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Experimental investigation of associative polymer performance for CO_2 foam enhanced oil recovery

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ABSTRACT

Polymer addition amplifies the foam flood performance by providing a substantial mobility control during the enhanced oil recovery (EOR). A conventional anionic polymer i.e. hydrolyzed polyacrylamide (HPAM) is widely used for polymer enhanced foam (PEF) flooding. In this study, the foam stability and viscosity performance of the conventional HPAM polymer were compared with a relatively new associative polymer. An associative polymer (i.e. Superpusher B 192) and the conventional polymer of same molecular weight were considered and the foam generation was performed using a widely used foamer i.e. alpha olefin sulfonate (AOS) and a foam stabilizer (betaine). FoamScan was used to measure the foam stability whereas, for foam viscometric measurements, a high-pressure high-temperature foam rheometer was utilized. An associative polymer showed an interesting combination and both the apparent viscosity and foam stability were found to be significantly high. The conventional polymer failed to provide a high foam strength in rheometric analysis whereas, an associative polymer showed an interesting viscosity profile and a two-fold increase in the foam apparent viscosity was observed. This study shows that the associative Superpusher B192 holds a bright potential in increasing the foam flood performance during EOR.

1. Introduction

A maximum performance cannot be achieved as gas injection into a mature oil field for enhanced oil recovery (EOR) usually results in a poor sweep efficiency caused by viscous fingering, gravitational override and a premature breakthrough (Falls et al., 1989; Green and Willhite, 1998; Kuuskraa et al., 2013; Xu et al., 2016; Zhang et al., 2015). Gas such as CO_2, when used to improve oil sweep efficiency, tend to have a lower density and viscosity compared to the oil that is intended to be displaced by CO_2 flooding. The CO_2 gas moves ahead of the oil, leaving behind most of the targeted oil in reservoir pores (Zhang et al., 2015). A foam is used to overcome the shortcomings and improve the sweep efficiency (Lee and Heller, 1990; Xu et al., 2016). Foam is a dispersion of gas in a liquid such that the liquid phase is continuous and some part of the gas phase is made discontinuous due to the formation of a thin film called lamella (Cao et al., 2015; Nonnekes et al., 2015; Zeng et al., 2016). In this form, the injected CO_2 mobility is significantly reduced and this provides more opportunity for the foam to invade and sweep previously un-swept or inadequately swept segments of the oil reservoir (Xu et al., 2015).

When CO_2 meets the oil, the oil viscosity is reduced which causes the oil to swell. This phenomenon also makes the oil leaner (Talebian et al., 2014; Zhang et al., 2015). Through the exchanges of the components (by extraction and evaporation) between the CO_2 and oil, the oil becomes lighter eventually and the CO_2 tends to become more dense and viscous (Kamali et al., 2015). The parity in density and viscosity between the CO_2 and oil is progressively diminishing, a key factor of a successful sweep efficiency (Kamali et al., 2015). It is essential that the foam remains stable and does not rupture in the presence of oil (Almajid and Kovscek, 2016). This is because a foam ruptures easily when it meets oil (Almajid and Kovscek, 2016; Li et al., 2010). Many attempts have been made to stabilize the foam lamellae, including the incorporation of CO_2 philic and oil resistant surfactants to delay the foam decay (Mannhardt et al., 1998; Simjoo et al., 2013). Others have employed nanoparticles to provide the lamellae with the needful viscoelastic property in order to overcome the small deformations without rupturing the lamellae wall (Farhadi et al., 2016; Sun et al., 2014). However, there exists a limiting lamellae thickness (h^*), if surpassed will cause the foam to collapse. A foam has a tendency to drain its liquid contents, making the lamellae thinner over

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time and eventually rupture. The liquid from the center of the lamellae will flow outwards to the plateau border. The plateau border is an intersection channel that joins the different lamellae bubbles (Farajzadeh et al., 2015). The liquid in the plateau border has a lower pressure compared to the liquid in the center of the lamellae film. Efforts are directed against the lamellae rapid thinning through the increase of the liquid viscosity by incorporation of polymer (Osei-Bonsu et al., 2015; Sydansk, 1994a; Xu et al., 2016; Xu et al., 2015). Another method to decelerate lamellar thinning is through gas and surfactant solution injection rates control. The foam quality in percentage is the ratio of the gas flow rate to the combined flow rates of surfactant solution and gas. If the foam quality is higher than 90%, a dry foam is found i.e. the gas fraction is increased and the surfactant solution fraction is reduced (Osei-Bonsu et al., 2016). As the foam gets drier, the capillary pressure increases and surpasses the lamellar thickness causing the foam coalescence and lamellae rupture. The apparent viscosity of the foam reaches a peak when the foam transitions take place from a low-quality to high-quality foam (Stevenson, 2012).

With a significant increment in foam stability and apparent viscosity, an in-depth mobility control can be achieved (Zhou et al., 2015). Throughout the last several decades, it has generally been acknowledged that foam collapse occurs at reservoir conditions and it incredibly hampers the foam flooding performance (Xu et al., 2016). The efficiency of foam flooding is largely depending on foam stability and viscosity, which shows the ability of the foam to propagate and sweep the reservoir (Xu et al., 2015).

Numerous authors agree that polymer addition to the conventional foam enhances both foam viscosity and stability and such polymer enhanced foams (PEFs) can be used as an effective mobility control agent (Dong et al., 2016; Petkova et al., 2012; Schramm and Isaacs, 2012; Sydansk, 1994a; Xu et al., 2016). A water-soluble polymer is generally added to a conventional foam to generated PEF and this increases foam stability, foam apparent viscosity and oil tolerance (Osei-Bonsu et al., 2015; Shen et al., 2006; Sydansk, 1994a; Xu et al., 2015).

