMC blend

1. INTRODUCTION

Drilling fluids are complex fluids which have to fulfill a multitude of tasks, such as lubricating and cooling the drillbit, or carrying the suspended rock cuttings to the surface. The drilling fluids are also used to fracture the rock or to pressurise the well in order to avoid well-collapse. To accomplish these diverse tasks the fluids contain various additives, such as polymer molecules and clay particles, that impart a complex rheological behaviour characterised by variable viscosity, viscoelasticity, yield stress and thixotropy (Lockett, 1992). One clay that is used sometimes as an additive in drilling muds, but has the enormous advantage of transparency when suspended in water, is laponite. It is a synthetic product which alone, or in combination with a polymer such as carboxymethyl cellulose (CMC), it produces fluids that have some of the properties of drilling muds.

The flow of drilling fluids is necessarily complex and still requires a significant amount of investigation to be better understood. These are inherently difficult and consequently the amount of experimental work done so far is rather limited (see Escudier and Presti, 1996). For instance, knowledge of pressure variations and of the corresponding detailed hydrodynamics are important to understand the flow of thixotropic fluids and especially to develop tools to accurately predict their duct flows. In fact, it is the control of pressure along the drillpipe and the annulus between drillpipe and wellbore that are required to eliminate accidents, such as rock fracture and the incursion of undesirable fluids into the well.

Suspensions based on laponite have been previously investigated, as in the annular flow experiments of Escudier et al (1995a). There, a blend of laponite and CMC was used to investigate the rotating flow in a concentric annulus and the onset of Taylor instability. An initial investigation of a laponite suspension and a laponite/ CMC blend in pipe flows was carried out by Escudier et al (1992), and more extensively covered by Escudier and Presti (1996) for the pure laponite suspension. The flow field was investigated in detail in the laminar, transitional and turbulent flow regimes and the authors concluded that laminar flow was accurately predicted by the Herschel-Bulkley model fitted to the equilibrium viscosity data and that transition Reynolds number was similar to that for Newtonian fluids. In turbulent flow the laponite exhibited drag reduction, as usually happens with polymer solutions, with reduced transverse turbulence relative to that of Newtonian flows.

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Still, further research is required to complete a description of the behaviour of laponite suspensions in pipe flow with emphasis on the following issues:

i) assessing the combined effects of polymer and clay mixture by studying separately, and in combination, the hydrodynamics of the blends as well as of the pure solutions and suspensions;

ii) analyse possible diameter effects upon the flow hydrodynamics;

iii) to characterise the yield stress behaviour of those solutions in different ways and to relate them to turbulent flow hydrodynamics.

Some of these tasks are currently being performed and the present paper reports on the first issue, namely the rheological characterisation and bulk flow properties of some laponite based fluids which will be extended in the future to include detailed meaurements of the mean and turbulent flow fields.

The remaining of this report is organised as follows: first, the fluids are characterised on the basis of data from the literature and our own rheological measurements. This is followed by a description of the pipe flow rig and instrumentation and the paper ends with the presentation and discussion of the results of the hydrodynamic measurements.

2. FLUID CHARACTERISATION

The fluids

The aqueous suspensions were based on the laponite RD clay manufactured by Laporte Industries. This laponite is a synthetic smectite clay with a structure analogous to the natural mineral clay hectorite. It is a layered hydrous magnesium silicate which is hydrothermally synthetised from simple silicates and litium and magnesium salts, in the presence of mineralizing agents. Further details of the chemical structure of laponite, its production and applications can be found in Laponite (1990).

Smectite clays swell as water, or polar organic solvents, enter the interlayer regions due to the hydration of the interlayer cations and the platelet surfaces. They have a structural negative charge due to the substitution of cations in the composite layers, which is independent of the level and type of electrolyte. Dilute suspensions of laponite in water with low electrolyte levels will remain as low viscosity "sols" of non interacting individual platelets for long time periods. However, the electrolyte level and type has a marked effect on the stability and thickness of dispersed laponite particles. At concentrations higher than 3%, the whole solution gels as face to face interactions between the electrical double layers of individual platelets make them virtually immobile. This gives rise to an equilibrium structure with an elastic response to applied shear stress until a critical yield stress is exceeded. The most important feature of the rheology of the clay suspensions is its ability to form colourless, transparent, highly thixotropic gels (Laponite, L64).

Aqueous suspensions of 1% and 1.5% w/w of laponite RD were produced for investigation in this work. A third fluid was a blend of 0.5% laponite and 0.07% of CMC. The 1.5% suspension and the blend were selected to allow comparison with the works of Escudier and co-workers (1992, 96). Blending laponite with CMC (sodium carboxymethyl cellulose) is suggested also by the manufacturer of laponite (Laponite, L61) as a way to increase the gel strength and its shear viscosity. However, the CMC utilized in this work (CMC grade 7H4C from Hercules with a molecular weight of 3 x 10^5 kg/kmol) was not the same as that used by Escudier and co-workers (1992, 1995-a and -b, 1996) who relied on a brand manufactured by Aldrich Chemical Co.

