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Effect of particle hydrophobicity on CO_2 foam generation and foam flow behavior in porous media

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HIGHLIGHTS

- Stable liquid CO_2 foam was generated with the aid of nanosilica particles.
- More CO_2 foam was observed as the particle surface changed from hydrophilic to somewhat hydrophobic.
- The particle-stabilized CO_2 foam displayed a significant effect on the reduction of the CO_2 mobility in porous media and on the improvement CO_2 apparent viscosity in capillary tube.

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ABSTRACT

Studies of CO_2 foam stabilized with silica nanoparticles at reservoir conditions were carried out for CO_2 foam enhanced oil recovery (EOR) application. In the study described in this paper, three types of silica nanoparticles with varied wettability were employed to study the effects of particle hydrophobicity on CO_2 foam generation at reservoir conditions. The results showed that nanoparticle surface hydrophobicity played an important role in CO_2 foam generation. More CO_2 foam was generated as the particle surface changed from strongly hydrophilic to somewhat hydrophobic. The bubble size of the CO_2 foam decreased noticeably as the particle surface became more hydrophobic. Nanosilica particle-stabilized CO_2 foam demonstrated a significant effect on the reduction of the CO_2 mobility at a phase ratio between 2 and 11. The particle-stabilized CO_2 foam also improved the apparent viscosity of the CO_2 as the mixture flowed through a capillary tube.

1. Introduction

Nano-scale solid particles, similar to surfactant molecules, can be attached to planar or curved liquid interfaces. Their ability to stabilize bubbles and emulsions has received increased attention in recent years [1,2]. The first investigation of solid particles stabilizing emulsions was by Ramsden in 1903; then Pickering noted that particles more wetted by water than oil stabilized oil/water emulsions by residing at the interface [3,4]. Different aspects of foam stabilization by solid particles have been demonstrated during the last decade. The stability of bubbles and emulsions formed by solid particles is due to their accumulation at interfaces, minimizing contact area between two fluids. Compared to surfactants, solid particles can be adsorbed irreversibly at the interface between two fluids due to their high adsorption energy (almost 10 times that of surfactants). The factors that control the equilibrium and stability of solid the particle layer at the fluid/fluid interface are attributed to at least three aspects: electrostatic repulsion, van der Waals attraction between particles, and capillary attraction [1,2,5]. The detailed behaviors of nanoparticle-stabilized emulsions and foams have been well reviewed by Binks and Jameson [2,6].

With an in-depth understanding of and control over the mechanism at work in various particle-stabilized, two-phase systems, further development of such methods for industry application holds great promise. For instance, nanoparticle-stabilized foams and emulsions have gained a lot of attention for applications in enhanced oil recovery. Espinosa et al. reported that CO_2-in-water foams have been generated using silica nanoparticles without the aid of surfactants [7]. Shah selected metal nanoparticles for thermal conductivity enhancement of supercritical CO_2 by rapidly reducing the viscosity of heavy oil [8]. By modifying their surface coating, silica nanoparticles were used to stabilize both water-in-oil and oil-in-water emulsions for conformance control application [9]. Andrew et al. recently summarized that silica nanoparticles

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with 50% SiOH coverage generated stronger, more stable CO_2 foams compared to PEG-coated silica particles [10].

Varies types of nanoparticles such as latex, metal and silica, have been studied in detail, and the correlations among test conditions of particle concentration, brine salinity, temperature and emulsion properties have been determined [11]. In this paper, we describe the results of a study on liquid CO_2 foam generation with the aid of nanosilica particles. The effects of nanosilica particle surface hydrophobicity on foam generation and foam texture were investigated. Nanoparticle-stabilized CO_2 foam flow behaviors such as mobility and apparent viscosity were also studied.

2. Materials

Two kinds of silica nanoparticle powder, or nanopowder, were obtained from Sigma–Aldrich and Wacker Silicones, respectively. The silica nanoparticle from Sigma–Aldrich (abbreviated as AS-silica) was a nanopowder with an average diameter of 12 nm. The powder was dispersed in 2.0% NaCl to form a nanosilica dispersion, which was used as CO_2 foam stabilizer. The silica nanoparticles obtained from Wacker Silicones (AW-silica) were coated with dimethylsiloxy, with particle size around 10 nm. In addition, crystalline silica nanoparticles, (C-silica) were prepared hydrothermally in the laboratory [12]. The size of these C-silica particles was around 70 nm. Throughout this study, all the chemicals were purchased and used as received, and the gas cylinder of CO_2 was 99.9% pure.

