



Experimental study on stability and rheological properties of aqueous foam in the presence of reservoir natural solid particles



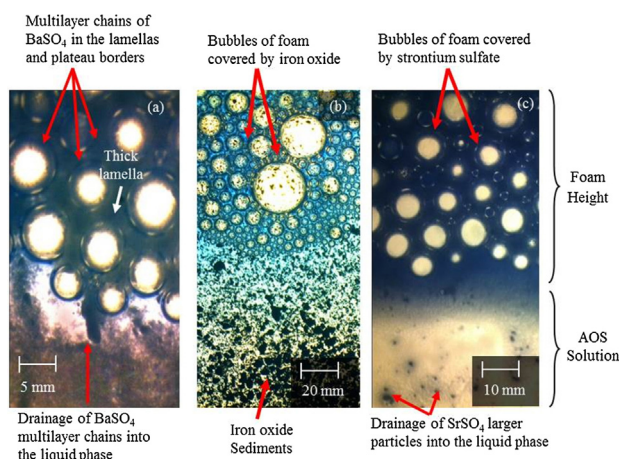
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HIGHLIGHTS

- Foam stability is critical for foam flooding in enhanced oil recovery processes.
- Micro- and nano-particles may improve or downgrade stability of foam.
- Foaming agent concentration, particle size/shape/wettability affect foam stability.
- Calcium carbonate, barium sulfate, and strontium sulfate particles improve foam stability.
- Calcium sulfate and iron oxide particles decrease foam stability.

GRAPHICAL ABSTRACT



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ABSTRACT

Gas injection and especially CO₂ flooding has been applied in many oil reservoirs globally to increase oil recovery factor in addition to its environmental friendly aspects. However, difference between fluid viscosities and densities, can cause interface instability where gas override and fingering may expedite gas breakthrough. Different types of foam have been proposed to improve interface stability. Yet, a major uncertainty is interaction of foam with natural reservoir particles which may improve or downgrade the performance and stability of foam. In this study we examined foam stability through solid-fluids interactions between solid particles of hydrocarbon reservoirs and aqueous foam. We tested five common reservoir particles of calcium carbonate, calcium sulfate, barium sulfate, strontium sulfate and iron oxide with different surfactant and particle concentrations. It is found that stability of foam in the presence solid particles is a function of density, shape, size, and wettability of particles where monolayer, bilayer of network or particles stabilise foam lamella or rupture foam structure. Results show that solid particles of calcium carbonate, barium sulfate and strontium sulfate enhance the thermodynamic stability of foam. This is due to the distribution of semi-hydrophilic solid particles, which form mono- and multi-layers of particle chains in foam lamellae and plateau borders. On the other hand, solid particles of iron oxide and calcium sulfate destabilise foam where particle swelling, adsorbed surfactant solution and settlement into liquid phase due to their high densities were observed. The results suggest that a comprehensive study of liquid and solid interaction is critical in design of any foam for enhanced oil recovery processes.

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1. Introduction

Gas injection and CO₂ flooding as enhanced oil recovery methods have been used successfully in many places around the world. In this kind of processes injected gas phase displaces oil through reducing interfacial tension and capillary effects, which improves ultimate recovery factor. However, high gas to oil mobility ratio is an unfortunate that causes gravity override, gas phase channelling, and viscous fingering. Therefore, high gas to oil mobility ratio results in poor sweep efficiencies and early breakthrough of displacing phase (gas) [1–3].

In gas injection processes, stability of displacing front is a main concern, and it is a function of many variables such as injection pressure, oil viscosity, type of the injected gas, miscibility conditions, among others. Previous studies were conducted to improve the stability of displacing front in gas injection processes such as miscible gas injection, water alternating gas injection and foam flood [4–12]. Miscible gas injection is designed to mobilize oil as a single phase flow in porous media and avoid two phase flow system and capillary effects, therefore gas may not breakthrough as a second phase [1–3,11–13]. Similarly, in water alternating gas injection, a slug of injected gas is followed by a slug of water to decrease the likelihood of early gas breakthrough while decreasing capillary effect through gas phase in porous media.

While there are many successful projects based on these recovery methods, difficulty in control of processes, cost of high pressure gas injection for miscible gas flood, and oil trapping by water phase in water alternating gas process, are challenges in place [11–14]. Another solution to control gas mobility and increase gas front stability is the use of surfactant-stabilised foam. This idea was first introduced by Bond and Holbrook in 1958 [15], and later many other investigations have been conducted on characterisation and use of foam in gas injection process [16–22].

Foam improves the performance of gas flooding processes through two mechanisms: first, the presence of a foaming agent and aqueous phase creates more favourable mobility ratio of displacing to displaced fluids, and second, gas diversion from the fractures and high permeability zones to lower permeability regions can take place, where both of these mechanisms increase the stability of displacing front and reduce the early breakthrough of gas [17,23–25].

