1 Capillary number and pressure drop

We agree with reviewer's comment that if the measurement of the gas-water relative permeability is not done in a condition that the viscous forces are not dominant, the measured relative permeability curve is not unique and by increasing the pressure gradient, a lower residual water saturation can be obtained. It is indeed the case for the gas-water core flooding experiments. However, the pressure gradient in the gas-water experiments is a few orders of magnitude higher in presence of foam. This is in fact one of the conclusions of Reynolds and Krevor [2]: "We demonstrate that, if measured in the viscous limit, relative permeability is invariant with changing reservoir conditions, and is consistent with the continuum-scale multiphase flow theory for water wet systems". Table 1 shows the measured pressure drops in our core flooding experiments, which are also plotted in Fig. 4. At high gas fractional flow (f_g, also called foam quality) the flow of foam is controlled by the generation/collapse of foam bubbles due to high capillary pressure. It is only the behavior of the bubbles and it does not mean that the flow is capillary-dominated. During the core flooding in this regime, we measured the pressure drop and average water saturation in different times, which is shown in Fig. 1. It can be seen that both the pressure drop and the liquid saturation fluctuate with time, which results in a relatively large uncertainty in the measured saturation. However, a very small fluctuation was observed for the measurement in the low gas fractional flows (see Fig. 2). Moreover, at the low gas fractional flow the measured pressure drops for different surfactant concentrations are in the same range.

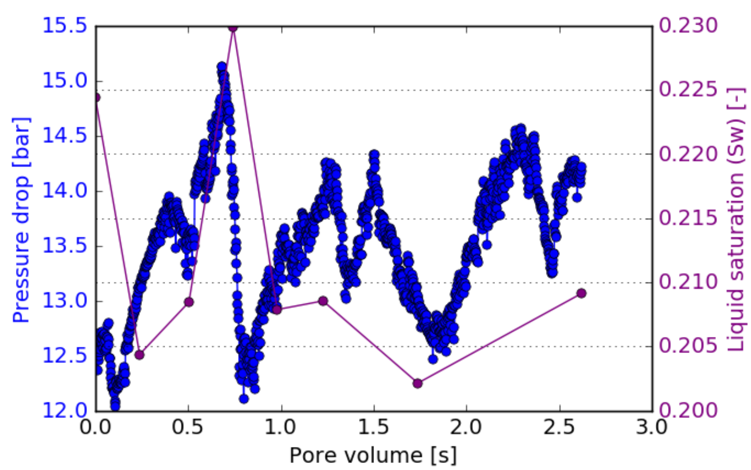

Figure 1: Pressure drop and water saturation after switching from f_g=0.6 to f_g=0.9, versus number of pore volumes of fluid injected into the core. High degree of fluctuation is observed at high fractional flow.

For the above reasons, we do not use the measurements in the high gas frac-

Table 1: Pressure drop measurements in the core flooding experiments; part of the experimental data for 0.5wt% AOS (shown in blue) is obtained from an experiments conducted in the same set-up but without CT scan measurements.

0.03wt% AOS		0.03wt% AOS		0.5wt% AOS	
f_g	Δp [bar]	f_g	Δp [bar]	f_g	Δp [bar]
0.692	4.284	0.672	13.436	0.881	13.300
0.594	3.644	0.892	8.868	0.905	13.328
0.386	6.970	0.476	10.277	0.715	11.179
0.490	5.559	0.892	8.923	0.934	18.122
0.900	1.807	0.573	12.085	0.975	10.504
0.697	2.917	0.778	14.141	0.214	8.210
0.189	8.454	0.949	3.060	0.316	8.915
0.090	7.468	0.725	14.366	0.417	9.615
0.799	2.221	0.836	11.432	0.515	10.570
0.285	8.759	0.096	5.616	0.611	11.645
		0.382	8.832	0.707	12.825
		0.624	12.747	0.804	14.030
		0.191	6.954	0.902	13.860
		0.980	1.608	0.953	9.735
		0.286	8.066	0.982	5.155
		0.048	4.830		
		0.827	13.444		