All fluids were prepared with the same procedure using Porto tap water. To prevent bacteriological degradation 100 ppm of formaldehyde was added and 60 ppm of sodium chloride increased the yield stress of the solutions. More than 100 litres of fluid were required to fill the pipe rig, and the solutions were mixed for 90 minutes and settled for more than 24 hours to allow complete hydration of the intersticial spaces between the clay particles. Before the rheological characterisation of the suspensions and/or its transfer to the pipe flow rig the suspensions were mixed for 30 minutes to full homogenization. All concentrations quoted in this work are weight concentrations.

Fluid rheology

The rheological characterisation of thixotropic, yield stress fluids is complicated by time dependency. These fluids are very common in a wide variety of industrial situations, from the cosmetic and pharmaceutical industries to the cleaning, agriculture, building or paper industries to name but a few, and it is not surprising to find out that there are virtually hundreds of papers on their rheology (see the 20 years old review of Mewis, 1979). Over the last thirty years there have been improvements both in rheological equipment and techniques for their characterisation of which the work by the following workers is just a small sample: Charm (1963), Keentok (1982), Nguyen e Boger (1983) and Cheng (1984). The accumulated experience has established a series of standard practices for carrying out the rheological testing of these fluids, as is reviewed in Nguyen and Boger (1992). Some of them were adopted to carry out this work.

Here, the fluids were characterised by means of measurements of the viscometric viscosity, the yield stress and of the storage and loss moduli in oscillatory shear flow. The measurements were carried out in the Rheolab MC100 rheometer from Physica, using the Z1-DIN double gap concentric cylinder geometry, which is adequate for these low viscosity suspensions as the gap sizes were more than 20 times the size of the larger particles, according to the information of the manufacturer. All rheological and hydrodynamic measurements were carried out at the same constant temperature of 25°C.

Viscometric viscosity

All non-Newtonian fluids in this work are shear-thinning and have an yield stress, and because they are also thixotropic fluids a flow-equilibrium test procedure had to be adopted to measure the viscometric viscosity. This procedure was established by Alderman et al (1988) whereby a shear stress is applied to the fluid sample and the shear rate monitored until steady state conditions are achieved after which the viscosity is measured. An example of such test is shown in Fig. 1 for the 1.5% laponite suspension. The upper curve represents the fluid response to a sudden increase in applied shear stress from 0 to 15 Pa whereas the lower curve pertains to a sudden decrease in applied stress from 35 Pa to 15 Pa. In both cases a steady state situation prevailed for $t < 0$ s. According to some phenomenological models (Papenhuijzen, 1972) thixotropy is associated with the occurrence of an internal fluid structure within which a network of connections is formed, as well as destroyed by deformation. Thus, an equilibrium situation arises after a given time as the rate of formation equals the rate of destruction of internal connections. The differences in both curves of Fig. 1 are related to the different equilibrium states at $t < 0$, but in both cases the response time is similar, of the order of 3000s. This value is similar to that reported by Escudier and Presti (1996) for their 1.5% laponite suspension.

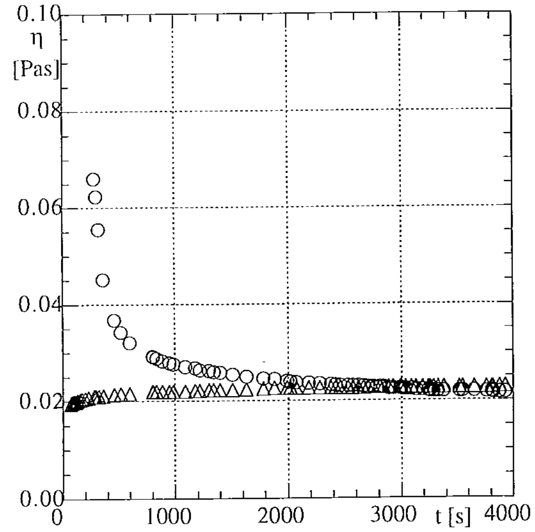

Figure 1- Variation of the viscometric viscosity with time for a 1.5% laponite suspension. At t=0 s a constant shear stress of 15 Pa is applied. O: τ= 0 Pa for t<0 s; Δ: τ= 35 Pa for t< 0 s.

Repeating the procedure for different applied stresses a viscosity curve is obtained which corresponds to the final equilibrium state for a wide range of shear rates. The variation of the equilibrium viscometric viscosity with shear rate is presented for all fluids in Fig. 2. The suspensions of laponite exhibit an increase of the viscosity with concentration and a strong shear-thinning behaviour without the Newtonian plateau at low shear rates. This latter feature is typical of fluids possessing an yield stress, which in fact can be thought of as an infinite viscometric viscosity. At high shear rates the viscosities are rather low, less than 10 times the viscosity of the solvent, even for the more concentrated suspensions.

