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A comprehensive review of experimental studies of nanoparticles-stabilized foam for enhanced oil recovery

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ABSTRACT

Nanoparticles-stabilized foam has recently attracted increasing attention for enhanced oil recovery (EOR) applications, largely due to the potentially high stability of these foams in the oil producing formations. There are several research articles on experimental studies of nanoparticles-stabilized foam for EOR applications. However, no previous attempts has been made to comprehensively review these existing literature. To fill this identified knowledge gap, we conducted the first comprehensive review on current status of static stability experiments, macroscopic and microscopic scale experimental studies of nanoparticles-stabilized foam for EOR applications. Influence of different critical parameters on the foam performance was reviewed. The results of the previous studies were discussed, challenges and conflicting findings were identified and directions for further studies were suggested. Experiments were conducted by the authors to complement some of the results in literature. From the reviewed literature, results of experimental studies indicated that the presence of nanoparticles at an appropriate concentration and favorable hydrophobicity will improved the foam static and dynamic stability in porous media. Several critical parameters like nanoparticles types, salinity, oil presence, temperature and pressure control the efficiency of nanoparticle-stabilized foam. Review of the experimental methods showed that the pore-scale mechanisms of nanoparticles-stabilized foam generation, stability, propagation, and residual oil mobilizations in porous media are not yet explicit due to limited studies. Nanoparticles-stabilized foams for EOR have not been implemented in the field due to limited understanding of influence of controlling parameters on foam performance and insufficient mechanistic and modelling studies. The remarkable potential of nanoparticles-stabilized foam to recover the trapped oil from the low permeability layer of the heterogeneous formation, due to the occurrence of foam diversion, and the use of fly-ash nanoparticles for EOR applications remains an interesting topics for future studies.

1. Introduction

1.1. Background and motivation

Oil recovery from the petroleum reservoirs can be achieved by primary, secondary and tertiary oil recovery methods. Primary and secondary recovery methods, depending on the reservoir characteristics, can only recover about 30–50% of the original oil in place (Alhomadhi et al., 2014; Muggeridge et al., 2014; Alyousef et al., 2017). Hence, the remaining oil in the petroleum reservoir remains the target of any enhanced oil recovery (EOR) operations such as chemical injection, gas injection, thermal oil recovery and microbial enhanced oil recovery. During enhanced oil recovery process, there is an improvement in the oil displacement and volumetric sweep efficiencies. This can be achieved

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through reduction of oil viscosity, capillary forces, interfacial tension and the development of a favorable mobility ratio between the displacing and the displaced fluid (Wei et al., 2014). This results in the eventual mobilization and the production of a substantial portion of the trapped residual oil in the reservoir at minimum cost (Payatakes, 1982). Gas injection with about 39% contributions to world's EOR remains one of the most commonly used EOR methods in the fields (Almajid and Kovscek, 2016; Alyousef et al., 2017).

During gas injection, hydrocarbon and non-hydrocarbon gases like methane, air, carbon dioxide, natural gas and nitrogen are injected into the reservoirs for the recovery of residual oil (Liu et al., 2011). Carbon dioxide gas injection contributes an estimate of 38% of US EOR production (Singh and Mohanty, 2017a,b). Gas injection can either be miscible or an immiscible gas flooding. In miscible gas flooding, the gas is injected either at minimum miscibility pressure (MMP) or beyond. Oil recovery is enhanced by the reduction of viscosity and interfacial tension as the injected gas mixes completely with the oil. In immiscible flooding, the injected gas does not mix with the reservoir oil. Reservoir pressure is maintained as the gas injection takes place below the minimum miscibility pressure (MMP) (Shokrollahi et al., 2013). However, any gas enhanced oil recovery process suffers from low areal and vertical sweep efficiencies (poor macroscopic sweep efficiency) because of gas higher mobility and lower density compared to oil (Rossen et al., 2010). This results in gas segregation, gravity override, viscous fingering and severe channeling of the injected gas through the high permeability streaks during gas injection EOR process (Andrianov et al., 2012).

Foamed-gas injection became popular in 1950s in order to mitigate the limitations of gas injection and improved the mobility of injected gas during gas injection EOR (Holbrook, 1958; Sun et al., 2014). Foam can be produced when a foaming agent containing liquid comes into contact with gases such as carbon dioxide, air, nitrogen, and sufficient mechanical energy is supplied that can cause the liquid to foam (Green and Willhite, 1998). Foam in porous media was defined by Falls et al. (1988) as dispersions of gas in liquid such that the liquid phase is continuous and some part of the gas phase is made discontinuous by thin liquid films called lamellae. Foam controls gas mobility by increasing the apparent viscosity of the displacing fluid and reducing the relative permeability of the gas phase. The displacing fluid apparent viscosity is increased by drag forces exerted by the moving bubbles on the pore walls while gas relative permeability is reduced by gas trapping. Results of some previous experimental studies revealed that the fraction of the trapped gas in the porous media can be as high as between 50% and 100% (Bernard and Jacobs, 1965; Friedmann et al., 1991; Nguyen et al., 2009). Foams apparent viscosities were also reported to be up to 1000 times higher than that of their constituent phases in some cases (Zhu et al., 2004; Liu et al., 2005). In heterogeneous porous media, foam helps to divert the injected fluid from the high permeability regions to the low permeability un-swept areas by lowering the gas mobility in the high permeability zones (Kovscek and Bertin, 2002; Skauge et al., 2002; Blaker et al., 2002).