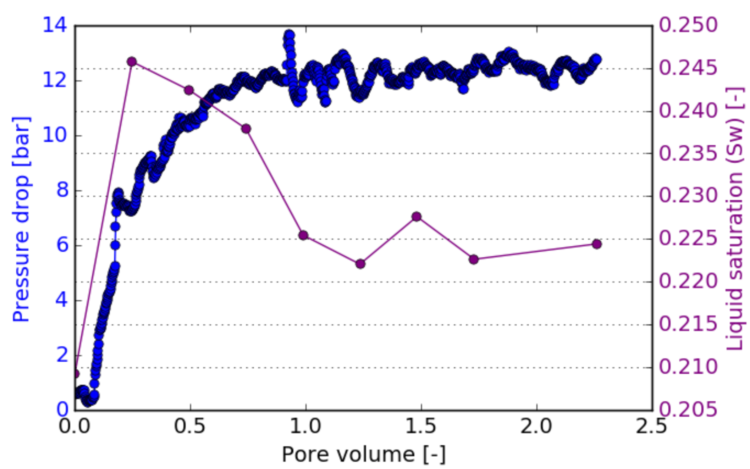

Figure 2: Pressure drop and water saturation after switching from f_g=0.99 to f_g=0.6, versus number of pore volumes of fluid injected into the core. A low fluctuation is observed at the low fractional flow.

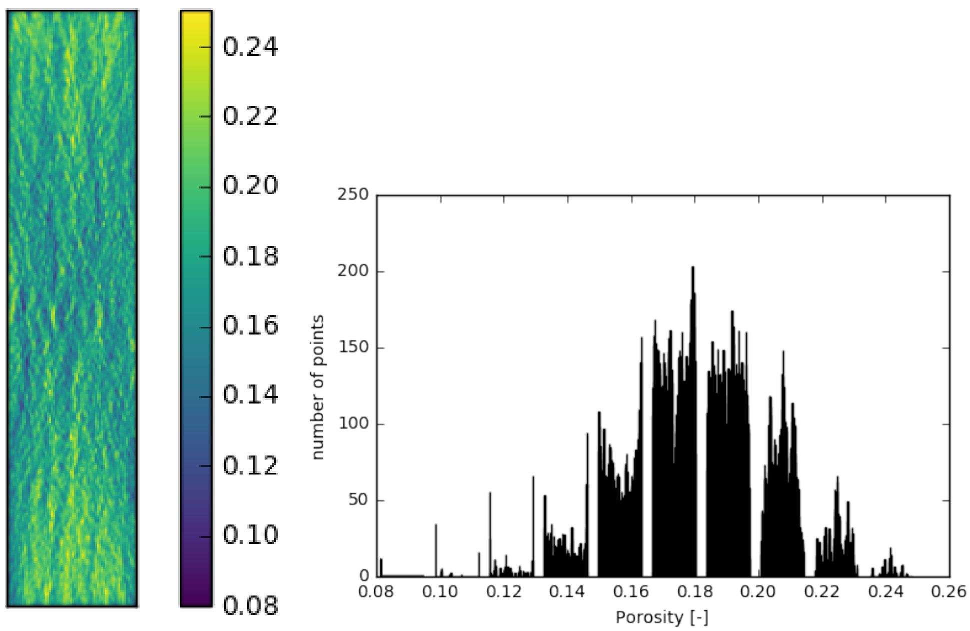

Figure 3: Porosity profile for a cross-section of the bentheimer core

tional flow regime for the estimation of the water relative permeability curves. In fact, we only use the data for low gas fractional flow (low quality) regime, at which the capillary pressure is lower and the flow of foam is dominated by the mobilization and trapping of bubbles.

The calculated capillary number, using the following equation from Reynolds & Krevor,

$$N_c = \frac{H}{L}\frac{\Delta p}{\Delta p_c}, \tag{1}$$

is plotted versus the measured liquid saturation in Fig. 5. For the relatively homogeneous core in our study (see the porosity profile in Fig. 3), we use a Δp_c of 5000 Pa, which is arguably larger than the actual value of the critical capillary pressure difference. The points depicted with gray markers show the data for the high gas fractional flow regime. The colored points show the data for the low gas fractional flow regime. It is clear from this figure that at a constant capillary number, the measured liquid saturation changes with the surfactant concentration. This shows that our measurements that are used in the calculation of the water relative permeability are not affected by the capillary-viscous force interplay.

As the reviewer has pointed out, reporting these values could have made it clear. Therefore, we decided follow the points raised by the reviewer and add a short appendix to the paper with the above analysis.

