Laboratory monitoring of CO_2 migration within brine-saturated reservoir rock though complex electrical impedance

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SUMMARY

We investigate the ability of complex electrical measurements to monitor the CO_2 front propagation within brine-saturated reservoir rock. A laboratory facility has been developed to perform CO_2-brine substitution experiments under reservoir conditions. In the present study, CO_2 is injected into a brine-saturated core while the complex electrical impedance is measured continuously using an array of four electrode pairs. Both magnitude and phase of the electrical impedance reveal the sensitivity to the injected fluid. We find that recent adaptations of the Cole-Cole model can explain quite well the observed variation of complex electrical impedance as a function of CO_2-brine saturation. This suggests the potential utility of complex electrical impedance measurements in an efficient CO_2-storage monitoring program.

INTRODUCTION

The complex electrical methods have widely been used for subsurface characterization in the last few decades. The applications have been sought in environmental characterization and monitoring (e.g., Pelton et al., 1978) and in interpretation of down-hole measurements in hydrocarbon-bearing rocks (e.g., Vinegar and Waxman, 1984). Several field and laboratory experiments have been conducted to investigate the frequency-dependence of electrical properties in the porous media such as in unconsolidated sands (e.g., Ulrich and Slater, 2004) or in sandstones (e.g., Knight, 1991). Recent studies conclude that complex electrical measurements have a good potential in efficient CO_2 storage monitoring (e.g., Kirichek et al., 2013; Dafflon et al., 2013). Investigating the possibility of predicting reliably the displacement of brine by CO_2 or vice-versa at the reservoir conditions, however, remained an undone task.

The objective of the present study is to investigate the applicability of complex electrical impedance to monitor the CO_2 migration within a brine-saturated core on a small laboratory scale.

EQUIPMENT AND MEASUREMENT TECHNIQUE

The experimental setup for this study is designed to measure the electrical response of a rock at high temperature and pressure, mimicking a deep reservoir. Additionally, the experimental setup allows us to monitor the migration of CO_2 within the core. A simplified sketch of the assembly is presented in Fig. 1. The hart of the setup is a cylindrical core of Bentheimer sandstone (26 mm in diameter and 142 mm in length, 22% porosity) embedded in a pressure chamber. Before the core was placed in the core holder, it was dried for 48 hours at a temperature of 105°C to remove any water adsorbed from the sample. Four electrode pairs, which measure electrical response of the system, are attached to the lateral surface of the core. The entire surface of the core and electrodes are sealed with a layer of silicone rubber. This sealing allows us to apply isostatic confining pressure (by means of hydraulic oil) on the core sample.

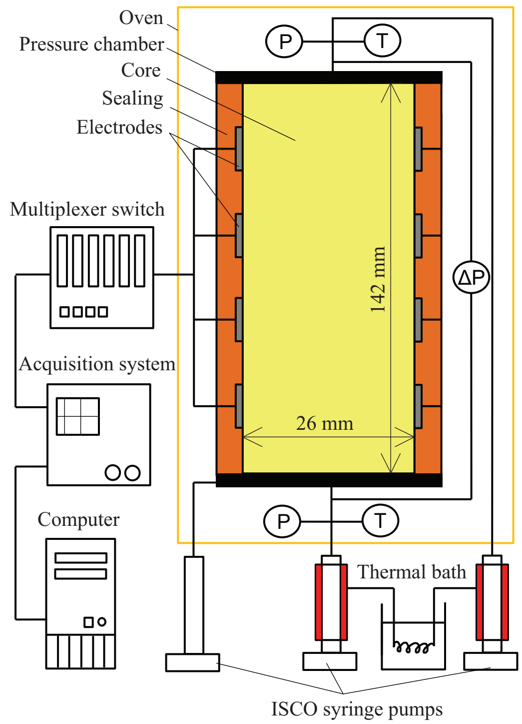

Figure 1: Schematic representation of the experiment.

The assembly has a vertical orientation that allows minimizing the gravitational instabilities and fingering effects during the fluid injection. The CO_2, due to its lower density, is injected from the top end of the core at a constant flow rate, controlled by a syringe pump. The brine, as a more dense phase, is flooded by another syringe pump from the bottom end of the core. In this study, we use a sodium chloride brine solution with salinity of 10000 ppm.

The temperature and pressure of the system are controlled by an oven and 3 ISCO syringe pumps. We employ 2 ISCO syringe pumps, one at each core end for CO_2 and brine injection. A third pump generates the confining pressure in the pressure chamber. The pore pressure and pressure drop over the core are monitored at both ends of the core. To establish the temperature equilibrium between the core and injecting fluids, we utilise the thermal bath which balances the temperature in the oven and that in the injection fluids within the ISCO pumps.

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The setup can generate pressure up to 110 bar and temperature up to 65°C in the sample.