Despite these favourable properties, foam is not thermodynamically stable and its physical structure can break down easily when two bubbles approach each other. This collapse in the structure of foam happens as liquid film between adjacent bubbles undergoes thinning, and as a result liquid film can rupture [25–27]. Various methods have been proposed to improve foam stability, such as increasing surfactant concentration, mixing different types of surfactants, and addition of co-surfactants and polymers to foaming agents. These solutions create a stable liquid film between bubbles which is called meta-stable super-thin film state, however, they are often expensive and might not be economical for large scale applications. Furthermore, these remedies may alter physical properties of the reservoir rocks that could result in a poor flow conductivity in porous media. Therefore, a thorough analysis of rock-fluids interactions is critical for the use of different compositions of foam in hydrocarbon reservoirs.

Foam stability can also be affected by the presence of dissolved species in other phases, such as second liquid phase containing fine solids. These species are naturally in the reservoir that may stabilise or destabilise the structure of foam. Foam stability in this condition is a factor of different parameters; firstly whether the solid species are strongly liquid affinitive and there is a tendency to be accumulated at the gas-liquid interface or not, and secondly, what are the impacts of accumulated particles on the interfacial properties and lamellae viscosities of gas-liquid interface.

Concentration of solid particles in liquid phase, their wettability, size and shape are critical parameters affecting bulk foam stability [28–39]. Concentration of solid particles defines the quantity of particle association in foam lamellae and at the plateau borders, which is a key factor for apparent viscosity enhancement of bulk foam [38–42].

Foam stability of silica and laponite particles at various concentrations with mixture of anionic and non-ionic surfactants were studied by many researchers [30–34,36,38,39,43,44]. A synergistic foam stability trend was reported, where it shows more prominent effects with increasing in the concentration of particles. The enhancement of synergistic effect is attributed to an increase in the density of adsorbed particle. At low-to-moderate surfactant concentrations, foam stability increases about 20% compared to the mixtures that have pure hydrophilic particles. The rationale for such improved stability is low surfactant concentrations where bridging flocculation of particles at foam interface produces enlarged and sterically strong interfacial barriers. Furthermore, at moderate surfactant concentrations, surface elasticity increases due to the presence of suspended particles in surfactant solution.

Horozov suggested the probable mechanisms which foam lamella stabilisation may take place. His suggested first mechanism is layering of solid particles inside liquid film and categorised them as a monolayer of bridging particles; a bilayer of close-packed particles and a network of particle aggregates (gel) [32]. Second, foam stabilising mechanism by particle comes into play if the particles are not completely water-wet. In this case particles tend to aggregate at foam-liquid interface where they may improve the mechanical stability of lamellae. On the other hand, strongly hydrophobic particles may behave differently, and destabilise foam structure. It was reported that intermediate contact angles (between about 40° and 70°) would be optimum to develop a solid-stabilised foam [30,32–34,39,41].

Analogous bridging mechanisms have been suggested for antifoaming behaviour of hydrophobic particles or mixtures of particles and oil [25]. Hydrophobic particles create a convex shape curvature on the surface of film at gas-liquid interface; thus capillary pressure decreases the thickness of liquid film. For hydrophilic particles, liquid film exhibits a concave meniscus at its surface; where capillary pressure is exerted in gas phase in opposite direction [45]. Furthermore, it should be noted that based on previous investigations, particles with rough edges on their surface, commonly found in commercial antifoams, can cause rupture in liquid film at even contact angles less than 90°. Consequently, rough hydrophobic particles are more effective antifoam agents than smooth particles, and therefore rounded solid particles stabilise bulk foam [45].

Alargova demonstrated that rod-shape particles can act as effective foam stabilisers in the presence of sodium dodecyl sulfate (SDS) surfactant [46]. They used rod-shape polymer particles with an average length of 23.5 μm and diameter less than 1 μm, which exhibited a contact angle of $\theta \approx 80^\circ$ at the air-water surface through the surfactant solution. Their fairly dilute micro-rod suspensions (0.2–2.2 wt%) in pure water, produced foam upon shaking and it showed remarkably a stable structure which last for more than three weeks even under drying conditions in an open vessel [46].

Nowadays, silica and metal nanoparticles are frequently used as a foam stabiliser agent for enhanced oil recovery processes [38,39,41,47]. It was found that nanoparticles at concentrations between 0.05–2 wt% can stabilise foam in the presence of both non-ionic and anionic surfactants. These types of nanoparticle foam are two to eighteen times more stable compared to the same foam without nanoparticles in its structure [34,38,39,41,47].

Properties and performance of particle-stabilised foam have been investigated by many researchers [30–33,36–40,42,43,47–50]. However, the effects of scales and

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