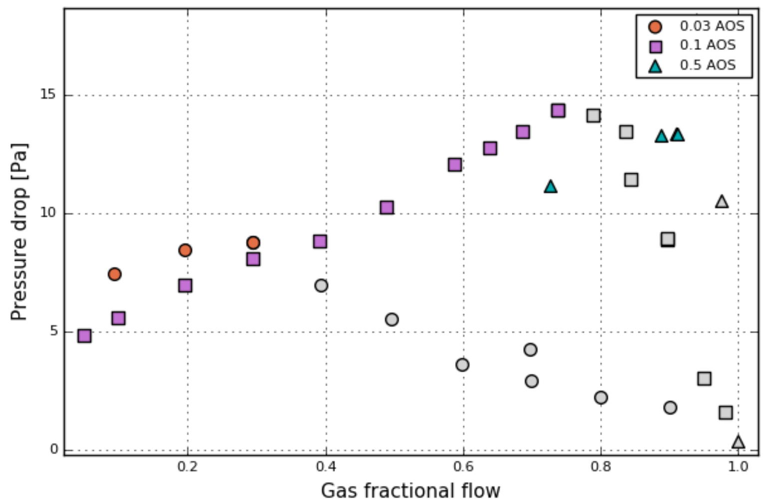

Figure 4: Measure pressure drop at different gas fractional flow for a constant total flow rate of 1 ml/min in a Bentheimer sandstone (φ=0.18, k=2.41$\times 10^{-12}$ Darcy); the light gray markers show the high quality foam regime.

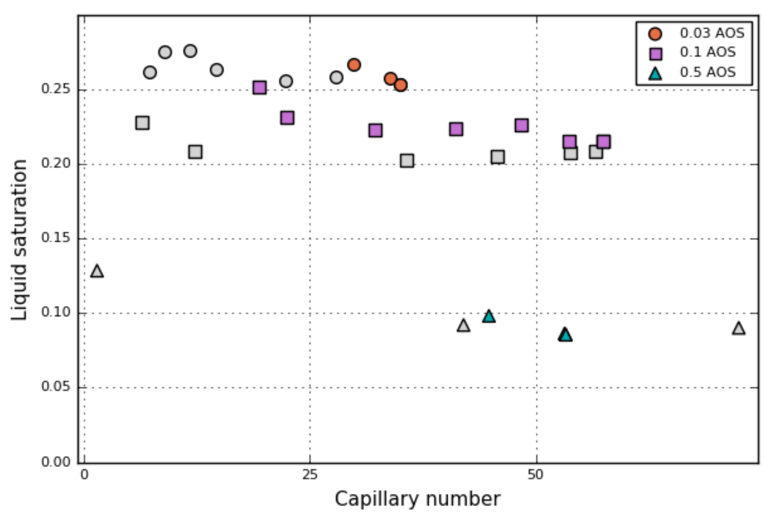

Figure 5: Measured saturation in the core flooding experiment versus capillary number at different AOS surfactant concentrations

2 Water-gas rel-perm in absence of surfactant

The fact that the relative permeability in the absence of surfactant needs to be measured at a high pressure gradient is pointed out by reviewer 1 and reviewer 2. The measurement that we have reported in the paper was not performed in our lab, but in a service company on a core sample from the same Bentheimer block on the request of one of our former colleagues at TU Delft. We did not study the data carefully and simply reported it in our work. After receiving the comments, we contacted the service company for more information and it turned out that the measurement is done in a core flooding experiment and the saturation is measured by monitoring the weight of the core holder. This experiment is, by no means, adequate. Therefore we removed the data from the manuscript, and replaced it with data from the literature [2]. Consequently, we slightly amend the manuscript and the conclusions accordingly. All the changes are shown in the revised manuscript with a different color.

Nevertheless, the main conclusions of the manuscript does not change as discussed in the next section.

3 Effect of *fmdry* on the foam model behavior

The main discussion of the paper is that the liquid relative permeability changes with different surfactant concentration, which includes zero surfactant, i.e., water-gas relative permeability. Unfortunately we don't have experimental data to support the last claim, which is clarified in the manuscript.

Reviewer 1 has raised a very relevant point: the water relative permeability in the absence absence of surfactant should be measured at a pressure gradient similar to the pressure gradients in presence of surfactant, e.g., in a centrifuge. What we would like to add is that the measured relative permeability in a centrifuge is still not enough to model the flow of foam in porous media, particularly in predicting the water saturation that can only be predicted by introducing a residual water saturation that is a function of the surfactant concentration.

