Measuring and modeling the behavior of a nanoparticle-stabilized CO_2-foam in porous media (PRF 57739-DNI9)

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1. Progress of the research. The second year of this grant was dedicated to: 1) complete a study on the generation of foam in the presence of particles and 2) validating with experiments the developed coupled model of foam and nanoparticle transport in porous media. A summary of the results from these two parts of the grant project is given herein.

1.1. Studying the generation of foam in the presence of nanoparticles using a microfluidic system. A study on the generation of foam in the presence of nanoparticles in porous media using microfluidics was performed (7). Drainage and co-injection tests were carried out and monitored with a high-speed camera. Convolutional neural network model was applied to quantify foam texture over time, efficiently and Figure 1 shows an example of the model performance.

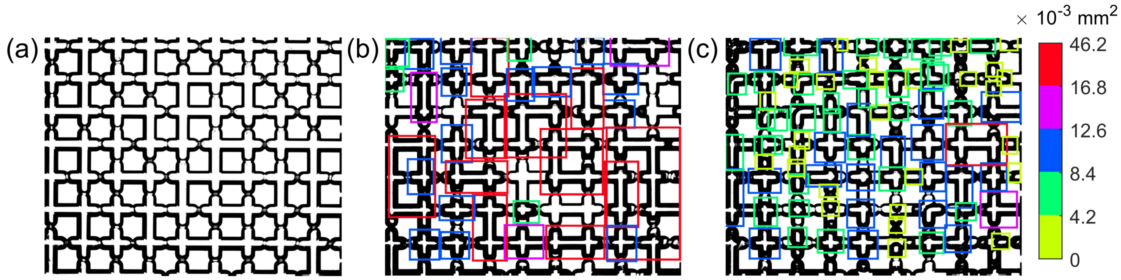

FIG. 1. *Bubble recognition using the CNN model in a microscopy image of the porous medium chip. (a) Chip saturated with surfactant solution without bubbles, (b) chip with surfactant solution and coarse foam, and (c) chip with surfactant solution and fine foam. Rectangular shapes represent the location and the size of the bubbles recognized by the CNN model and their color is related to their size.*

Processed microscopy images showed a generation process characterized by early snap-off, followed by lamella-division, and finally leave-behind. In the presence of nanoparticles, the latter stage was delayed due to resistance to drainage imparted by capillary forces within the liquid films. Following a previous experimental study, a relationship between the generation rate and pressure gradient was derived. It resembles the classical constitutive equation for foam generation (5; 2; 4; 3; 1), i.e., $r_g \propto \nabla P^{\alpha}$, indicating that the generation of a foam in the presence of nanoparticles and surfactant follows the same mechanism of a foam stabilized only with surfactant. From the modeling prospective this is important for the formulation of the constitutive equation of foam generation. It is suggested that classical constitutive equation for generation can still be regarded for a foam created in the presence of nanoparticles.

1.2. Measuring and modeling foam flow in the presence of nanoparticles and accounting for gas compressibility. A one dimensional (1D) set-up was built to carry out experiments of foam transport in porous media in the presence of nanoparticles. The nanoparticles and the surfactant were selected upon preliminary stability tests to identify the system where a synergistic behaviour of nanoparticles and surfactant could occur. Silicon dioxide nanoparticles (US3437, US Research Nanomaterials, Inc), produced by Laser Gas Phase Synthesis and CTAB (Cetyl Trimethyl Ammonium Bromide, Sigma-Aldrich) were selected for this study. Stability tests allowed to select the concentration of the materials in solution and the results are reported in Figure 2.

