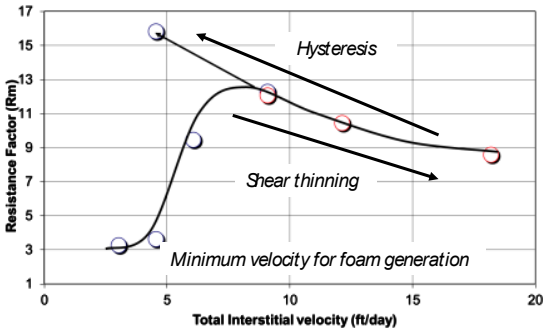
Reducing CO_2 flow using foam and gel-foam

Foams are commonly used during EOR operations both for conformance improvement and in-depth gas mobility control, with varying success. For the use of foams as gas flow blocking agents, the foam emplacement and its resistance to gas flow as well as its durability and stability are of the utmost importance for the efficiency and economics of the process. In the present context, we expect to use foams as a blocking agent to secure a CO_2 storage or limit the CO_2 flow rate at a given location.



Dense CO2 , 40°C, 130b,

Figure 1: Typical behavior of foam when increasing the total interstitial velocity. An hysteresis may occur with decreasing velocity, yielding higher resistance to gas far from the well (Nabzar, 2014, ADRAC, Abu Dhabi).

Two categories of foams are usually distinguished: "weak foams" and "strong foams" and the transition between these two types is often abrupt and requires a minimum pressure gradient or a minimum critical velocity . Weak or coarse foams induce only low resistance to flow (low gas mobility reduction factor, or MRF) while strong foam leads to much larger resistance to flow (with non-dense gas like N_2 the induced MRF can reach values greater than 1000). For CO_2, the mobility reduction factor is usually much lower and the maximum attainable value decreases rapidly with CO_2 density. With supercritical dense CO_2 it was inferred from laboratory studies using classical foaming agent that probably only coarse foams-emulsions could be formed. However, from recent studies, gas mobility reduction factors as high as 25 could be obtained indicating the formation of strong foams. The objective of the laboratory work underway is to determine the CO_2 foam properties in terms of mobility reduction factor on typical porous media representative of CO_2 storage. Because foams may have a limited lifetime, it is also proposed to study the generation of CO_2 gel-foams. For the latter, we will use a gel formulation tested in another work package.

We use two experimental setups to study foams: low and high pressure to represent non-dense (gaseous) and dense CO_2–brine systems. Both consist in co-injecting CO_2 and brine in which a surfactant is added. In the low pressure system, we follow the water saturation (average and longitudinal profile) using a Magnetic Resonance Imaging (MRI) system. In the high pressure

system, an X-ray system is used to monitor the water saturation in a similar way. We show here some results using the MRI system.

In the experimental set-up used in this study, brine and CO_2 are co-injected at the top inlet face of the sample (Figure 2). The liquid and gas flow rates are respectively imposed using a pump and a gas controller, and the outlet pressure imposed by a membrane back-pressure regulator. During injection, we continuously measure by standard MRI techniques the saturation profiles and the T_2 relaxation time distributions typically every minute. The flooding cell is custom built and specifically designed for MRI systems (sample diameter 20 mm, maximum sample length 50 mm, NMR probe diameter 30 mm, maximum confining pressure of 80 bar, temperature 30°C). A typical experiment consists in first co-injecting brine and gas, then brine is replaced by a solution of the same brine but containing a surfactant (in this case a classical AOS type surfactant with concentration 0.5 wt%). We vary the total flow rate Qt by a factor of 100, from 1 cc/h up to 100 cc/h, corresponding in this case to interstitial velocity $v=Qt/S\phi$ between 1.6 and 160 cm/h, or between 0.3 and 30 ft/day in usual engineering units. Another experimental variable is the volumetric gas to total flow rate ratio f_g, typically from 0.4 up to 0.9.

