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Improved sweep efficiency due to foam flooding in a heterogeneous microfluidic device

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ABSTRACT

In this work, the flow behavior of foam and its impact on mobility control in displacing oil are investigated using a glass microfluidic device comprising a complex heterogeneous porous medium. The medium, fabricated with a centrally located low permeability zone and two high permeability zones on its sides, is initially saturated with crude oil. A blend of surfactants are used to stabilize CO_2 foam in the presence of crude oil. Flow behavior in the microfluidic device is captured using a high-resolution camera. Foam is able to mobilize and recover oil trapped in the low permeability zone by increasing the resistance to flow in the high permeability zones and diverting the surfactant solution into the adjacent low-permeability zone. Foam remains gas-rich in the high permeability zones and solvent-rich in the low permeability zone throughout the experiments. The observed displacement dynamics are explained by characterizing channel geometries and calculating capillary entry pressure values for various fluids and zones of the medium.

1. Introduction

Flow instabilities are caused by heterogeneities and unfavorable contrasts of viscosity and density between the resident and displacing phases, and often lead to poor sweep efficiencies in enhanced oil recovery (EOR) (Aryana and Kovscek, 2012; Furtado and Pereira, 2003). The displacing fluid may flow through high-permeability zones and bypass trapped oil in adjacent low permeability zones in heterogeneous porous media (Ma et al., 2012). The resulting low sweep efficiency is a primary concern in many heterogeneous reservoirs (Gulick and McCain, 1998). Foam injection has the potential to improve sweep efficiency by increasing the viscosity of the displacing fluid and lowering the mobility ratio (Guo and Aryana, 2016). Experimental observations suggest that foam is generated in high permeability zones initially, then diverted into low permeability areas, thus improving the sweep efficiency (Fernø et al., 2016). Several laboratory experiments have shown that foam acts as a blocking agent, delaying and redirecting the transport of chemical solutions in heterogeneous porous media (Conn et al., 2014; Shi et al., 2015).

Microfluidic devices have been used to study the behavior of fluids inside microstructures in EOR to observe flow behavior within the micropore network (Karadimitriou and Hassanizadeh, 2012b). Insights into microscale displacement processes help elucidate fundamental mechanisms responsible for the observed flow behavior (Quennouz et al., 2014). Micromodel experiments are often conducted using homogeneous porous media, which do not address the mechanisms responsible for fluid diversion in heterogeneous systems at the pore scale (Muggeridge et al., 2014) (Riche et al., 2014). In many heterogeneous microfluidic devices used in flow experiments, the porous media consist of cylindrical or rectangle pillars with different radii and spacing (Conn et al., 2014; Jeong and Corapcioglu, 2003; Ma et al., 2012; Sayegh and FIisher, 2009). Even though such a geometry does create a porous medium, it does not resemble the complexity of network of channels encountered in subsurface reservoirs. Microfluidic devices featuring complex networks of channels with rigid walls would be useful to simulate real reservoir conditions (Mijatovic et al., 2005). The material used in the fabrication of the microfluidic device may limit its use. For instance, PDMS based devices may suffer from swelling, undergo property changes with time, deform under moderate pressures, or experience dissolution due to exposure to several common solvents (Karadimitriou and Hassanizadeh, 2012a; Karadimitriou et al., 2014; Lee et al., 2003; Whitesides, 2006). Glass based devices do not suffer from these limitations (Liu et al., 2016; Sayegh and Fisher, 2008).

This work aims to demonstrate that, in heterogeneous porous media, capillary entry pressure in conjunction with apparent foam viscosity is responsible for mobility control effects of foam and the resulting improved sweep efficiency. The experimental program uses a

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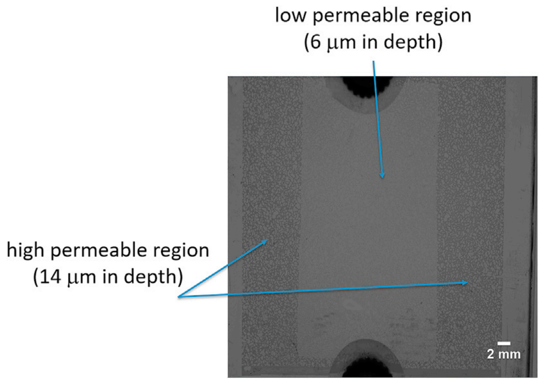

Fig. 1. Image of the heterogeneous microfluidic device.

microfluidic device comprising a porous medium featuring a two-dimensional representation of a sample of a Berea sandstone (Guo et al., 2017), where, due to differential depth, the medium includes a central low permeability zone abutted on both sides by relatively high-permeability zones. A high-resolution achromatic camera is used to capture images during dynamic displacement experiments; the high resolution affords the possibility of viewing the medium in its entirety and being able to discern features as small as 10 µm. Flow behavior of water and foam in the heterogeneous porous medium is observed at various flow rates, and sweep efficiency in the oil saturated medium as a result of water and foam injection is investigated. Capillary entry pressure (CEP), which is the critical pressure drop that must be overcome to drive a given fluid inside a pore space (Conn et al., 2014; Hui and Blunt, 2000), is calculated for each permeability zone and the relevant fluids based on the geometry of the channels in the porous medium. Contributions of high and low permeability zones to overall oil recovery are evaluated, and displacement mechanisms in the heterogeneous porous medium are discussed in the context of the observed behavior.

