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Research paper

Influence of viscosity modifier nature and concentration on the viscous flow behaviour of oil-based drilling fluids at high pressure

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A B S T R A C T

This work deals with the effect of viscosity modifier nature and concentration on the rheological properties of model oil-based drilling fluids (OBM) submitted to high pressure. The oil-based fluids were formulated by dispersing, with a high shear mixer, two selected organobentonites in a mineral oil, at room temperature. The viscous flow behaviour of the corresponding dispersions was characterised as a function of pressure, organoclay nature and organoclay concentration, using a controlled-stress rheometer equipped with both pressure cell and coaxial cylinder geometries. A factorial Sisko–Barus model, which takes into account both shear and pressure effects in the same equation, fitted the experimental pressure–viscosity data fairly well.

The influence of disperse phase concentration on the shear-thinning characteristics of these organoclay dispersions is related to the development of different microstructures, which depend on organoclay nature. In this sense, the resulting microstructure has been attributed to the cohesion energy between microgels domains. From the experimental results obtained, it can be concluded that the viscous flow behaviour of the OBM investigated is strongly affected by organoclay nature and concentration. The pressure–viscosity behaviour of these dispersions is mainly influenced by the piezoviscous properties of the oil and the properties of the continuous phase. The Sisko–Barus model proposed can be a useful tool, from an engineering point of view, for calculating pressure losses in the different sections of the bore, as well as being of significant help to solve other additional problems, such as hole cleaning, induced fracturing, and hole erosion during the drilling operation.

1. Introduction

Oil-based drilling fluids called oil based muds (OBM) are dispersions usually showing a complex rheology. Regarding the nature of their continuous phase, fluids used in drilling and completion wells can be classified into two main groups, water-based and oil-based. The main functions of these fluids are: i. To carry cuttings from the bottom of the hole, transport them up and remove rock bit at the surface. ii. To cool and clean the drill and the bit. iii. To maintain the stability of borehole. iv. To lubricate the gap between the drilling string and the wall of the hole. v. To prevent the inflow of fluids from surrounded rocks. vi. To form a thin and low-permeable filter cake. vii. To be non-damaging to the producing formation. viii. To be non-hazardous to the environment and personnel (Chilingarian and Vorabutr, 1983; Menezes et al., 2010).

Most of global drilling operations use water-based muds (WBM), because of their lower environmental impact, whereas only 5–10% of the wells drilled use OBM (Caenn and Chillingar, 1996; Meng et al., 2012). Nevertheless, OBM have interesting features to overcome certain undesirable characteristics of the water-based ones, such as better lubrication and higher boiling points (Khodja et al., 2010). Basically, OBM can be classified into three categories: (1) All-oil muds, consisting of a mixture of organoclay (OC) and synthetic or mineral oil, which are used for minimum pressure losses and low permeability reservoirs; (2) Oil muds, consisting of OC, emulsifiers, oil and water (2–10 m%), which are designed for well stabilisation at high temperature; (3) Invert oil muds, consisting of OC, emulsifiers, oil, additives and water (up to 40 m%), which are used for shale stability and improved penetration.

The relationship between flow behaviour and composition is an important issue to formulate suitable OBM. Regarding composition, clays are a key component for developing some specific properties of these dispersions, which will be submitted to the extreme pressure and temperature conditions of the wellbore. Concerning OBM, organophilic bentonites have been extensively used due to both good dispersing properties in the oil phase and filtration characteristics (Jordan et al., 1965). These OC result from the reaction of smectite-type and amine cationic groups, without addition of supplementary additives (Hauser, 1950; Jordan, 1949).

Regarding flow properties, OBM are frequently submitted to extreme shear, temperature and pressure conditions in downhole operations. During the circulation of the drilling fluid around the

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wellbore, the shear rate may vary from zero to more than 1000 s^{-1}, whilst temperature can vary from values below 5 °C in water settings to above 200 °C at the bottom during the round trip. In addition, the pressure exerted by the mud column may be as much as 1400 bar at the deepest part (Darley and Gray, 1988). These severe conditions may change the bulk rheological behaviour of the dispersions because of pressure–temperature-dependent viscosity changes and particle–particle interactions modifications (Briscoe et al., 1994).

Several authors have examined the evolution of WBM viscosity with pressure and temperature, temperature being the most important factor (Santoyo et al., 2001; Wang et al., 2010). Furthermore, other studies have been mainly focused on the use of new additives as rheology-modifiers to improve drilling operation. With this aim, recent studies have concentrated their efforts on how to overcome the hole instabilities, related to the aqueous media at extreme conditions, by using different additives, such as viscoelastic surfactants or synthetic polymers (England and Parris, 2010; Wang et al., 2011).