3. Methods

3.1. Preparation of silica nanoparticle dispersion and measurement the particle hydrophobicity

The aqueous silica dispersions were prepared by mixing the silica nanopowder into 2.0% NaCl: the NaCl solution was placed in a high speed blender into which silica particles were added, then blended on high speed for 5 min, followed by an hour of sonication. This silica nanoparticle dispersion had an average particle size ~100 nm.

The silica nanoparticle hydrophobicity was determined by contact angle measurement (OCA 30, FDS Inc.). To measure the contact angle, several drops of the silica nanoparticle dispersion were dispersed on a glass slide and dried at room temperature. Then a water drop was placed on the modified glass slide. Using the CCD camera, the shape of the water drop was recorded and the image was analyzed using a software package from Dataphysics Company to estimate the air/water/nanosilica contact angle.

3.2. Nanoparticle stabilized CO_2 foam generation

The apparatus used to generate nanoparticle-stabilized, CO_2 foam is shown in Fig. 1. Two ISCO syringe pumps (model 260D) inject silica nanoparticle dispersion and liquid CO_2 into the glass beads-packed column. Three floating piston accumulators reserve nanosilica dispersion, liquid CO_2, and the effluent, respectively. Three TEMCO backpressure regulators (BPR) maintain the required operation pressure. The injected liquid CO_2 and the silica nanoparticle dispersion are mixed within the glass beads column by a strong shearing force. Pressure drop across the glass beads column is measured by a Honeywell 3000 differential pressure transducer connected to a Daq56 data acquisition system, which records pressure response with time. The mixture then flows out from the glass beads column into a capillary tube. The differential pressure across the capillary tube is measured by another differential pressure transducer. After leaving the capillary tube, the fluid flows into

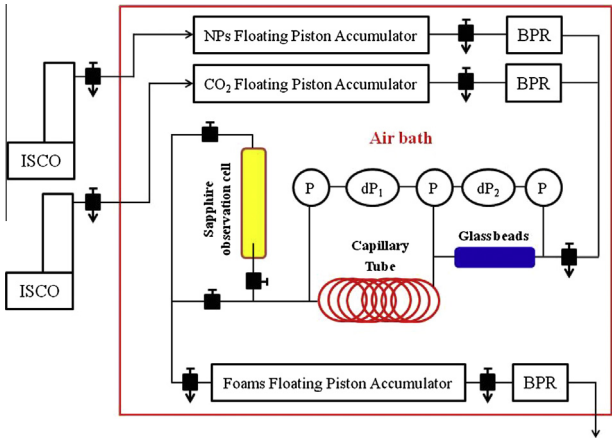

Fig. 1. Schematic diagram of dynamic foam generation and the mobility test setup.

the sapphire observation tube, which is designed for observing CO_2 foam morphology and foam bubble size. The entire apparatus, except for syringe pumps, is placed in an air bath to maintain a constant temperature throughout the experiment.

Foam generation and mobility measurements were conducted at 25 °C and 1200 psig. In order to evaluate the effect of silica nanoparticles on CO_2 foam generation and mobility reduction, a series of baseline experiments (base) were performed at various flow rates by simultaneously injecting CO_2 and 2.0% NaCl (without silica nanoparticles) into the glass beads column and capillary tube. Each baseline experiment was continued until a steady-state pressure drop across the glass beads column was achieved. Following the baseline experiment, the CO_2 foam generation experiments were performed by simultaneously injecting CO_2 and nanosilica dispersion into the glass beads column and capillary tube at flow rates and phase ratios similar to those used in the baseline experiments.

3.3. Characterization

3.3.1. Determine the mixture mobility

During CO_2 foam generation, a lab-made, glass beads-packed column was used to mix CO_2 and nanosilica dispersion to generate CO_2 foam. The properties of the glass beads column are listed in Table 1. The pressure drop across the column was used to estimate the total mobility of the CO_2/nanosilica dispersion (foam mobility). The mobility can be calculated by Eq. (1):

$$\lambda = \frac{\left(\frac{q}{A}\right)}{\left(\frac{\Delta p}{L}\right)} \tag{1}$$

where q is the flow rate of the fluids in glass beads column; A and L are the length and diameter of the glass beads column, respectively; and Δp is the pressure drop along the glass beads column.

3.3.2. Measurement of the mixture's apparent viscosity

After the CO_2 foam was generated in the glass beads column, it flowed into the capillary tube. The apparent viscosity of the CO_2 foam/CO_2 + brine in the capillary tube can be calculated from the

Table 1
Properties of glass beads packed column.

Length (inch)	3.94
Diameter (inch)	0.18
Porosity (%)	36.82
Pore volume (ml)	0.60
Permeability (D)	25.04