Fig. 2 includes the viscosities of a suspension of pure laponite at a concentration of 0.5% as well as of a solution of pure CMC at a concentration of 0.07%. These two fluids have viscosities five to ten times lower than the viscosity of the 0.5% laponite/ 0.07% CMC blend for shear rates between 10 s^{-1} and 1000 s^{-1}. The 0.07% CMC solution is clearly thicker than the 0.5% laponite suspension, and the evolution of the low shear rate data of the latter suggests that it also has a yield stress. The synergetic effect of the blend is clearly shown in the corresponding viscosity which has values similar to the viscosity of the pure 1.5% laponite suspension with only about a third the total amount of additives. Laponite (L61) indicated this possibility based on a single shear rate measurement. The viscosity data were fitted by the Herschel-Bulkley model which resulted in the parameters listed in Table 1 and are represented by the solid lines in Fig. 2. The dashed line pertains to the Herchel-Bulkley model (Eq. 1) fitted to the viscosity data of the 1.5% suspension of Escudier and Presti (1996). The viscosity of their suspension was higher than that of our corresponding fluid for reasons that will be explained later.

$$\eta = \frac{\tau_{HB}}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \qquad (1)$$

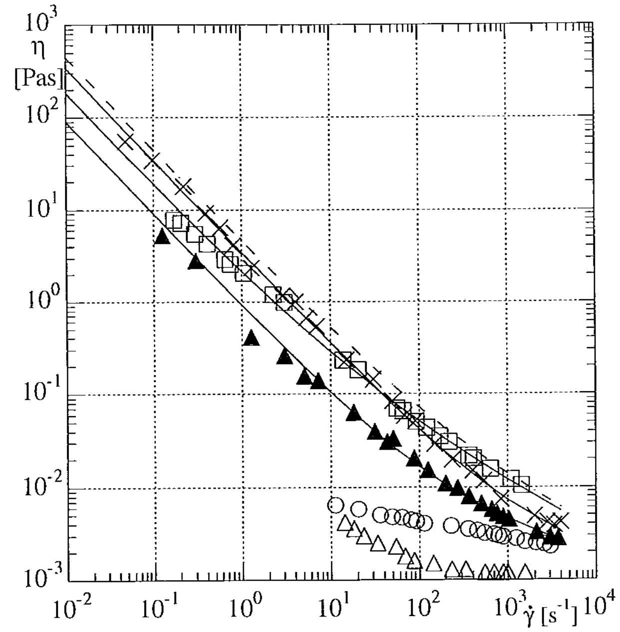

Figure 2- Viscometric viscosity of all suspensions in the equilibrium state. O 0.07% CMC; Δ 0.5% laponite; □ 0.5%/0.07% laponite/CMC; ▲ 1% laponite; X 1.5% laponite; full lines represent fitting by the Herschel-Bulkley model. Dashed line represents the fitted Herschel-Bulkley model for Escudier and Presti's (1996) 1.5% laponite.

Table 1- Parameters of the Herschel-Bulkley stress model fitted to the viscosity data. Includes data from Escudier and Presti (1996).

Solutions	n	K [Pas^n]	τ_{HB} [Pa]
0.5/0.07% laponite/CMC	0.492	0.347	1.8
1% laponite	0.685	0.033	0.9
1.5% laponite	0.676	0.037	3.4
1.5% laponite: Esc. & Pre	0.535	0.240	4.4

Oscillatory shear flow

Measurements of the storage (G') and loss (G'') moduli in oscillatory shear flow were carried out for all fluids but the maximum shear amplitude for linear behaviour was so small that accurate results were difficult to obtain, especially with the more dilute fluids.

For the 1% and 1.5% laponite suspensions the fluid elasticity was lower than for the laponite/CMC blend at high frequencies as can be assessed in Table 2 which lists typical values of the ratio G'/G" in two frequency ranges. As assessed by this test the elasticity of the 1.5% laponite suspension and of the blend was higher than that of dilute tylose and CMC solutions tested by Coelho and Pinho (1998) and of the dilute xanthan gum solutions of Pereira and Pinho (1999) whereas the ratio G'/G'' of the 1% laponite suspension was rather small. Again, the synergetic effect of the polymer-clay blend is well shown in that G'/G'' is similar to that of the 1.5% suspension containing three times more additives but no polymer. This is certainly due to the reinforcement of the internal structure of solid particles by the polymer molecules (Boger, 1994). Of relevance is also the very low ratio of moduli for the 1% suspension.