To demonstrate the above claim, we tried to use a single water-relative permeability and fit the foam model to the pressure gradient data for different surfactant concentrations. As stated by reviewer 1, the measured liquid saturation in our experiment is close to the parameter *fmdry*. Therefore, we assign the lowest measured liquid saturation (for each experiment) to the parameter *fmdry* and optimize the rest of the foam model parameters. For the parameter optimization, we use the least-square method and the method suggested by Boeije and Rossen [1]. We choose the relative permeability with the lowest residual water saturation (0.5 wt% AOS), because the parameter *fmdry* must be able to acquire values larger than the residual water saturation.

The foam model with a fixed value of *fmdry* fitted to the pressure gradient measurements for 0.1 wt% AOS-nitrogen flooding is shown in Fig. 6 (Boeije & Rossen method) and Fig. 7 (least square fit). By fixing the value of fmdry to the lowest measured water saturation, it is not possible to fit the foam model

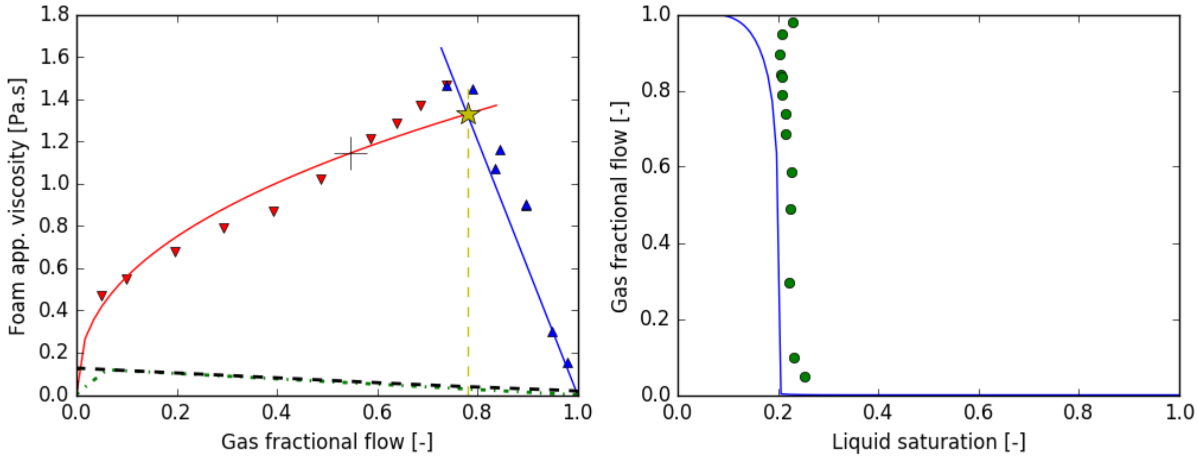

Figure 6: Fitting foam model to the 0.1 wt% AOS-N_2 core flooding data using the method of Boeije & Rossen with a fixed *fmdry*=0.202; the black dashed line (left) shows the final fit to the experimental data

to the rest of the measured pressure gradient (apparent foam viscosity) data. However, by letting the optimization method to optimize the *fmdry* parameter, it converges to a value that is close to the chosen residual water saturation and therefore does not fit to the measured water saturation data (Fig. 8).

4 Other comments

1. The experimental set up section is missing key details such as the permeability of the core and details of the core holder construction. I cannot tell if the core is epoxied into the PEEK holder or if it is of the Hasseler sleeve type design. If there is an overburden pressure applied, please specify it. The interfacial tensions of all of the fluids should be mentioned for completeness.

Reply: more detail is added to the experimental section now. The bentheimer core was covered with epoxy but not glued into the core holder. Instead, the dried epoxy on the surface of the core was shaped with a threading machine so the epoxy-covered core could be placed into the core holder, as shown in Fig. 9. A confining (overburden) pressure equal to the injection pressure was applied, which is equal to the back pressure (95 bar) plus the pressure drop in the core.

The interfacial tensions are also added to the paper, also in the following table.