We first focus in this brief document on the onset of foam at the lowest flow rate (1 ml/h or 1.6cm/h, Figure 3). The sample is a Clashach sandstone of porosity 20.2% and permeability 1550 mD. The sample was used for several foam experiments before this one and therefore adsorption of the surfactant on the solid surface is stabilized. A foam generating a strong pressure drop is only observed when the water saturation is low enough (~15%), corresponding to high capillary pressure close to irreducible water saturation (Figure 3). This is achieved after a few pore volume (Figure 3). Then, at a nearly constant water saturation and during a few pore volume, a strong foam is abruptly formed as indicated by the sharp increase of the pressure drop at t= 6.2 hr. Interestingly, the saturation profiles (Figure 4) are nearly uniform for strong foams and this uniform profile is gradually achieved starting from the middle of the sample.

Recorded pressure drops for different total interstitial velocities are shown in Figure 5. Typically, for a given flow rate, pressure and saturation are measured during at least 5 pore volumes. For increasing flow rates, a smooth increase of the pressure drop is not observed for unclear reasons. We note that the differences of pressure drops between increasing and decreasing velocities differ also in terms of saturation. Also, at v=75 cm/h, the pressure drop obtained for increasing velocities has larger fluctuations. Finally, the mobility reduction factor is calculated as the ratio of the measured pressure drop to the one in single phase flow conditions at the same flow rate:

$$MRF = \frac{\Delta P_{foam}}{\Delta P_{water}} = \frac{\mu_{foam}}{\mu_{water}} = 4648 v^{-0.94}$$

With this definition, MRF corresponds to the ratio of the foam apparent viscosity to the water viscosity. It varies between 47 and 2946 and can be modeled using a power law in which an exponent close to -1 is found. This means that the pressure drop is nearly independent of the flow rate for the conditions studied here.

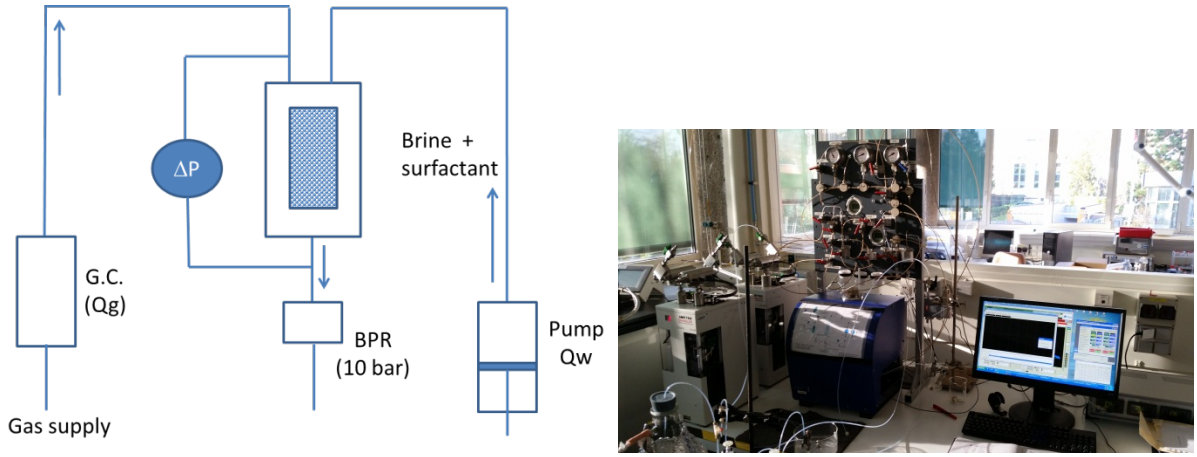


Figure 2: Schematic of the experimental set-up using NMR imaging. Gas controller (G.C.): controller to impose a fixed gas flow rate. Back pressure regulator (BPR): used to set the outlet pressure. The MRI system is a 20 MHz compact permanent magnet system from Oxford Instrument.