Table 2- Typical ratio between the storage and loss moduli at two ranges of frequency.

Solution	G'/G''	G'/G''
Frequency	1-5	5-10
1% laponite	0.12	0.14
1.5% laponite	3.1	1.7
0.5/0.07 lap/CMC	2.9	1.9

Yield stress

The yield stress of a fluid is intimately related to the bond forces within the structure of the suspension and therefore it is a measure of the force required to break it when it is fully formed, ie, when it is under a static condition. For stresses higher than the yield stress the internal structure of the fluid has either been destroyed or is in a dynamic equilibrium state in which case new internal connections are being formed whilst others are breaking. It is the transient nature of these effects that lead to fluid thixotropy. Frequently, this transient behaviour is rather strong and so the yield stress is associated with fluid thixotropy.

In the past there has been some controversy regarding the existence of yield stress (Barnes and Walters, 1985), but it is quite clear that for engineering purposes the yield stress is a useful concept of relevance to industrial processes involving suspensions, such as handling, storage, piping and transport in reservoirs, to name but a few. Since yield stress fluids possess an internal structure, their rheology can depend on the past history of deformation, as was shown in Fig. 1. The yield stress property is also very sensitive to the duration and type of test procedure (Cheng, 1986) and especially so for time-dependent fluids as is the case in this work.

The yield stress can be obtained using direct and indirect procedures as described by Nguyen and Boger (1992). Both techniques were used in this work: the direct techniques were the creep test and the increasing stress test defined by the American Petroleum Institute (API), whereas the indirect methods were the extrapolation by known rheological models, as well as polynomial expressions, of the above equilibrium viscosity data. The final results will be presented here together with a brief description of individual results. The reader is referred to Nguyen and Boger (1992) for more details of these tests.

In the creep test increasing values of the shear stress were applied to the fluid sample for a period of time and then removed. When the applied stress was higher than the yield stress there was a final deformation at the end of the experiment. The test is exemplified in Fig. 3 which presents typical deformation curves for different applied stresses when the sample was the 1% laponite suspension. For stresses of 0.6, 1.5 and 1.75 Pa there was no residual deformation, but that was not the case for an applied stress of 1.9 Pa.

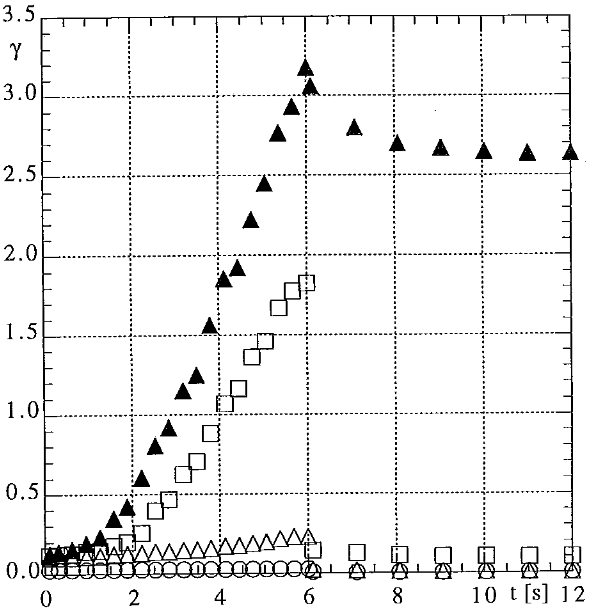

Figure 3- Variation of sample deformation with time in a creep test for the determination of the yield stress for the 1% laponite suspension: O τ= 0.6 Pa; Δ τ= 1.5 Pa; □ τ= 1.75 Pa; ▲ τ= 1.9 Pa.

In the case of the increasing stress test of API (see Speers et al, 1981 for further details) the yield stress was the maximum stress value identified by Pryce- Jones (1952) and Papenhuijzen (1972) which, according to the more recent interpretation of Liddell and Boger (1996), corresponds to the stress marking the transition between the viscoelastic and purely viscous behaviour.

In the indirect methods the equilibrium viscosity data were fitted by two typical rheological equations, the Casson model (Eq. 2) (Casson, 1959) and the Herschel-Bulkley model (Skelland, 1967), as well as by third, fourth and fifth order polynomials. The fitting by the Herschel-Bulkley model is shown by the solid lines in Fig. 2 whereas examples of the fitting by the polynomials are illustrated in Figs. 4-a) and -b) presenting plots of the same data in linear and semi-log coordinates, respectively. Higher-order polynomials showed physically unrealistic behaviour and therefore were not considered.

$$\eta = \frac{\tau}{\dot{\gamma}} \text{ with } \sqrt{\tau} = \sqrt{\tau_{Cas}} + \sqrt{\eta_\infty \dot{\gamma}} \qquad (2)$$

For all fluids an increase in the order of the polynomial fitting resulted in a small decrease of the yield stress, of about 10% for the 1% laponite suspension and the blend and of 3% for the 1.5% laponite suspension, as can be seen in Table 3 where all the yield stress values obtained by polynomial fitting are listed..

