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Aqueous foam stabilized by partially hydrophobic nanoparticles in the presence of surfactant

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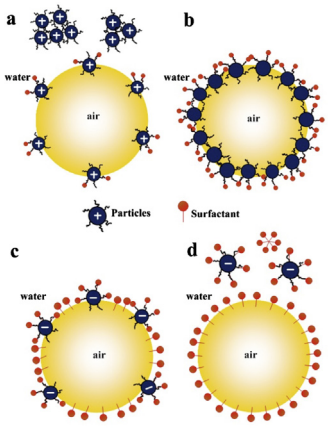
HIGHLIGHTS

- There exists moderate SDS concentration for the most stable SiO_2/SDS foam.
- The enhanced viscoelasticity of air–liquid surface improves the foam stability.
- The SiO_2/SDS foam mitigates the viscous fingering instability in sandpack.

GRAPHICAL ABSTRACT

The concentrations of SDS from a to d increase in turn.



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ABSTRACT

Although foam has been widely used in petroleum industry, its instability is still a problem during its applications. Here, partially hydrophobic modified SiO_2 nanoparticles were used with sodium dodecyl sulfate (SDS) to increase the foam stability. Surface tension, interfacial dilational viscoelasticity, and ζ potential of SiO_2/SDS aqueous dispersion had been determined and correlated with foam stability and plugging ability in porous media. The experimental results showed that SiO_2 nanoparticle had a synergetic effect on foam stability with SDS at proper concentrations, and more stable foam could be obtained from SiO_2/SDS dispersion compared to SDS solution. It is deduced that SDS molecules help the nanoparticles to move to air–liquid interface at moderate concentration, and thus the dilational viscoelasticity increased consequently. SiO_2/SDS foam showed a good plugging performance in the sandpack flooding experiment. Foam stability was enhanced with nanoparticles adsorbed on the surface of liquid film, so bubbles did not rupture easily in porous media. As a result, more gas was trapped in the sandpack to prevent gas breakthrough. These fundamental results may guide the application of nanoparticle-stabilized foams in oil field.

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1. Introduction

The demand for crude oil increases drastically globally in recent years. Gas flooding is a general and economic oil recovery technique [1]. But the low viscosity of gas relative to that of crude oil makes it too moveable in porous media. The adverse mobility ratio usually causes viscous fingering between gas and oil, which is unfavorable for oil recovery when gas is injected into reservoir separately [2]. Formation plugging with foam fluids provides an effective way to restrain viscous fingering. Foam fluids have already been used in various petroleum production technologies, such as drilling [3], fracturing [4], acid matrix-stimulation treatments [5], EOR (enhanced oil recovery) [6], etc. Foam blocks some pore throats because it provides resistance to flow due to contact angle hysteresis of lamellae (Jamin effect). The apparent viscosity of foam is generally several orders of magnitude greater than that of gas. Therefore, it restrains gas viscous fingering and increases oil recovery ratio [7].

Foam is generally unstable both thermodynamically and kinetically, especially under formation condition. Nanoparticles are adopted to increase foam stability recently in food industry [8], forth flotation [9], EOR [6,10]. Unlike surfactant molecules, the adsorption of nanoparticles at the air–liquid interface is normally irreversible. When the amount of adsorbed nanoparticles is enough, the elasticity of the interface increases accordingly [11]. The enhanced dilational elasticity leads to the inhibition of bubble coarsening. Numerical simulation results also show that bubble coarsening can be slowed down by increasing the compression elastic modulus E [12]. Besides, the adsorbed nanoparticles also hinder the water flow at bubble surface and thus slow down film thinning [13,14]. Ravera et al. [15] studied the silica nanoparticle dispersion with different amount of cationic surfactant CTAB. The particle surface changed from hydrophilic to hydrophobic by CTAB adsorption, and would be more hydrophobic with CTAB concentration increase [16]. Binks et al. [17] also confirmed that silica nanoparticles and surfactant could produce stable foam together at suitable surfactant concentration. And at high CTAB concentration, Noskov et al. [18] and Zhang et al. [19] found that the dispersion became opacitas, indicating particle aggregation. In that case, the surface property of dispersion was dominated by adsorbed surfactant only. By combining silica particle and anionic surfactant (SDS), Ahuali et al. [20] obtained a kind of very stable nano size emulsion with an average diameter of 400 nm. The SDS molecules adsorbed on the surface of silica nanoparticle and formed a supercharged system. In oilfield, nanoparticle-stabilized foams have also attracted researchers' attention recently [10]. In the previous work [6], we evaluated the nanoparticle-stabilized foam stability and effectiveness in enhanced oil recovery at pore scale and micromodel scale. It was found that this kind of foam improved EOR significantly, which might attribute to its high stability.