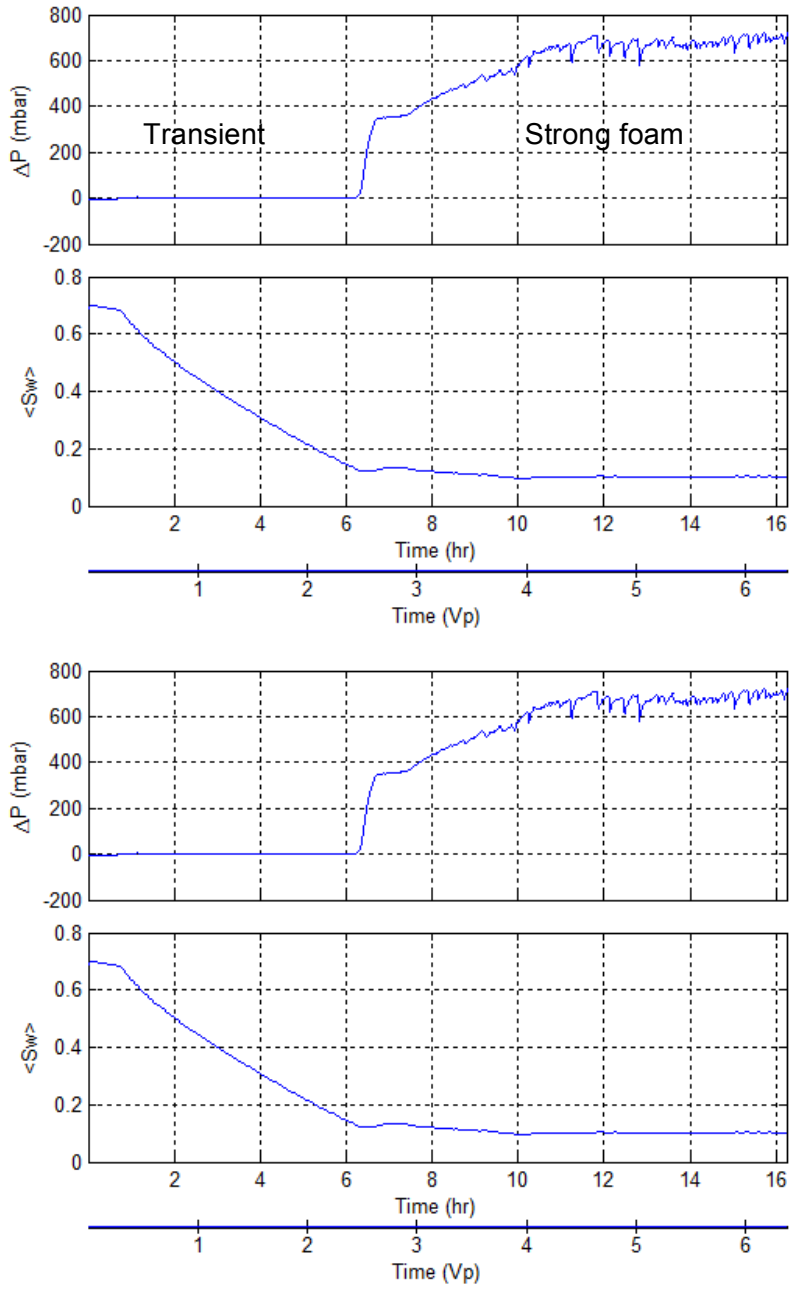


Figure 3: Generation of foam at a low interstitial velocity (1 ml/h, 1.6 cm/h). See text for explanation. Clashach sandstone, porosity 20.2%, 1550 mD, f_g=0.6, brine 35 gr/l, AOS type surfactant concentration 0.5 wt%.

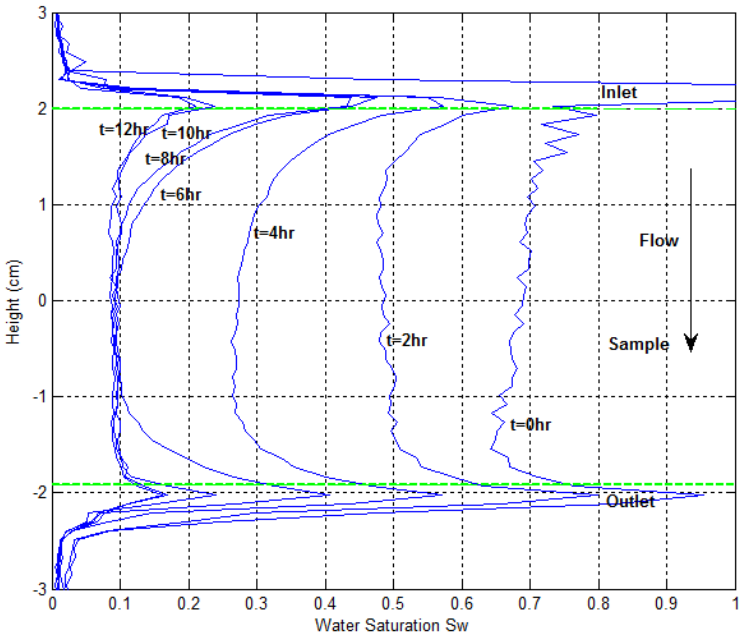


Figure 4: Local saturation profiles corresponding to figure 3 at different times. At t=6 hr, a strong foam is present. The spikes at the inlet and outlet correspond to the liquid present in the injectors. The average saturation is calculated with the values between the green horizontal lines.