The results of the various direct and indirect measurements of the yield stress are summarised and compared in Table 4. There is a fair agreement between the direct measurement results for the 1%

suspension and the blend, whereas a difference of less than 20% is seen for the 1.5% laponite suspension.

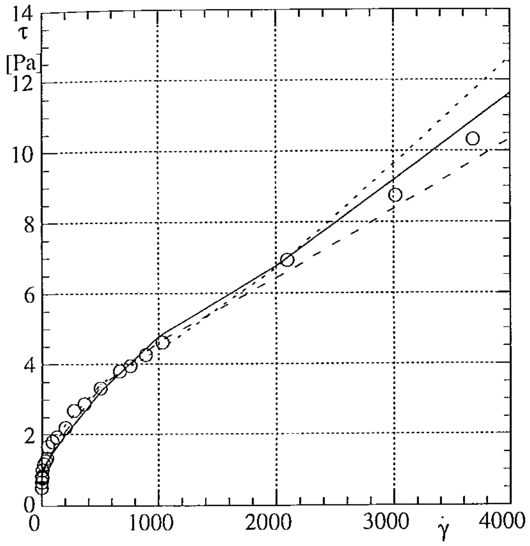

Figure 4-a)- Fitting by third, fourth and fifth degree polynomials of the equilibrium shear stress for the 1% laponite suspension in linear coordinates: full line (third order); long dashed (fourth order); short dashed (fifth order).

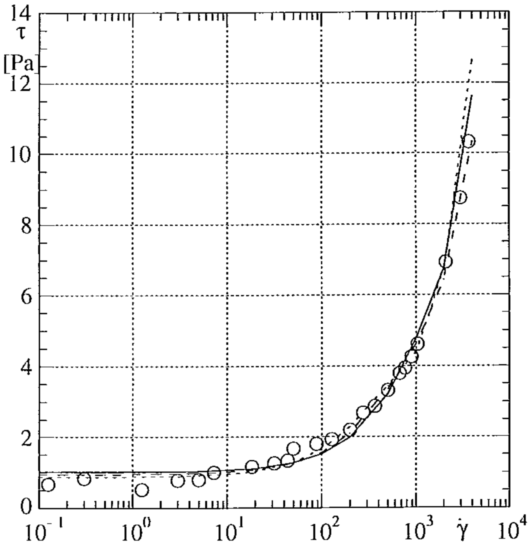

Figure 4-b)- Fitting by third, fourth and fifth degree polynomials of the equilibrium shear stress for the 1% laponite suspension in logarithmic coordinates: full line (third order); long dashed (fourth order); short dashed (fifth order).

Table 3- Yield stress values obtained by polynomial fitting

Solution	third order	fourth order	fifth order
Lap 0.5%/0.07% CMC	2.30	2.14	2.07
laponite 1%	1.02	0.96	0.88
laponite 1.5%	3.60	3.60	3.52

Table 4- Yield stress values obtained by the various methods. τ_c: creep; τ_s: increasing stress; τ_p: polynomial fitting; τ_{Cas}: Casson model fitting; τ_{HB}: Herschel-Bulkley model fitting.

Solution	τ_c	τ_s	τ_p	τ_{Cas}	τ_{HB}
Lap 0.5%/0.07% CMC	2.2	2.3	2.2	2.3	1.8
laponite 1%	1.8	1.7	1.0	0.8	0.9
laponite 1.5%	5.8	4.8	3.6	3.3	3.4

The values of stress obtained in the different groups of methods are obviously different. To understand this point it suffices to say that the creep test measures the yield stress without destroying the inner structure of the sample whereas the indirect measurements rely on a procedure that requires a different, less ordered state of dynamic equilibrium. In any case, it is clear that the yield stress increases with additive concentration and in spite of the different testing procedures the difference between the yield stress values obtained by direct and indirect methods is not too large, with the indirect methods always resulting in lower values.

From a critical assessment of these results one may conclude that the yield stress values are 0.93, 2.13 and 3.4 Pa for the 1% laponite suspension, the 0.5/0.07% laponite/CMC blend and the 1.5% laponite suspension, respectively. For the 1.5% laponite suspension Escudier and Presti (1996) obtained a yield stress of 4.4 Pa using the Herschel-Bulkley fitting. A comparison between the viscosity of both 1.5% suspensions shows that theirs is slightly thicker. This difference could be attributed to ageing; Escudier and Presti (1996) state that their fluid was used a week after preparation and that they observed, as confirmed by the manufacturer, that the laponite suspensions thicken with time, whereas in our case the fluid was used within a couple of days.