There are multiple interactions in the surfactant/nanoparticle stabilized foam, such as interaction between surfactant molecules, interaction between surfactant and nanoparticle, interaction between nanoparticles [21]. So the overall effect at the foam interface is quite complicated. Interfacial dilational viscoelasticity bases on the relaxation processes at the air–liquid interface and also determines the resistance of an interfacial layer to external disturbance [22,23]. It includes the information of orientation, desorption and adsorption of molecule at air–water interface. Despite the significant works on surfactant with hydrophilic SiO_2 nanoparticle, there is little study on surfactant with hydrophobic SiO_2 nanoparticle. Besides, the performance of nanoparticle stabilized foam in porous media is, as yet, unclear.

In this paper, partially hydrophobic SiO_2 nanoparticles and SDS were used to prepare aqueous foam. The co-adsorption of silica nanoparticle and SDS at air–water interface was studied through dynamic surface tension measurement. Interfacial change was monitored by measuring the interfacial dilational viscoelasticity. The foam stability was assessed, and the optimal SDS concentration of the most stable foams for a given value of SiO_2 concentration (1.0 wt%) was also determined. Furthermore, its plugging ability across a sandpack was measured to verify the control of viscous fingering.

2. Experimental

2.1. Materials

Partially hydrophobic SiO_2 nanoparticle (HDK, H15) was supplied by Germany Wacker Chemical Co., Ltd. It is nearly spherical with an average diameter of approximately 14 nm. Its specific surface area is about 200 m^2/g. Weight loss is less than 0.6 wt% after being dried for 2 h at 105 °C. Its water contact angle is about 80°. pH of the dispersion is adjusted to 6.0–6.5 in all the experiments. In our previous study, we have found that the foam was the most stable with 1.0 wt% SiO_2 and proper surfactant concentration [6]. So in this study, the concentration of SiO_2 nanoparticle was set at 1.0 wt% unless specified otherwise.

SDS was purchased from Sigma (USA), with the purity > 99.0%. The critical micelle concentration (CMC) of SDS in water was 0.23 wt% at 25 °C. Ethanol (Sinopharm Chemical Reagent Co., Ltd., China) was used as a co-solvent to disperse the partially hydrophobic nanoparticle into water. Deionized water was used in all the experiments. Nitrogen was supplied by Tianyuan Inc. (China), with a purity of 99.9 wt%. All glasswares were cleaned with a surfactant free cleaning agent. Experiments were conducted at room temperature unless specified otherwise.

2.2. SiO_2/SDS dispersion preparation

In order to produce well dispersed aqueous suspensions, SiO_2 nanoparticles were wet with ethanol first, then water was added to make a suspension contained ethanol less than 3 wt%. The ethanol was removed by repeated sedimentation–redispersion in pure water to assure the residual ethanol was less than 0.1 wt% [24]. The SiO_2/SDS dispersions were prepared by adding a known mass of SDS into the SiO_2 suspensions. The dispersions were stirred constantly for at least 6 h to reach adsorption equilibrium, and followed by 2 h of sonication. The dispersion is a little hazy at low SDS concentration. It seems that the some of particles may flocculate in the dispersion. But the dispersion became clear and transparent as SDS concentration increased. Finally, the dispersions were sealed for use.

2.3. ζ potential of SiO_2/SDS dispersion

The ζ potential of SiO_2/SDS dispersions were measured with a Malvern zetasizer (Nano ZS90, Malvern instruments Ltd., UK). The equilibrated dispersion was sonicated for 30 min, and then transferred into a disposable cell for ζ potential. The cell was kept at 25 °C for 120 s. Each sample was measured for at least 5 times and averaged. The ζ potential values were calculated according to Smolochowski equation automatically by the zetasizer.

2.4. Foam generated from SiO_2/SDS dispersion

Foam was prepared using a Warning blender (GJ-3S, Qingdao Senxin Machinery Equipment Co., Ltd., China). 100 mL dispersion was poured into the blender and stirred for 3 min at 8000 rpm. The generated foam was transferred immediately into a glass cylinder to record the foam volume. The volume change over time was also