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Research paper

Experimental study on the application of an ionic liquid as a shale inhibitor and inhibitive mechanism

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ABSTRACT

Wellbore instability is caused to a great degree by shale hydration, which results from the interaction between the exposed shale formation and water-based drilling fluids in the exploration of oil and natural gas reservoirs. In this paper, an ionic liquid (ILB) is utilized as an efficient shale inhibitor in water-based drilling fluids to minimize shale hydration. The inhibitive property of ILB is evaluated by hot-rolling dispersion, capillary suction time and bentonite swelling tests. The test results indicate that 0.05 wt% ILB exhibits superior inhibition performance than 5 wt% conventional inhibitor potassium chloride (KCl) and its inhibition effect is approximately equal to that of 2 wt% polyether diamine (PA). But different from KCl and PA, the presence of low concentration of ILB can also improve the rheological properties of water-based drilling fluids at high temperature, and meanwhile has no adverse effect on their filtration property. The investigation of inhibition mechanism indicates that the thermal stability of Na-Mt is greatly improved due to the intercalation with cationic group of ILB, leading to excellent inhibition property of ILB at high temperature. Furthermore, the adsorption of ILB in the interlayer of Na-Mt weakens the hydrophilicity of Na-Mt, which further inhibits water ingress.

1. Introduction

Shale instability accounts for 90% of wellbore instability related problems in the process of drilling in the exploration of oil and natural gas reservoirs (Perez et al., 2007; Morton et al., 2005). Shale stability depends to a great degree on the interaction between the exposed shale formation and drilling fluids. Shale is primarily composed of clay minerals, which are extremely sensitive to water because of its large surface area and consequential strong adsorption capacity. In water-based drilling fluids sodium bentonite is dispersed in water-continuous phase. Water-sensitive shale takes up water immediately from water-based drilling when shale is in contact with water-based drilling fluids, which will result in clay swelling and dispersing, then weakens the wellbore stability and even leads to serious wellbore collapse. At the same time, cuttings from shale formations are incorporated into the drilling fluids, which cause problems such as poor rheological, filtration properties control and low solids removal efficiency (Caenn et al., 2011; Skalle, 2011). Therefore, shale presents particular challenges to drilling worldwide and a variety of drilling fluids and shale inhibitors have been designed to reduce or/and eliminate clay-water interaction, in order to improve wellbore stability of shale during drilling (Simpson et al., 1994; Bland et al., 1996).

Wellbore stability can be obtained with oil-based drilling fluids because of organo-montmorillonite dispersed in an oil-continuous phase (Caenn et al., 2011; Yan, 2012). However, the disadvantages such as high cost, environmental limitations and complex disposal greatly limit the wide application of oil-based drilling fluids. Consequently, water-based drilling fluids formulated with shale inhibitors are the preferred choice. Generally, shale inhibitors can be classified into inorganic salts, cationic surfactant, cationic polymer, glycols, modified asphalts and silicates. The earliest and most widely used shale inhibitors are simple inorganic salts such as potassium chloride (KCl). In any case KCl can be effective to inhibit clay swelling, however, the presence of large quantities of KCl (from 2% to 7% by weight) in the drilling fluids can adversely affect rheology, filtration control and biological ecosystems (Akhtamanesh et al., 2013; Zhong et al., 2011). A variety of polymers in combination with KCl show a higher performance of shale inhibiting as compared to KCl alone. However, polymers alone offered little success in providing the satisfactory results and the polymers need to be used in combination with KCl (Kjøsnes et al., 2003; Patel et al., 2007). Sodium silicate shows highly inhibitive properties but has shortcomings of rheological control for drilling fluids

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(McDonald et al., 2002). Although cationic polymers can effectively inhibit clay swelling, they are incompatible with other additives. Moreover, ammonium compound and its derivatives as additives were used as shale inhibitors in the field for a long time, but various kinds of amine have the shortcomings (Van Oort, 2003; Gholizadeh-Doonechaly et al., 2009). For example, quaternary alkyl ammonium salts are incompatible with anionic additives and hexamethylendiamine has odor. In recent years, a new class of shale inhibitor called polyether diamine (PA) has been developed and applied in drilling field due to its excellent inhibition (Mahto et al., 2013; Guerrero et al., 2006). In addition, it has been reported that synthesized nanocomposite exhibited good shale inhibitive property (Akhtamanesh et al., 2013; Rajat and Vikas, 2015).

Ionic liquids (ILs) are unique organic salts which are composed of cations and anions but they can exist in the liquid state at room temperature. Because of their excellent properties such as high thermal stability, insignificant vapor pressure, compatibility with organic, inorganic and polymeric materials, and designable structure and so on, ILs have attracted great interest for a wide range of industrial applications, including gas-separation, polymerization, liquid-liquid extraction, as green solvents replacing various organic solvents (Neung et al., 2006; Singh et al., 2014; Macfarlane et al., 2014; Takahashi et al., 2012). ILs are known as a new substitution for their incomparable superiority to the conventional organic compounds in such applications. There are only a few reported papers which treat ILs as clay inhibitors in the exploitation of petroleum. The first generation of quaternary ammonium-based ILs were only evaluated compared with KCl and trimethylammonium chloride (TMAC) at room temperature and the inhibition capacity of the ionic liquids was much better than that of KCl and TMAC(Berry et al., 2008). Compared with quaternary ammonium-based ILs, ILs composed of imidazole cation group are a new kind of ionic liquids with higher thermal stability. It has been reported that imidazole-based ionic liquids displayed excellent inhibition property and can improve rheological and filtration properties of water-based drilling fluids at high temperature (Yang et al., 2017; Luo et al., 2017).