3. HYDRODYNAMIC MEASUREMENTS

Experimental set-up and uncertainties

The pressure drop and flow rate measurements were carried out in the flow rig described in Pereira and Pinho (1994). It consisted of a long 26 mm inside diameter vertical copper pipe belonging to a closed circuit. The fluid was pumped from a 100 liter tank through a rising pipe and then through a 90 diameter long descending pipe to the test section of 232 mm of length, and then a further 27 diameters down, back to the tank. The flow was controlled by two valves and one by-pass circuit, and a 100 mm long honeycomb was located 90 diameters upstream of the test section to help ensure a fully developed flow in the test section. Four pressure taps were drilled in the test section separated by a distance of 65 mm. Equal longitudinal pressure gradients measured in consecutive pairs of taps, and equal velocity profiles measured by LDA at the beginning and end of the test section, but not reported here, confirmed a fully-developed flow situation.

The pressure drop was measured by means of two differential pressure transducers, model P305D-S20 and P305D-S24 from Valydine, and the flow rate was measured by an electromagnetic flowmeter Mag Master from ABB Taylor, which was incorporated in the rising pipe, 15 diameters downstream of the closest flow perturbation. All these instruments were connected to a 386 PC by a data acquisition Metrabyte DAS-8 board interfaced with a Metrabyte ISO4 multiplexer, both from Keithley.

The flowmeter was capable of measuring the volumetric flow rate in the range 0 to 5 l/s with an accuracy of 0.04% of full scale. As a further check to its accuracy the velocity profile measurements carried out by LDA were integrated to yield a computed flow rate which never differed by more than 1% from the value of the flowmeter.

As far as the uncertainty of the pressure measurements is concerned it is important to recall that these were carried out for fully developed flow, thus eliminating such sources of uncertainty as the hole pressure error of Novotny and Eckert (1973). All the pressure taps were drilled carefully to avoid the appearance of spurious edge effects and had the same geometry so that any systematic errors would cancel out in the pressure difference measurement. The recommendations of Shaw (1960) and Franklin and Wallace (1970) for the design of pressure taps and the quantification of pressure measurement errors were followed and it was estimated that the associated contribution to the overall uncertainty was less than 1.5% at a high Reynolds number. Taking into account the other sources of uncertainty, such as accuracy of the transducers, calibration errors, zero drift effects and statistics, the total uncertainty of the pressure difference measurements was estimated, by application of the root-mean square equation, to vary between 1.6 and 7.2% at low and high flow rates, respectively.

Results and discussion

The bulk hydrodynamic behaviour of the various fluids is shown in Fig. 5 which plots the Darcy friction factor as a function of the Reynolds number. The Reynolds number is here based on the viscosity at the wall which was obtained from the measured shear stress and the rheogram of the fluid. The figure includes data for water flows, the Newtonian friction factor expression of Geiringer (1963) (obtained for copper pipes) and Virk's asymptote for the maximum drag reduction with polymer solutions (Virk et al, 1970). Note that Geiringer's expression gives numerical values of f practically identical to those produced by the Blasius' equation for a smooth pipe. For all solutions a similar maximum bulk flow velocity of about 4.6 m/s was reached but that corresponded to maximum Reynolds numbers of 135 000 for water and 32 500, 21 200 and 13 300 for the 1% and 1.5% laponite suspensions and the laponite/ CMC blend, respectively. It should be emphasised that the pressure and flow rate measurements were only initiated after those quantities were observed to remain constant with time. The Newtonian data are consistent with previous results from various sources in the literature.

All non-Newtonian solutions show drag reduction, but especially so the blend of laponite and CMC. The data for 1.5% laponite compares well with that of Escudier and Presti (1996) for an identically concentrated suspension. Some degree of drag reduction was expected on account of shear-thinning as is well known from the work of Dodge and Metzner (1959). Their expression for the friction factor of inelastic power law fluids is here presented as Eq. (3), casted in terms of the wall Reynolds number and the Darcy coefficient.

$$\frac{1}{\sqrt{f}} = 0.8685 n^{0.25} \ln\left(\frac{2n}{3n+1} \mathrm{Re}_w \sqrt{f}\right) + \frac{2.4095}{n^{0.75}}(1-n) - \frac{0.2}{n^{1.2}} \quad (3)$$

This equation is plotted in Fig. 6 for several values of the power law exponent and it clearly shows that for strong shear-thinning fluids, say n< 0.5, drag reductions in excess of 20% can be observed.

