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Application of nanofluid to control fines migration to improve the performance of low salinity water flooding and alkaline flooding

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ABSTRACT

Low salinity water (LSW) and alkaline flooding have been recognized as the two efficient improved oil recovery techniques to unlock residual oil. It has been widely reported that the efficiency of these methods critically improves with decreasing salinity and increasing pH of the slug injected during LSW and alkaline flooding respectively, and greater amount of oil can be recovered in these conditions. However, these chemical environments of low salinity and high pH are very unfavorable for in-situ particles retention and as a result, fines migration and subsequent formation damage is an accompanying phenomenon with these techniques. Therefore, one should choose the optimum salinity rather than the lower one to enhance the efficiency of a typical LSW project and also, the optimum pH for the injected slugs rather than the higher one to improve the efficiency of an alkaline flooding project. These limitations make the design of such flooding projects very difficult and challenging. This experimental work aims to probe nanoparticle (NP) treatment of colloidal particles migration occurred during the mentioned unfavorable conditions for particles retention. Zeta potential and turbidity analyses have been utilized as quantified tools to examine the effect of NPs on the interactions of colloidal particles with the medium surface. It was found that MgO NP can modify the zeta potential of the medium and in turn remarkably retain the colloidal fines in the presence of very low concentration of both monovalent and divalent salts; therefore, fines migration induced during low salinity conditions can be prevented. Furthermore, the presence of MgO NP on the beads surface significantly modifies/increases the point of zero charge (PZC) from around 3 to around 9 which in turn justifies the retention of particles in a wide range of alkaline conditions. It was found that the MgO NP-treated medium tends to retain around 97% of the in-situ fine particles at very alkaline conditions. Therefore, pre-flush of the medium with a slug of MgO nanofluid prior to alkaline flooding or LSW injection into the reservoir can serve as a promising remedy to counteract against the colloidal particles migration subsequently induced. This technique is of great interest in field application where improving oil recovery is desired; however, fines migration and subsequent formation damage should be avoided.

1. Introduction

Low-salinity water (LSW) flooding has been widely documented as a promising improved oil recovery technique in literature (Ashraf et al., 2010; Morrow and Buckley, 2011; Tang and Morrow, 1997, 1999). In this process, the brine chemistry has been recognized as an important parameter critically affecting the efficiency of the process. Different laboratory and field studies have proved the remarkable low salinity effect on the ultimate oil recovery and reported greater oil recovery with decreasing the ionic strength of water (Ashraf et al., 2010; Hassenkam et al., 2012). On the other hand, the brine chemistry drastically affects the interactions of colloidal particles, situated on the pore walls, with the medium surface (Lager et al., 2008; Nasralla et al., 2011). The resultant electrostatic surface forces existing between a particle and the rock surface, which are strongly functions of the pH and ionic strength of the permeating fluid, are much more repulsive when the salinity of injected water falls below a critical value, which is a case in a typical low salinity water flooding project. Therefore, during low salinity water injection into the reservoir the in-situ colloidal particles, situated on the pore chambers, tend to dislodge and migrate through the bed. This problem may be much more challenging within the zone stripped

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from multivalent cations, which is created ahead of the LSW front. The stripping of the divalent ions from the injected LSW takes place because in a low saline environment the divalent ions show more affinity to adsorb onto the clays than in a high saline environment (Appelo, 1994; Suijkerbuijk et al., 2013); therefore, the fluid ionic strength in the stripped zone is even lower than that of injected LSW. Thus fines migration is an accompanying phenomenon with any LSW flooding project.

Although some early studies argued the positive effect of fines migration induced by LSW flooding on improving oil recovery, there are a lot of recently published articles which disapprove the remedial effect of migrating fines on additional oil recovery. Yuan and Shapiro (2011) reported that the mobilization and re-capturing of the reservoir fines can plug the pores in water swept zones which in turn lead to increase sweep efficiency. However, the authors indicated that the effect of fines migration-assisted mobility control technique seems to be limited. Furthermore, plugging of the reservoir pore throats results in severe injectivity loss which in turn ruins the applicability of the process (Sorop et al., 2013; Yuan and Shapiro, 2011). The other suggested mechanism for improving oil recovery by LSW flooding has been attributed to the role of migrating fines as a carrier of oil droplets (Tang and Morrow, 1999). However, this hypothesis was questioned by Zhang et al. (2007) who reported the oil recovery improvement by flooding of reservoir cores with LSW; however, they observed no clay in the production stream and in the oil/brine interface (Aladasani et al., 2012; Zhang et al., 2007). It may be worth mentioning that Cissokho et al. (2010) reported the additional oil recovery in Kaolinite-free cores which also shows that the LSW-assisted improving oil recovery does not especially need the presence of clays (Aladasani et al., 2012; Cissokho et al., 2010).