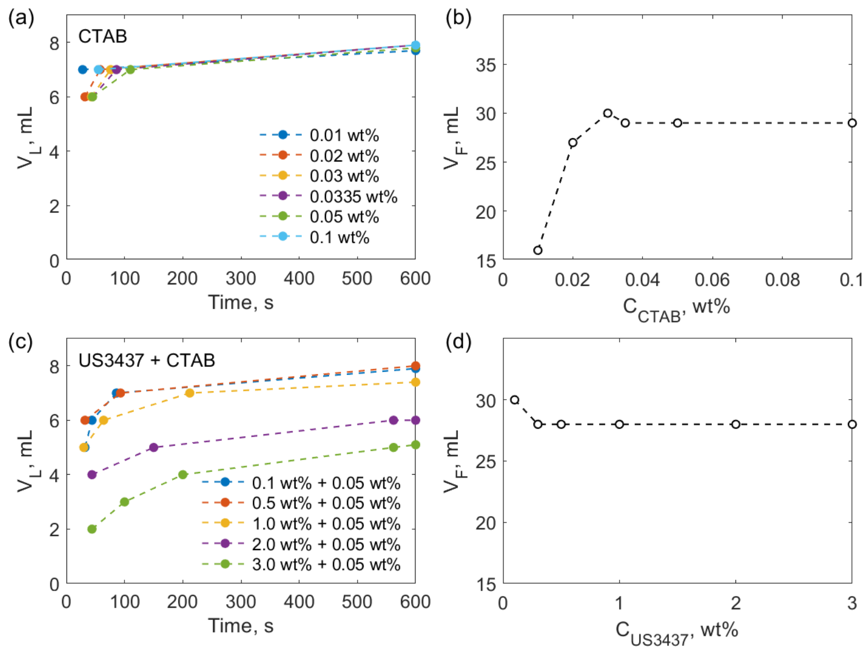

FIG. 2. *Volume of the liquid phase over time and initial foam volume for a given surfactant solution.*

The 1D set-up is schematically reported in Figure 3. It consists of a piston pump (Cole-Parmer, U.S.A.), two pressure transducers (P61, Validyne Engineering, U.S.A.), a gas-flow controller (F-210CV, Bronkhorst, U.S.A.), and two columns (Cole-Parmer, U.S.A.) packed with glass particles (430–600, μm, P-0230, Potters Industries). The pressure transducer monitors the pressure drop through each column while the fraction collector collects the effluent for the column. Nitrogen gas (99.99 % purity, Welding Supply, U.S.A.) is injected into the columns to generate foam. UV-Vis (Cary 60, Agilent) is used to determine the concentration of nanoparticles in the effluent.

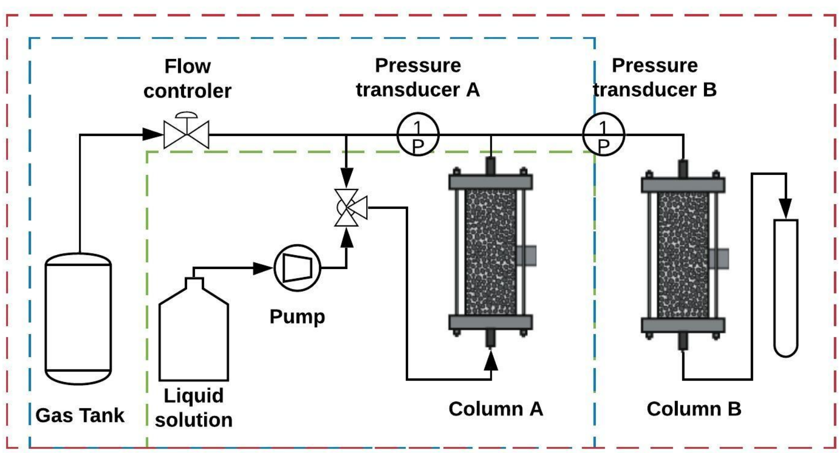

FIG. 3. *Schematic diagram for the developed 1D set-up. Components indicated by the green dash line are applied for nanoparticle transport experiments while devices covered by the blue dash line are used to study the foam generation. Nanoparticle delivery will need each component shown in the scheme.*

Moreover, our earlier model (6) has been extended to account for the compressibility of the gas phase as it has been observed to be a dominant behaviour during the 1D tests.

Experiments and modeling are still ongoing and an article is in preparation for the journal Water Research.

2. Impact of the research on the career of the PI and student involved. Two manuscripts were published in the second year grant period:

1. Li, Q. and Prigiobbe, V. (2019). Studying the generation of foam in the presence of nanoparticles using a microfluidic system. In press in *Chemical Engineering Science.* https://doi.org/10.1016/j.ces.2019.115427.
2. Li, Q. and Prigiobbe, V. (2019). Modeling nanoparticle transport in porous media in the presence of a foam. *Transport in Porous Media*, https://doi.org/10.1007/s11242-019-01235-9.

Moreover, the PI and the PhD student presented their work at the international conference on porous media Interpore hold in Valencia, Spain, May 6–10, 2019:

1. Title of the oral presentation: Studying the generation of foam in the presence of nanoparticles using a microfluidic system.
2. Title of the poster presentation: Modeling nanoparticle transport in porous media in the presence of a foam.

References.

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[6] Q. Li and V. Prigiobbe, *Modeling nanoparticle transport in porous media in the presence of a foam*, Transport in Porous Media, (2019).

[7] Q. Li and V. Prigiobbe, *Studying the generation of foam in the presence of nanoparticles using a microfluidic system*, Chemical Engineering Science, (2019), p. 115427.