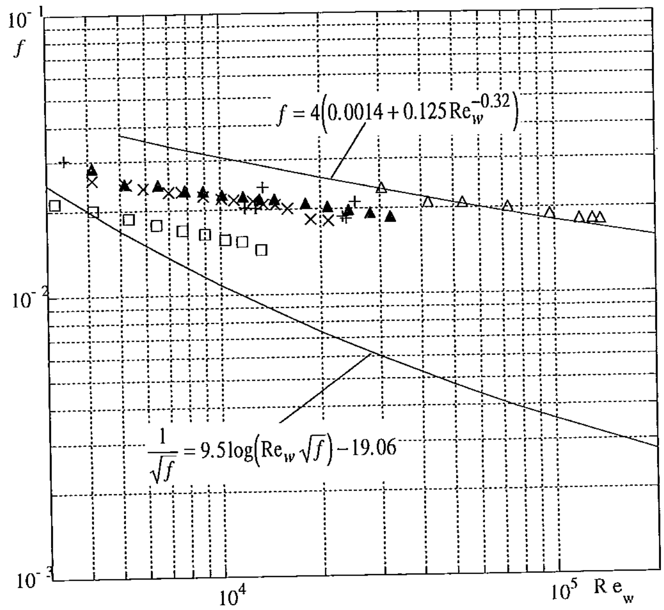

Figure 5- Darcy friction factor as a function of the wall Reynolds number: □ 0.5%/0.07% laponite/CMC; ▲ 1% laponite; × 1.5% laponite; + 1.5% laponite from Escudier and Presti (1996); Δ water.

Under turbulent flow conditions the shear rates prevailing in the pipe are rather high, to which correspond stresses well above the yield stress. If we were to fit a power law viscosity model to the viscosity data at shear rates encountered within a given pipe flow, the corresponding value of n can then be used to predict the purely viscous friction factor using Eq. (3) and hence the amount of viscous drag reduction DR_v by means of Eq. (4). In Eq. (4) f_{st} represents the friction factor of the shear-thinning fluid and f_N the corresponding Newtonian coefficient at the same wall Reynolds number. This process is rather cumbersome as it implies a different viscosity fit for each flow condition. Since under turbulent flow conditions the shear stresses are significantly higher than the yield stress, the value of n of the Herschel-Bulkley fit (in Table 1) can be used instead to provide an accurate estimate of DR_v. This has been done and the result is shown in Fig. 7.

$$DR_v = \frac{f_{st} - f_N}{f_N} \times 100 \quad (4)$$

Simultaneously, the total drag reduction DR can also be calculated from Eq. (5), where f is the measured friction coefficient. The difference $DR - DR_v$ can now be attributed to rheological effects other than the viscosity.

$$DR = \frac{f - f_N}{f_N} \times 100 \quad (5)$$

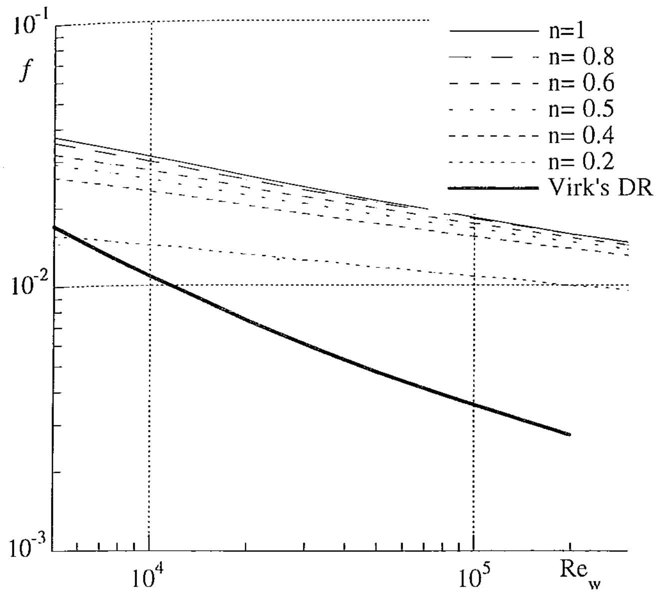

Figure 6- Variation of the friction factor for purely viscous shear-thinning fluids as a function of the wall Reynolds number, according to Dodge and Meztner (1959).

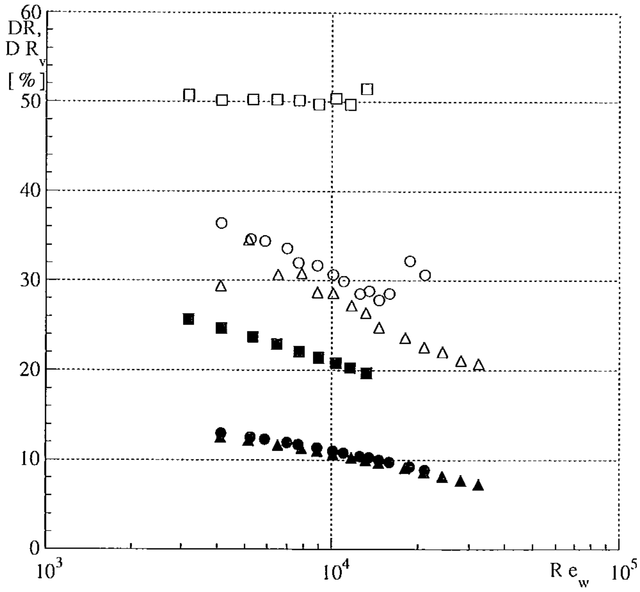

Figure 7- Drag reduction intensity: □ 0.5%/0.07% laponite/CMC; Δ 1% laponite; O 1.5% laponite. Open symbols: total drag reduction *DR*; Closed symbols: shear-thnning drag reduction DR_v