In our present work, the inhibition performance of another imidazole-based ILs was evaluated in comparison to KCl and polyether diamine (PA) through different test methods. The inhibition mechanism of the ionic liquid was also investigated by using X-ray diffractometry (XRD), Fourier transform-infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), contact angle tests and scanning electron microscopy (SEM).

2. Experimental work

2.1. Materials

1-octyl-3-methylimidazolium tetrafluoroborate (CAS #: 244193-52-0), abbreviated as ILB, was supplied by Shanghai Yijiang Chemical Co. Ltd., China. Fig. 1 shows the structure formula of ILB. It has a molecular weight of 282.13 g/mol and its purity is 98%. Polyether diamine (PA) was donated by the Magcobar Mud Co. Ltd., China. Sodium montmorillonite (Na-Mt) with a cation exchange capacity (CEC) of 90 mmol/100 g, which is the major component of sodium bentonite, was obtained from Zhejiang Fenghong new material company, China. Its mineralogical composition was: montmorillonite, 85.0; quartz, 2.0; anorthite, 4.0; mica, 5.0 and hematite, 3.0. Partially hydrolyzed polyacrylamide (PHPA), KCl and all other reagents were used without further purification.

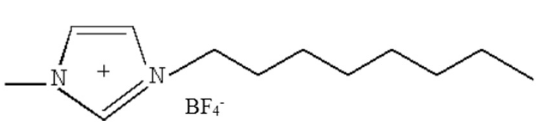

Fig. 1. The structure formula of ILB.

2.2. Preparation of drilling fluids

A fresh water-based drilling fluid composed of distilled water, Na-Mt and Na_2CO_3 (with a weight ratio of 1000: 40: 2) was prepared following the American Petroleum Institute standard (API RP 13I, 2004). The fresh water-based drilling fluid was incorporated with PHPA (0.3 wt%) and the dispersed system was subjected to pre-hydrate for 24 h at room temperature to obtain the polymer water-based drilling fluid.

2.3. Inhibition performance test

2.3.1. Hot-rolling dispersion test

This method simulates the behavior of cuttings from shale formation incorporation in the drilling fluid for a long time during the drilling process (Khodja et al., 2010). Because of its simplicity, low cost and better repeatability, hot-rolling dispersion test is the most widely used method and has been adopted by American Petroleum Institute (API, 1997). Each sample was tested three times, with the average values reported. This method can evaluate the inhibition performance of an additive at high temperature.

Test procedure was executed by API drilling fluid indoor test criteria (API, 1997) and the shale cuttings were obtained from the reservoirs of Bohai Oilfield, China. The shale sample consists of 33.0% clay minerals, which are composed of 70.0% illite smectite mixed layer, 9.0% kaolinite, 6.0% chlorite and 15.0% illite. 50 g dry shale sample seized through 6–10 mesh was added to 350 mL drilling fluid formulated with different additives in aging jar. Afterwards, the fluids with shale sample were rolled in a roller oven at 160 °C for 16 h. After thermal aging, the sample was washed with distilled water and was screened on a 40 mesh sieve. The recovered sample was dried for 4 h at 105 °C in a drying oven. The rate of hot-rolling recovered shale is expressed using the following equation:

$$R(\%) = m/50 \times 100\% \tag{1}$$

where R is the rate of cuttings recovery (%) and m is the weight of recovered shale. The greater R is, the better inhibition performance of the tested sample is.

2.3.2. Capillary suction time test (CST)

This method simulates free water of water-based drilling fluid under the capillary suction pressure of a porous filter cake penetrate (filtrate) into the formation, and the inhibition performances of additives are determined by the time of filtration. The method is rapid and easy, and the petroleum and gas industry uses CST technique to characterize shale inhibitor to minimize its effect on shale formation (Wilcox et al., 1987; Crowe, 1990; Berry et al., 2008). But the repeatability of this method is poor and each sample was measured three times at least, with the average values reported.

A 30 g dry shale sample (screened by 100 mesh sieve) was added into 250 mL of base fluid or base fluid containing different additives in the Waring blender container and the blend was stirred at the shear rate of 539 s^{-1} for 5 min. After that, 250 mL dispersion system was allowed to hydrate for 15 min and a 1 mL sample was withdrawn for the CST testing (ZH9644, China). The shorter the CST is, the better the inhibition performance of the tested sample.

2.3.3. Bentonite swelling test

This method simulates shale linear expansion caused by the invasion of water-based drilling fluids filtrate into the formation (Mao et al., 2015). This method needs a long time to measure one sample, which is only used in laboratory. The dried bentonite of 5 g was compacted in a container at a certain pressure (5.0 MPa) for 5 min and the initial height (H_0) of the compacted bentonite was measured. Then, the bentonite was soaked in the fluids formulated with different additives in a shale expansion instrument. The linear height (H_1) at different time within