Despite these advantages, foams are unstable due to rapid collapse of their thin liquid interfacial films and will require surface active and stabilizing agents for continuous generation and long-time stability (Rio et al., 2014). For enhanced oil recovery (EOR) applications, the generated lamellae should be long-lasting and should be able to translate from pore to pore in the reservoir in the presence of resident brines, oils and at high temperatures (Zhu et al., 2004; Falls et al., 1988; Kam and Rossen, 2003). Stable aqueous foams generation has been achieved using surfactants, polymer and proteins (for food foams) as the conventional foaming and stabilizing agents for several decades (Romero et al., 2002; Murray and Ettelaie, 2004; Romero-Zerón et al., 2010; Samin et al., 2017). It has been demonstrated experimentally that gaseous bubbles can be prevented from coalescing by the adsorption of surfactant, polymers and protein molecules at foam air-water interface (Rossen, 1996; Bournival et al., 2014; Zhang et al., 2015). Polymers can also increase the continuous-phase viscosity and formed a chain-network between droplets (Xu et al., 2017).

However, at reservoir conditions, especially as the foam contacts the resident brines and crude oils in porous media, surfactant-stabilized foam, polymer enhanced foam and protein foams become unstable due to the faster rate of collapse of the thin liquid films at the gas-liquid interface (Zhu et al., 2004; Yekeen et al., 2017b). The stabilizing species possess high tendency to degrade in the reservoir in presence of oil and at high salinity and temperatures and may modify the physical properties of the reservoir rocks (Yusuf et al., 2013; Rafati et al., 2016). For polymer enhanced foam, there is high tendency for the polymer to loss its viscosity-enhancing properties at high temperature and salinity (Kutay and Schramm, 2004). Polymer molecules can also increase up to 10 to 15 times of their original concentration in the aqueous phase in the formation, causing pore throats blockage and formation damage (Emrani and Nasr-El-Din, 2017).

The foamability and stability of the conventional foams has been investigated in previous experimental studies through bulk-scale stability experiments (Farzaneh and Sohrabi, 2015), bubble-scale stability experiments (Osei-Bonsu et al., 2015), and pore scale visualization experiments (Almajid and Kovscek, 2016). Results of these studies showed that oil was very destructive to the static and dynamic stability of surfactant foam irrespective of the surfactant type. In a more complex system when oil is present in porous media, Almajid and Kovscek (2016) found that the snap-off of oil close to the pore throat in the micromodels hindered effective generation of lamellae. This phenomenon was termed “hindered generation”. As a result of high coalescence and rapid destabilization of the conventional foams. The cost of the foam EOR projects are usually prohibitively expensive and the projects are likely to be uneconomical for large scale applications (Nguyen et al., 2014). The effectiveness of surfactant-stabilized foam is also greatly affected by the high rate of adsorption of surfactant molecules on reservoir minerals and rock surfaces (Lee et al., 2015; Yekeen et al., 2017c).

The principal mechanisms of lamellae destruction and aging process are liquid drainage, coalescence, and coarsening (Fameau and Salonen, 2014; Krzan et al., 2013). The instability of the inter-bubbles films results in bubble breakage and merging of the two smaller bubbles to form larger bubbles due to rupture of liquid films between bubbles (Bubbles coalescence) (Briceño-Ahumada et al., 2016; Langevin, 2017). According to Krzan et al. (2013), foam drainage is the major mechanism of lamellae destruction in aqueous foams due to the influence of gravitational acceleration, viscous force and capillary pressure between the adjacent bubbles. In foam coarsening, there is diffusion of gas from smaller bubbles to bigger bubbles because of the higher Laplace pressure (the pressure difference between the inside and outside of any bubble) on smaller bubbles (Saint-Jalmes, 2006; Martinez et al., 2008). Hence, the smaller bubbles vanish with time resulting in an increase in average bubble size (Hilgenfeldt et al., 2001).

Due to the limitations of surfactant-stabilized foam, polymer enhanced foam and protein foams, the use of nanoparticles as foam stabilizing species for EOR applications has recently attracted prodigious attention. The presence of the foam stabilizers (nanoparticles) at the gas-liquid interface of the foam aids in mitigating the limitations of the conventional foams. The advantages of nanoparticles as foam stabilizers has been identified from previous studies as high and sustained stability at reservoir conditions (Khajehpour et al., 2016; Singh and Mohanty, 2015, 2017a; Maestro et al., 2014). This can be attributed to the irreversible adsorption and aggregation (accumulation) of nanoparticles at the gas-liquid interface of the foams and Plateau borders. The adsorbed nanoparticles improved the foam stability by reducing the direct contact between the fluids to prevents liquid drainage, gas diffusion, and the rate of film rupture and bubbles coarsening (Maestro et al., 2014; Karakashev et al., 2011; Yu et al., 2012a; Li et al., 2016). Compared to surfactants, nanoparticles are less prone to adsorption on reservoir rocks and clay minerals during migration. The results of previous experimental studies showed that nanoparticles can be transported with little retention in porous media and without causing core plugging in the pore throats due