Clearly, the largest drag reduction effect is that of the clay-polymer blend. It has the largest total drag reduction as well as the largest difference $DR-DR_v$, certainly due to the synergetic effect of the polymer on the clay. Both suspensions of pure clay have viscous drag reductions of around 10% and total drag reductions of about 30%, but decreasing as the Reynolds number increases. A similar trend of drag reduction with Reynolds number was observed by Escudier and Presti (1996).

Drag reduction in pure clay suspensions must be phenomenologically different from that of polymer solutions. In the latter case *DR* is usually associated with the interaction between turbulence and the molecular conformation which affects the rheological properties, and in particular the elongational characteristics. In the case of suspensions drag reduction is frequently attributed to particle migration from the wall region (Lumley, 1978) but in the case of the laponite suspensions a second mechanism could be acting. These thixotropic, yield stress fluids have an internal structure whose equilibrium is affected by the flow hydrodynamics and, by implication, by turbulence. Turbulence raises the level of stresses in the flow and thus it contributes to a higher rate of destruction of internal connections which reduces the viscometric viscosity.

Escudier and Presti (1996) reported that the values of yield stress and viscosity obtained from direct LDA laminar pipe flow measurements were much lower than those obtained by rheological measurements, in their case by data fitting the Herschel-Bulkley equation. This means that under laminar flow conditions the equilibrium state of the fluid has a less ordered structure than during the rheological measurements. A more violent flow as is typical in turbulence will certainly enhance this effect which will further destroy the internal structure. The destruction of internal structure reduces the fluid viscosity and consequently the measured friction factor will correspond to a much higher Reynolds number than that based on the rheological viscosity.

However, there was another finding by Escudier and Presti (1996) which suggests the simultaneous presence of yet another *DR* mechanism: they found that the transverse turbulence, normalised by the axial bulk velocity, was much lower than for Newtonian fluids. In the former mechanism, where *DR* is due to a lower viscosity than expected on the grounds of rheology, the turbulent flow field should only be affected by the Reynolds number, but the reduction of transverse turbulence is significantly higher than expected on that ground.

The reduction of transverse turbulence accompanying *DR* measured by Escudier and Presti (1996) is akin to that observed with polymer solutions. With these solutions *DR* is associated with elastic effects, such as an increase of the extensional properties. Thus, it thus seems that even for a pure clay suspension there is a complex interaction between the internal structure of the fluid and its rheology. Unquestionably, such combination is present for the clay/ polymer blend.

Future research should be aimed at clarifying these points by completing our bulk flow investigation with detailed mean and turbulent velocity measurements as well as an investigation of different types of pure suspensions, and in particular yield stress fluids having no thixotropy.

CONCLUSIONS

A detailed investigation of the rheology and turbulent bulk pipe flow characteristics of clay suspensions and one clay-polymer blend was carried out. The clay suspensions were based on laponite RD from Laporte Industries at weight concentrations of 1% and 1.5% and the blend was made of 0.5/0.07% by weight laponite/ CMC 7H4C (from Hercules).

The fluids were thixotropic and so the measurement of the viscometric viscosity had to follow an equilibrium procedure. The fluids exhibited yield stress which was measured by two direct methods and two curve fitting procedures. The yield stress values were of around 0.9, 2.1 and 3.4 Pa for the 1% laponite, the blend and the 1.5% laponite fluids, respectively. The oscillatory shear flow test showed that the 1% laponite suspension was almost inelastic, whereas the 1.5% laponite and the blend exhibited some elasticity. In particular, the blend exhibited a strong synergetic effect in that the levels of viscosity and of elasticity were far higher than for the isolated additives and of similar magnitude as for the more concentrated suspensions.

The turbulent pipe flow bulk measurements showed drag reduction with the difference between the total and the shear-thinning drag reductions of the order of 10 to 20% for both pure laponite suspensions but increasing to 25 to 30% for the blend. It was speculated that this $DR - DR_v$ of the pure laponite suspensions could be due to increasing levels of destruction of the internal structure, leading to a strong decrease of the viscosity, plus a second mechanism more akin to that found with polymer solutions. Further research is deemed necessary to clarify these points.

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