Surfactant	0.03wt% AOS	0.1wt% AOS	0.5wt% AOS	Amphosol
Surface tension [mN/m]	38.4	32.5	33.9	33.4

2. The choice to measure the water/gas relative permeability in a centrifuge

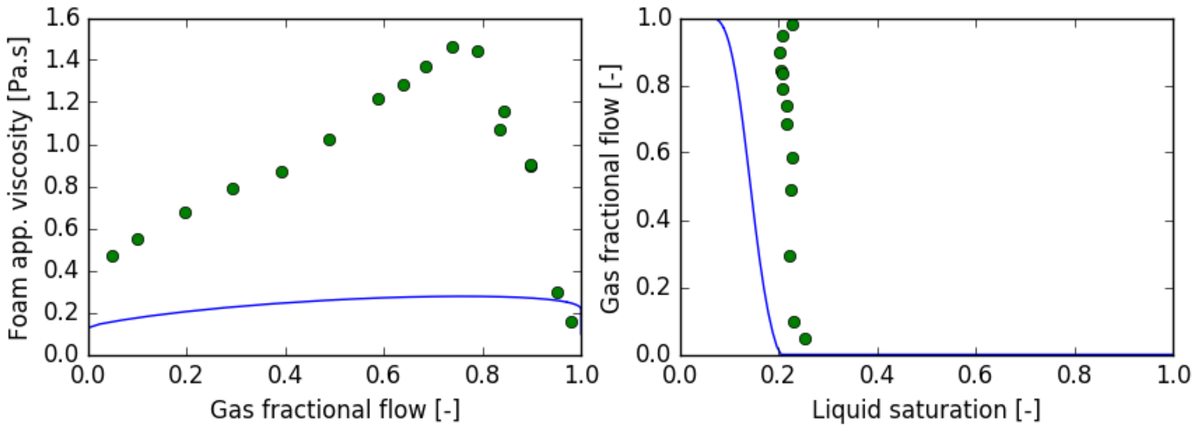

Figure 7: Fitting foam model to the 0.1 wt% AOS-N_2 core flooding data using a least-square optimization method with a fixed $fmdry$=0.202

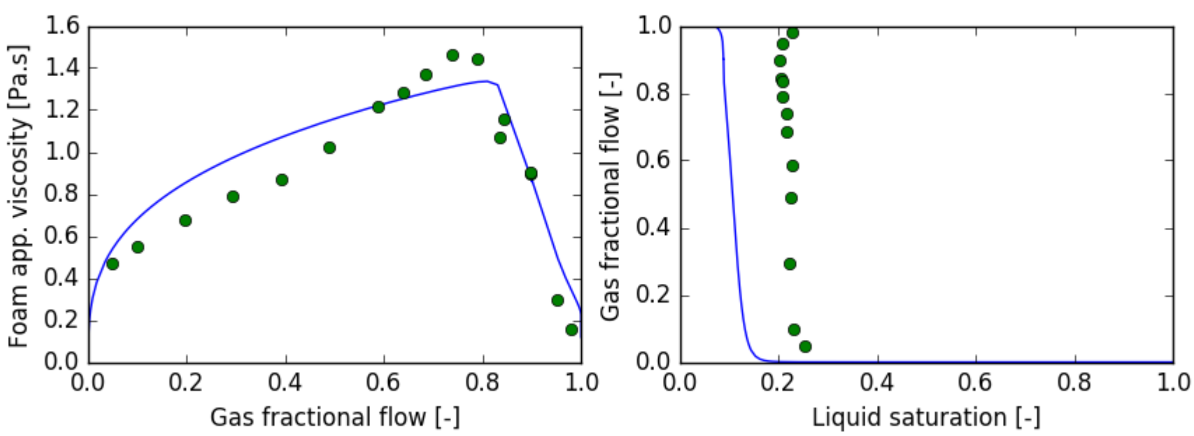

Figure 8: Fitting foam model to the 0.1 wt% AOS-N_2 core flooding data using a least-square optimization method with a variable $fmdry$