Hydrolyzed polyacrylamide (HPAM) polymers have been widely used as oilfield polymers, whereby the physical properties of HPAM are determined based on its negative charge caused by the hydrolysis process. The degree of hydrolysis (DOH) controls the stability of aqueous phase and the viscosity of HPAMs. A very low DOH causes the reduction of polymer solubility in aqueous phase whereas a high DOH could decrease the salinity tolerance. The mechanical degradation of HPAM could take place when it is exposed to high shear rate. Exposure to the temperature that is higher than 90 °C could cause thermal degradation. In addition to shear rate and temperature, salinity could affect the performance of HPAM polymers by reducing the solution viscosity. This is because of salinity increases, which is caused by the charge shielding mechanism and coiling up of polymer molecules (Lande, 2016; Xu et al., 2016).

Some researchers have investigated the effects of various process variables such as polymer types, concentration and molecular weights, surfactant types and concentration, and salinity effect on PEF performance by using the sandpack as the foam generator (Sydansk, 1994a; Zhu et al., 2004). It can be concluded that the foam characteristics improved significantly with the addition of polymer. A substantial increase in the foam stability is exhibited even in the presence of a small concentration of polymer. The PEF is also studied in the presence of crude oil and it was found that the viscosity of crude oil affects the foam stability. The PEF performance in the presence of high viscous crude is better than in the presence of low viscous crude oil (Sydansk, 1994b). Azdarpour et al. (2013) and Wang et al. (2008) studied the foam stability by generating the PEF at room temperature and pressure using AOS and SDS in combination with HPAM polymers of different molecular weight. The results showed a significant increase in the foam stability due to an increase in foaming solution viscosity (Azdarpour et al., 2013; Wang et al., 2008). Lande (2016) also blended AOS with HPAM polymer at room conditions and a prominent delay in liquid drainage from foam lamella can be observed due to incorporation of polymer (Lande, 2016). Many studies have been done using AOS and it is reported that AOS has a good performance with good compatibility with polymers (Huh and Rossen, 2008; Lande, 2016; Shen et al., 2006; Wang et al., 2008). An investigation on the application of a novel Chinese polymer and its comparison with HPAM has been carried out and it is concluded that a novel Chinese polymer (i.e. AVS) with AOS in a porous media study obtained a high foaming factor as compared to the conventional polymer free foams. (Xu et al., 2015, 2016).

Field implementation of polymer addition with CO_2 foam has also shown better results for heterogeneous reservoirs (Li et al., 2006). A pilot polymer enhanced foam test was conducted in Gudao oilfield in 2003 (Dong et al., 2016; Li et al., 2009). This field was initially water flooded, which was then followed by a polymer flooding after 26 years. Due to high heterogeneity of this area, various problems, including polymer production and an increase in water cut occurred. After 20 months, PEF injection was performed for about 3 months, a significant improvement in oil production i.e. from 75.1 t/d to 149.4 t/d was observed in producers whereas the water cut was reduced to 5.8%. This pilot test showed that the PEF also holds huge potential for the polymer flooded reservoir (Dong et al., 2016; Li et al., 2006).

Telmadarreie and Trivedi (2015, 2016) presented an experimental study for fracture carbonate reservoir in which a conventional HPAM polymer (Floppam 3330s) with CO_2 foam was utilized for oil recovering after the surfactant flooding (Telmadarreie and Trivedi, 2015, 2016). The experiments were conducted on a specially designed fractured micromodel to analyze the performance of CO_2 foam and PEF flooding phenomena. The bubbles of PEF pushed the injected surfactant/polymer into the untouched matrix portion. Results of both static and dynamic tests were presented and a good relationship between the foam stability and crude oil recovery was obtained. An improved foaming solution viscosity and bubble stability during PEF increased the displacement of heavy crude oil and the results were significantly higher than the conventional foam application (Telmadarreie and Trivedi, 2015, 2016).

Besides that, Hernando et al. (2016) presented an extensive experimental work to achieve high foam stability by utilizing different foaming agents and polymers to screen out the best surfactant/polymer combination (Hernando et al., 2016). They used two different polymers (i.e. anionic and an associated polymer) prepared in 2 wt% KCl brine at room temperature and pressure conditions. A classical non-ionic polymer and an associative polymer, which contains a small amount of hydrophobic group and acrylamide/acrylate backbone were utilized in this study. They found a good foam stability and foam flow resistance after using an associative polymer at 20 °C and low-pressure conditions (Hernando et al., 2016).

Pu et al. (2017) utilized different anionic and non-ionic polymer acrylamide (PAM) polymers at the HTHP reservoir conditions (Pu et al., 2017). They used both N_2 and CO_2 gases for PEF generation in the presence of crude oil. PEF provides the highest tolerance to crude oil due to the formation of the stable emulsion at the lamella interface. The highest performance of CO_2 PEF was found at above the supercritical conditions of CO_2. Additionally, the mobility control and oil recovery were significantly enhanced by incorporating these polymers in strong heterogeneous formation (Pu et al., 2017).

The mobility control using PEF was found to be higher than the conventional foams due to their high viscosity and stability. A micromodel and a porous media studies were presented to investigate the flow characteristic of conventional foam and PEFs through the porous media (Dong et al., 2016; Huh and Rossen, 2008). The behavior of PEFs was different from the conventional foams in porous media. According to the apparent viscosity of the PEFs, the shear thinning flow behavior was observed more than the conventional foams (Huh and Rossen, 2008; Wang et al., 2008; Zhu et al., 2006). The rheological characterization of foam has been known as a complex task and numerous parameters such as foam quality, foam texture, temperature, pressure and chemical types and concentration have to be considered. Moreover, a rigorous