2. Materials and methods

2.1. Design and fabrication of microfluidic device

The pore network is based on work by Alaskar (2013), where in a binary image of a thin section of a Berea sandstone, pore bodies are connected such that the final image honors the pore size distribution of the sandstone (Alaskar et al., 2013). The porous medium is approximately 1.6 inches × 1.4 inches and comprises two high permeability and one low permeability zones. The low permeability zone is positioned in the middle of the device (Fig. 1), and the two high permeability zones are positioned on the sides of the low permeability zone. The sum of the areas of the two high permeability zones equals that of the low permeability zone. Channels vary in width from 5 to 100 µm and have a uniform depth of approximately 14 and 6 µm in the high permeability and low permeability zones, respectively. The porosity of the low permeability zone is approximately 34% and the high permeability zones have a porosity of approximately 43%. The permeability contrast between the high and low permeability zones is approximately two (0.28 Darcy versus 0.13 Darcy).

The pore network is etched on a Borofloat wafer (2 inches × 2 inches x 0.12 inches) using a standard photolithography technique (Fan and Harrison, 1994). Different permeability regions are created by varying the exposure time of the substrate to the etchant (BD Etchant, TRANSENE). Channel geometry is characterized using a 3D laser measuring microscope (LEXT OLS4000 Olympus). Inlet and outlet ports are created in a blank Borofloat wafer, and the etched substrate is thermally bonded to the blank Borofloat cover plate at 640 °C. NanoPort connections (IDEX N-333) are glued (Loctite Epoxy) on the inlet and outlet ports.

2.2. Experimental setup and procedure

A syringe pump (Harvard Apparatus PHD ULTRA™ 4 400) is used for liquid injection and an ISCO pump (100D TELEDYNE ISCO) is used for foam generation. A crude oil (Gullfaks Blend, 45.9 cp and 0.9029 g cm^{-3} at 20 °C) is used as the resident fluid and 30,000 ppm sodium chloride (Sigma Aldrich) brine is used as the displacing fluid. At the conclusion of each displacement experiment, the microfluidic device is cleaned by flushing the medium with 10 pore volumes (PVs) of deionized water (DI water, Nanopure II, Barnstead, Dubuque), toluene and ethanol in series. The medium is restored to a fully oil saturated condition by flushing the medium with 20 PVs of crude oil and the medium is aged overnight.

A 1000 ppm 1:1 mixture of lauramidopropyl betaine (Rhodia Co) and alpha-olefin sulfonate (Stepan Co) in DI water is used as the surfactant solution and CO_2 (research grade, United States Welding, USA) is used as the gas phase in all experiments. Foam is generated inside the microfluidic device by injecting carbonated water through a tube with an inner diameter of 25 µm. A 40 ml accumulator is used to prepare the carbonated water solution by mixing CO_2 gas under 200 psi and 30 ml surfactant solution. Temperature is controlled by a circulator at 0 °C, and an ISCO pump (100D TELEDYNE ISCO) injects water in the bottom of the

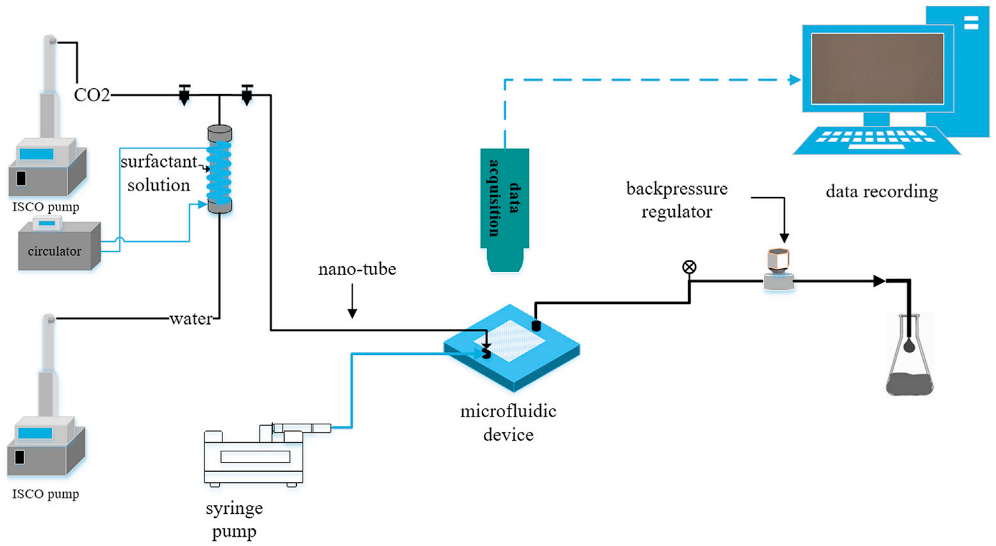

Fig. 2. Schematic illustration of the microfluidic experiment set-up.