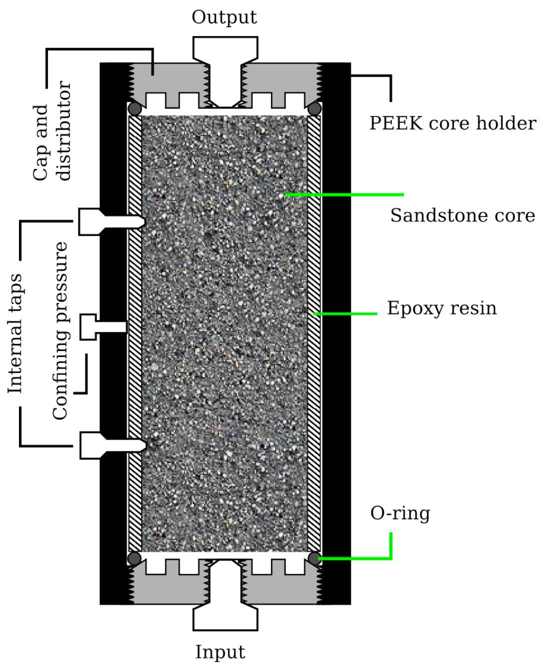

Figure 9: Core holder design

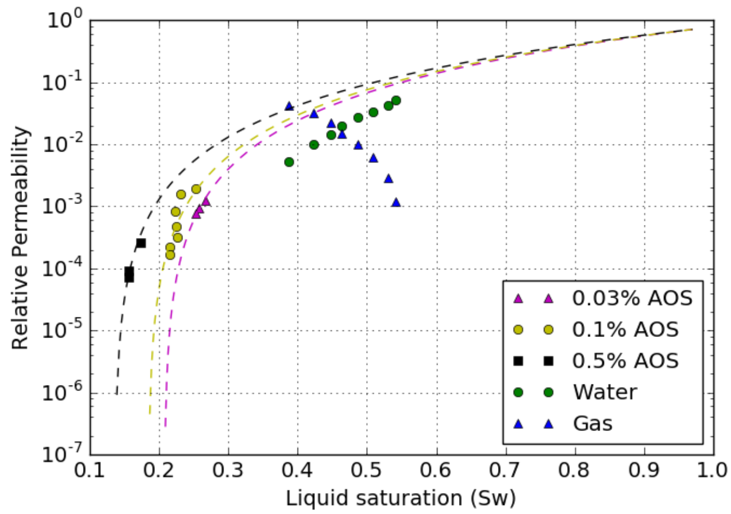

Figure 10: Water relative permeability in presence of different concentrations of AOS, and the gas-water rel-perms in the absence of surfactant

but to measure the foam relative permeabilities in a coreflood apparatus is disconcerting. One might ascribe the differences measured to differences in the measurement techniques. So some further commentary and justification are needed. More details about the centrifuge technique are also needed (i.e., RPM at the very least) because of the interplay of capillarity and viscous forces described above. Small RPM on the centrifuge could be ascribed to the differences measured in Swc.

Reply: we eliminated those data points as they were not measured in a centrifuge, but in a core flooding experiment. Instead, we used the water-nitrogen rel-perm data from the work of Reynolds & Krevor [2].

3. It is mentioned that the coreholder is installed vertically. What steps are taken to minimize CT-scanning artifacts that result from this geometry? Did the authors measure the spatial distribution of water saturation during the various experiments? These could/should be described.

Reply: we used the measurements from the middle section of the core, since it is known that the effect of beam hardening at that section of the core is minimal. We always measured the spatial distribution of the liquid saturation.

4. Foam is composed mainly of gas and so it is a compressible fluid. I suggest writing Eq. (1) as it should be written for a compressible fluid. That is, the difference between the square of the pressures, and so on, should be used.

Reply:

5. In considering the mobility of the foamed gas, the authors explicitly separate the mobility of foam into relative permeability and viscosity—note

that they report foam apparent viscosity in Fig. 4(a). This point needs some discussion as it has been argued rather strongly elsewhere that such a separation is inappropriate for foam and now here it is being done.

Reply: we only see the effect of foam on reducing the mobility of the gas phase in the relative permeability. The apparent foam viscosity is a way of reporting the scaled pressure drop measured in the core flooding experiments. We understand that it can be confusing to the reader. We have clarified it in the text.

References

[1] Christian Simon Boeije, William Rossen, et al. Fitting foam-simulation-model parameters to data: I. coinjection of gas and liquid. *SPE Reservoir Evaluation & Engineering*, 18(02):264–272, 2015.

[2] CA Reynolds and S Krevor. Characterizing flow behavior for gas injection: Relative permeability of co2-brine and n2-water in heterogeneous rocks. *Water Resources Research*, 51(12):9464–9489, 2015.