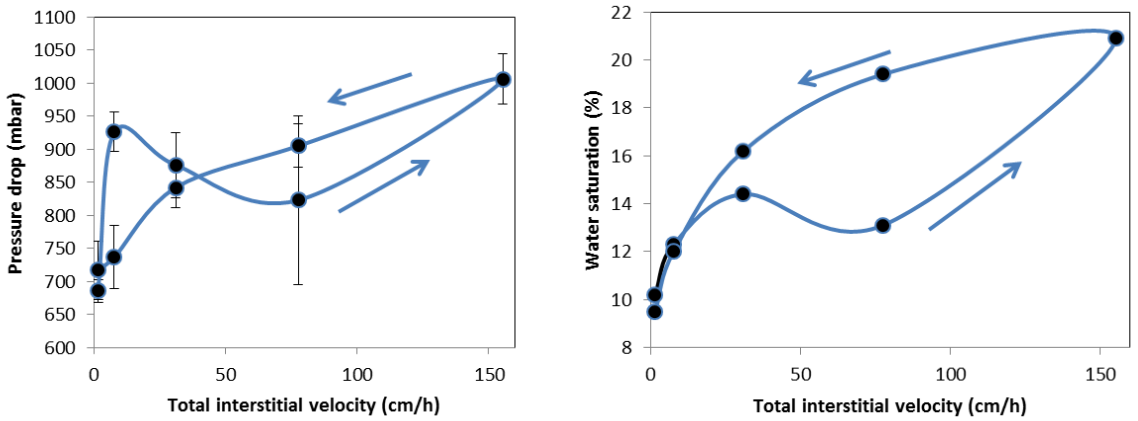


Figure 5: Measured pressure drops and average saturation for different increasing and then decreasing interstitial velocity, fg=0.6. The pressure fluctuations (variance) are indicated by the bars (they are not error bars).

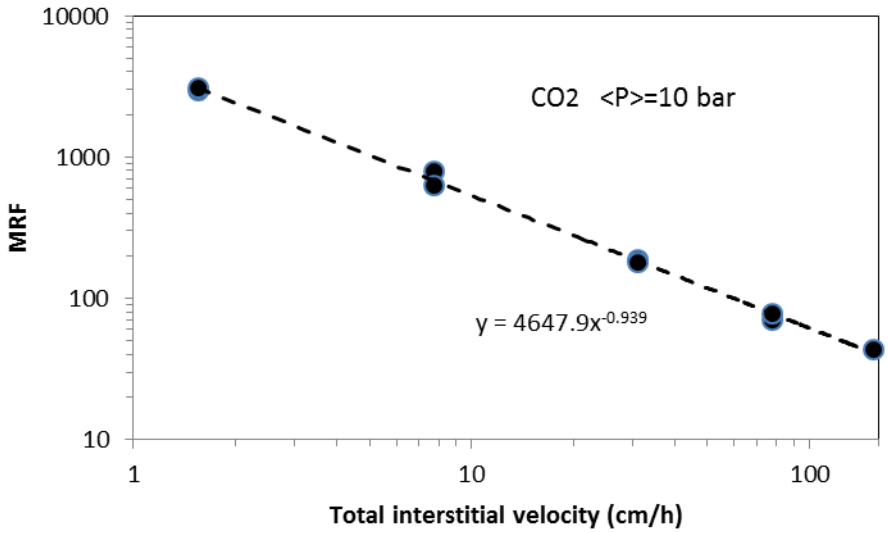


Figure 6: Mobility Reduction Factor (MRF) for a CO_2 foam experiment on a Clashach sandstone of permeability 1550 mD and porosity 20%. MRF values are calculated using data from figure 5.

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