For OBM, studies concerning the effect that pressure exerts on both their rheological behaviour and physical properties are very scarce. Combs and Whitmire (1968) studied the effect of temperature and pressure on the rheology of OBM formulated with OC, and found that the change in continuous phase viscosity was the main controlling factor. Politte (1985) concluded that the plastic viscosity could be normalised using the viscosity of the oil medium, whereas the yield stress is a weak function of pressure. Besides, Houwen and Geehan (1986) found a simple model to determine both yield-stress and high-shear-rate viscosity of invert muds as a function of pressure and temperature, using up to four parameters. In most cases, changes observed in physical properties and flow behaviour of OBM have been explained on the basis of the effect that both temperature and pressure exert on the viscosity of the continuous phase (Gandelman et al., 2007; Herzhaft et al., 2001). Much less attention has been devoted to the effect that nature and concentration of viscosity modifiers exert on the rheological properties of oil dispersions submitted to high pressure (Ghalambor et al., 2008), probably due to the experimental constraints involving high pressure rheology measurements with fluids that exhibit non-Newtonian behaviour. Consequently, the overall objective of this work was to study the effect that viscosity modifier nature and concentration exert on the rheological properties of model OBM submitted to high pressure.

2. Experimental

2.1. Materials

Two commercially available OC, denoted as B34 and B128 and provided by Elementis (Belgium), were used in the present study. Their chemical formula and some physical characteristics are shown in Table 1.

A mineral based lubricating oil, SR-10 (916 kg/m^3 and 115 cSt, at 40 °C) supplied by Verkol (Spain), was used as base oil for the formulation of OBM.

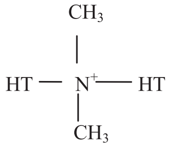
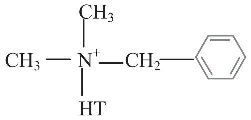
2.2. Samples preparation

Organobentonite dispersions were prepared by mixing OC (at concentration of 1, 3 and 5 m%.) in SR-10 oil base, at room temperature, using a high mixer Ultraturrax (Ika, Germany), at a rotational speed of 9000 rpm for five minutes. Prior to high shear processing, the OC were wetted with the oil, at room temperature, in a low shear mixer using a conventional four blade impeller.

2.3. X-ray diffraction (XRD)

XRD measurements were carried out on OC powders and their oily dispersions, at room temperature, using a Bruker S8 Advance (Germany) diffractometer equipped with a secondary monochromator, a Brentano Bragg geometry goniometer and a copper cathode as X-ray source. The samples were subjected to Cu Kα radiation with a wavelength of 0.15406 nm. The 2θ angles varied from 1.5° to 20°, single scanning step of 0.017°, and measurement time of 6 s per step. The high intensity peaks in XRD curves show the d_{001}-spacing, which have been included in the Bragg equation to determine interlayer distance of each organically modified bentonite.

Table 1
OC used in this study.

Commercial name	Clay mineral	Abbreviated notation for intercalated ions[a]	Chemical formula	d_{001} (nm)[b]
Bentone 34	Bentonite	2M2HT	 $HT-\overset{CH_3}{\underset{CH_3}{N^+}}-HT$	2.767
Bentone 128	Bentonite	2MBHT		3.344

[a] The abbreviations of quaternary ammonium ions corresponds to: M: methyl, B: benzyl, HT: hydrogenated tallow.

[b] Basal spacing determined by X-ray diffraction (XRD).

2.4. Optical microscopy

Optical microscopy observations were carried out by using an Olympus BX52 (Japan) microscope, equipped with an Olympus C5050Z camera and an objective of 20× and 50×. An electric heating system LTS 350 (Linkam, UK) coupled with microscope stand was used to maintain the temperature constant. The OC dispersions were carefully poured into a sample holder and spread under the glass cover slip at room temperature. Before observations, all samples were heated up to 40 °C to compare both optical and rheological results.

2.5. Viscous flow measurements

Viscous flow measurements were performed using a controlled-stress rheometer, MARS II from Thermo-Scientific (Germany). Rheological data were obtained using a coaxial cylinder geometry (41 mm inner diameter, 1 mm gap, 60 mm length) at atmospheric pressure, and a coaxial cylinder-pressure cell D400/200 at high pressure. The cell D400/200 is a pressure vessel of 39 mm of inner diameter. Inside the cell, an inner cylinder of 38 mm diameter and 80 mm length was put in contact with a sapphire surface at the bottom of the vessel by a steel needle. This inner cylinder was equipped, at the top, with a secondary magnetic cylinder (36 mm diameter, 8 mm length), magnetically coupled to a tool outside the cell, which was connected to the motor-transducer of the rheometer. The pressure cell was connected to a hydraulic pressurisation system through a needle control valve.

A pressure transducer GMH 3110 (Gresingeg Electronic, Germany), able to measure differential pressures ranging 0 to 400 bar (0.1 bar resolution), was used.

Both atmospheric and high pressure rheological measurements were performed at 40 ± 0.1 °C using a circulating silicone bath.

Steady-state flow curves were obtained without sample pre-shear. The measurements were carried out by applying an increasing shear rate ramp, in the range comprised between 0.01 and 1000 s^{-1}. Two replicates of each rheological test were performed on fresh samples. The experimental error in viscosity was always inferior to ±5%. Due