To the so far knowledge, the underlying mechanisms explaining the improvement in oil recovery due to LSW flooding seem to be still debated. Nevertheless, there are a lot of publications disapproving the remedial effect of fines migration on the additional oil recovery obtained by LSW flooding. On the other hand, it has been widely documented that lowering of the salinity of the water to be flooded modifies the wettability of the rock toward more water-wet state (Berg et al., 2010; Cense et al., 2011; Rivet et al., 2010; Sorop et al., 2013). Berg et al. (2010) addressed wettability alteration as a main mechanism to improve oil recovery obtained during LSW flooding and clearly indicated that their findings rule out the other mechanisms including interfacial tension reduction, fines migration, and selective plugging of water-bearing pore spaces. Furthermore, it has been widely reported that low saline water, whose ionic strength is much lower than that of the rock, tends to exchange cations with the rock surface; therefore, modifies the rock surface charge toward more negative values (Lager et al., 2008; Nasralla et al., 2011). Consequently, electrostatic attractive forces between the rock surface and crude oil, which made the oil be trapped in the pores, is reduced which in turn results in improving oil recovery (Lager et al., 2008; Nasralla et al., 2011; Nasralla et al., 2013). Therefore, wettability modification and alteration of the forces balance between the medium surface and crude oil seem to be the main mechanisms explaining/justifying the effect of LSW flooding on unlocking the trapped oil. It is worth mentioning that the water salinity should be adjusted within a narrow salinity window which is low enough to be able to modify the wettability of the rock and/or reduce the attractive electrostatic forces between crude oil and rock (Sorop et al., 2013); and at the same time high enough to remain in-situ fine particles intact and prevent clay swelling and migration (Pingo-Almada et al., 2013). This precisely designed LSW flooding project, conducted in a controlled formation damage regime, is of particular interest in field application where improving oil recovery is desired yet colloidal particles migration and subsequent formation damage should be avoided (Berg et al., 2010; Cense et al., 2011).

Another technique to unlock the residual oil which has gained very considerable attention is alkaline/caustic flooding (French and Burchfield, 1990; Liu et al., 2010; Stoll et al., 2011). In this technique alkali can be utilized (1) as a pre-flush slug, (2) in conjunction with polymer and surfactants, (3) as a major recovery agent. Injection of an alkaline pre-flush agent can lead to precipitate hardness ions and in turn, precondition the reservoir to accept the surfactant; therefore, the surfactant can be protected from precipitation which in turn improves the efficiency of the surfactant flooding (French and Burchfield, 1990; Holm and Robertson, 1981; Krumrine et al., 1985). Furthermore, the alkali utilized in alkaline/polymer (AP) injection and alkaline/surfactant/polymer (ASP) flood can enhance the efficiency of polymer flooding projects. In this process, polymer is added to the water as a viscosifying agent to improve sweep efficiency and prevent fingering during water injection into the reservoir (Garmeh et al., 2012; Hild and Wackowski, 1999; Kazempour et al., 2012; Lei et al., 2011; Perez et al., 2012; Seright et al., 2009; Urbissinova et al., 2010); however, the early adsorption/loss of polymer on the rock surface can deteriorate the cost-efficiency of the process. This challenge seems to be handled by the effect of alkali utilized in AP injection and ASP flood, which results to mitigate the adsorption/loss of the expensive polymer and/or surfactant which in turn makes the process more cost-effective (Flaaten et al., 2010; French and Burchfield, 1990; Kazempour et al., 2012; Liu et al., 2008; Liu et al., 2010; Stoll et al., 2011). Furthermore, the alkali injected as a principal recovery agent can react with the oil to form in-situ generated natural surfactant named as petroleum soap which can reduce the interfacial tension and in turn unlock the trapped oil (Liu et al., 2010; Stoll et al., 2011).

In an alkaline flood the pH of the reservoir environment can be significantly altered ranging from 13.5 to near 7.0 (Krumrine et al., 1985). This high-pH environment can alter the charge density of the medium surface toward more negative values; consequently, in-situ soaps can be formed due to reaction of alkali with naphthenic acids in crude oil (Ehrlich and Wygal, 1977; Kazempour et al., 2012; Liu et al., 2008). In addition, the increasing pH of the reservoir environment can provide favorable condition for AP flooding so that the polymer adsorption onto the rock surface is reduced with increasing pH (Kazempour et al., 2012; Krumrine and Falcone, 1987). Furthermore, French and Burchfield (1990) investigated the effect of alkali on surfactant adsorption/retention onto the grain surface of Berea sandstone cores. The authors revealed that the surfactant adsorption was reduced by 49% when the pH of the permeating fluid was increased from 6.3 to 10.2 (French and Burchfield, 1990). Therefore, it is of great interest to further increase the pH of the reservoir environment during any kind of alkaline flooding to gain the aforementioned benefits; however, there is a very great concern regarding the pH-dependent interactions between the permeating fluid, the indigenous colloidal particles, and the medium surface.

Very high alkaline environment may result to form intractable scales or precipitates which can block the pore throats and in turn decline the productivity index (Krumrine et al., 1985). Alkaline chemicals can also disturb the interactions existing between clays and the medium surface resulting fines migration and/or clay swelling which in turn result in severe permeability impairment (Krumrine et al., 1985; Somerton and Radke, 1983). It is worth mentioning that the resultant surface forces between a negatively charged fine particle and the medium surface at the pH values greater than point of zero charge (PZC) seems to be dominantly repulsive resulting particles detachment and migration. Therefore, it seems that colloidal particles migration is an integrated part of any