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Mapping of foam mobility in porous media

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Abstract

We report an experimental study of the motion of foam in granular porous media using X-ray Computed Tomography. The experiments consist of the co-injection of nitrogen and a surfactant solution in natural sandstone to generate foam. When foam reaches the steady-state flow regime, we replace a fraction of nitrogen by a tracer gas with a high X-ray absorbance (Xenon). This enables us to map out the local foam mobility distribution with a high spatial resolution. The rate of change of tracer concentrations enabled us to separate the convection and dispersion effects of the tracer. The foam mobility distribution is non-uniform, contrary to current belief, and depends strongly on the flow rates of liquid and gas. In vertical experiments, foam mobility increases from the center to the boundary. Within the flow domain, the trapped foam fractions range from 15 and 67% depending on gas and liquid flow rates. Foam seems to be less mobile towards the outlet, consistently a stronger foam development.

Keywords: Foams; Porous media; Permeability reduction; Mobility distribution; Stationary gas; X-ray Computed Tomography; Tracer gas

1. Introduction

Foam is one of the more widely used mobility control and profile correction agents in oil and gas recovery operations. In the last three decades, many oil recovery applications relied successfully on foam. A brief list of such applications includes enhanced oil recovery (EOR), acid diversion during matrix acidizing and gas blocking. In order to meet the growing demand of more difficult foam applications, especially for EOR purposes, more efforts are needed to gain a deeper insight on the physics of foam flow in porous media. This work is concerned with a more detailed description and quantification of local foam mobility and gas trapping during steady-state foam flow.

The rheology of foam in porous media depends critically on the bubble density and the fraction of gas trapped in the pores; bubble density, together with the bubble size distribution, are sometimes referred to as foam texture. The resistance of foam films to flow depends critically on bubble density. On the macroscopic level, the bubble density accounts for the high (apparent) viscosity of foam. The trapped gas, on the other hand, reduces greatly gas relative permeability by blocking a large fraction of flow channels. Foam mobility, i.e. the ratio of gas partial permeability to apparent gas viscosity, conceals the subtle interplay of these two factors (i.e., apparent viscosity and gas trapping). Many past studies relied on the macroscopic foam mobilities measured during foam core flooding to find the relation between

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foam texture and rheology. They used flow measurements to study indirectly the gas-trapping phenomenon.

Bernard, Holm and Jacobs (1965) among others estimated trapped gas by displacing foam flowing at the steady state in with distilled water in sand packs. However, this technique actually determines a "trapped gas fraction" induced by the injected water, which is rather different from that associated with foam flow. Nguyen et al. (2003) and Zitha et al. (2003) showed with the aid of X-ray Computed Tomography that liquid injection modifies the gas trapping pattern and thus strongly influences the related pressure-gradient. In another CT scan study with carbon dioxide (CO_2) foams. This study will focus on the mapping foam mobility using a special X-ray gas tracer with a much lower solubility in water than CO_2.

Several authors determined the trapped gas fractions with almost undisrupted foam local flow patterns using gas tracer technique. Nahid (1971) appears to be the first to use this approach. He determine trapped foam fraction during the steady-state flow of helium foam in Berea sandstone, by displacing the native foam with foam made with 20% methane and 80% helium. Therefore methane plays the role of the tracer and, with no changes in foam properties and flow conditions, he could assume that the local foam structure was unperturbed. From an analysis of the concentration profile of the tracer (methane) at the effluents, neglecting the mass transfer of tracer from flowing foam into trapped gas, Nahid estimated that about 32% of pore volume contained stationary gas. Later, Friedmann et al. (1991) used 20% krypton as the tracer gas to determine the steady-state trapped gas fraction during nitrogen foam flow in Berea sandstone. They reported highly asymmetric effluent tracer profiles, suggesting a significant diffusion of tracer into the stationary gas and, although more unlikely, into the liquid. To increase the accuracy of the determination of trapped gas fractions from effluent concentration profiles, Radke and Gillis (1990) developed a model for the transport of the gas tracer during foam flow in porous media. Fitting the model to the concentration profiles of dual tracer gases (hexafluoride sulfur and methane) in nitrogen foam determined at the outlet of a Berea core, the authors found large amounts trapped gas (ranging from 72 to 99%), which increased with liquid fraction. They also stressed the importance of the partitioning of tracer into the stationary and the gas phases by diffusion, but ignored the resistance of the foam films to that diffusion. Nguyen et al. (2002) reported recently a study of the permeability of foam films showing to tracer gases showing that foam films greatly resist tracer diffusion. This supports the idea of little tracer transfer to trapped gas used by Nahid in the analysis of effluent profiles. Nguyen (2003) presented experiments and rigorous analysis of tracer transport during foam flow in transparent microflow models. However, these authors found that bubble trapping and remobilization, even in the steady-state regime, severely distorts the effluent concentration profile. Hence, it is hard to extend these results to three-dimensional case. The knowledge of in-situ foam mobility patterning remains crucially needed for describing mechanistically foam behavior.

The purpose of this paper is to develop a method for determining directly local foam mobilities from which we can derive directly the trapped gas fraction. In our experiments, we map the distribution of the local mobility during steady-state nitrogen foam flow in sandstone cores, using the X-ray Computed Tomography (CT) imaging. The gas tracer used in the experiments is Xenon gas (Xe), with a high X-ray absorption. This enables us to track the mobile foam, and thus estimate the trapped foam fraction. Besides the dynamics of gas trapping process, we also use this method to examine the diffusion of the tracer across trapped foam domain. This will demonstrate how foam modifies the convection-dispersion of the tracer gas. This article has the following structure. Section 2 describes in detail the principle and procedure of the method. Section 3 begins with the attenuation of tracer mixture on X-rays for different Xenon concentration and homogeneous sandstones. It continues with the visualization of Xenon propagation in the absence and presence of foam in vertical sandstone cores. This quantifies the quasi-stationary foam and its sensitivity to fluid rates. Important implications of the results and conclusions complete the article.

2. Experimental

2.1. Principle

Consider a parallel beam of X-ray photons with sufficient small width propagating through a slab of porous rock, which confines mobile and stationary nitrogen foams at the quasi-steady state. The slab is virtually divided into regular voxels (i.e., a voxel is a three dimensional pixel including the slab width) whose size is sufficiently small so that they can represent the variation in properties of the slab. The incident beam attenuates due to photons either being absorbed by the atoms of the materials (core-holder materials, rock, surfactant solution and gas), or being scattered away from their original directions of travel. These effects are customarily evaluated together through a single coefficient, $\hat{\mu}$,