Wayne Kerr precision component analyser 6640A is used to measure the frequency-dependent amplitude $|Z^*|$ [Ω] and phase angle ϕ [°] of the complex electrical impedance, which is defined as:

$$Z^* = |Z^*|e^{i\phi}. \quad (1)$$

Each measurement is conducted in a time interval of 90 seconds for the frequency range of 20 Hz to 3 MHz.

METHOD

The frequency-dependent electrical impedance of the CO_2-brine substitution as a function of saturation have been investigated using the following relaxation model (Kavian et al., 2012):

$$Z^*(\omega, S_b) = \frac{e^{(\mu_1+\beta_1 S_b)}}{1+(i\omega e^{(\gamma_1+\eta_1 S_b)})^{\alpha}} - \frac{e^{(\mu_2+\beta_2 S_b)}}{1+i\omega e^{(\gamma_2+\eta_2 S_b)}}, \quad (2)$$

where ω is the angular frequency ($\omega = 2\pi f$, f being the frequency), S_b is the brine saturation and μ_1, β_1, γ_1, η_1, α, μ_2, β_2, γ_2, η_2 are fitting parameters.

The best-fit values of the complex electrical impedance are used to characterise the effect of the partial saturation. These parameters are calculated by minimising the residual:

$$Residual = \left(\frac{\sum_{n=1}^{N} \mid Z_m^*(\omega_n, S_b) - Z_d^*(\omega_n) \mid^2}{\sum_{n=1}^{N} \mid Z_d^*(\omega_n) \mid^2} \right)^{\frac{1}{2}}, \quad (3)$$

where N is the number of frequencies, ω_n are angular frequencies, S_b is a brine saturation, Z_m^* and Z_d^* are model and experimental complex impedance, respectively.

EXPERIMENTAL PROCEDURE AND RESULTS

Gaseous CO_2 is injected into the empty pores of the sandstone core. The system temperature is set to T=38.1 °C. The ambient pressure is gradually increased to the reservoir pressure of P=80.7 bar.

The experiment is split into six stages. During the 1st stage, the electrical response of the CO_2-saturated system during the pressure build-up is monitored. At the 2nd stage, electrical measurements are conducted during brine injection into the CO_2-filled core. The 3rd stage of the experiment involves measurements of the CO_2-brine displacement at a flow rate of Q=1 ml/min. The 2nd and 3rd stages are repeated to check the repeatability of the results and the sensitivity of the measurements. Finally, the core is flushed with brine. The procedure for the experiment is similar to Kirichek et al. (2013). However, in order to monitor the CO_2 front propagation the number of electrode pairs is extended to four and all the channels are recorded separately to capture the spatial variation along the core length.

The measured complex electrical impedance for all four electrode pairs are illustrated in Figure 2. The amplitude $|Z^*|$ and phase ϕ of the complex electrical impedance are shown for frequencies of 1 kHz, 10 kHz, 100 kHz and 1 MHz. Both $|Z^*|$ and ϕ show significant sensitivity to the change in saturation of the injected brine and dense CO_2 into the core. The partial and full saturation can be distinguished from the amplitude data during the CO_2-brine and brine-CO_2 substitution. The phase measurements discern only the full saturation during the brine-CO_2 substitution. However, during the CO_2-brine displacement both full and partial saturation effects can be distinguished from the phase data.

From top to bottom, 8 panels in Figure 3 represent the sequence of electrode-pairs along the length of the core (the bottom panel representing the farthest electrode pair from the CO_2 injector). The front propagation can clearly be distinguished by the different pairs of electrodes as the CO_2 moves through the core.

Figure 3 shows the laboratory measurements (circles) and model predictions (lines) for the partially saturated core using the best-fit parameters for the frequency range from 20 Hz to 3 MHz.

The experimental results are validated using the relaxation model given in Equation 2, which shows superposition of two mechanisms. The first term on the right-hand-side of Equation 2 defines an equivalent circuit which corresponds to a CO_2 saturated core. The second term can be regarded as an equivalent circuit for the mineral-brine system. The superposition of these mechanisms represents the CO_2-brine displacement processes in a porous rock. Individual contributions and measured data are illustrated in Figure 4.

The majority of borehole logs focus mostly on the DC measurements. By using the AC electrical measurements, one can acquire and interpret additional down-hole information within a single logging campaign. This can be of special relevance to CO_2 storage monitoring projects. Furthermore, the standard borehole logs usually have a similar frequency range and scale as in the experiments that we have conducted in the laboratory.

CONCLUSIONS

New laboratory experiments have allowed us to establish a range of the electrical properties when the porous medium is saturated with either brine or dense CO_2. Both $|Z^*|$ and ϕ show significant sensitivity to the change in saturation of the injected brine and dense CO_2 into the core. The measured data are in a good correspondence with theoretical prediction. Our results suggest that complex electrical properties can be used to monitor the CO_2 migration and reduce the uncertainties in field data interpretation.

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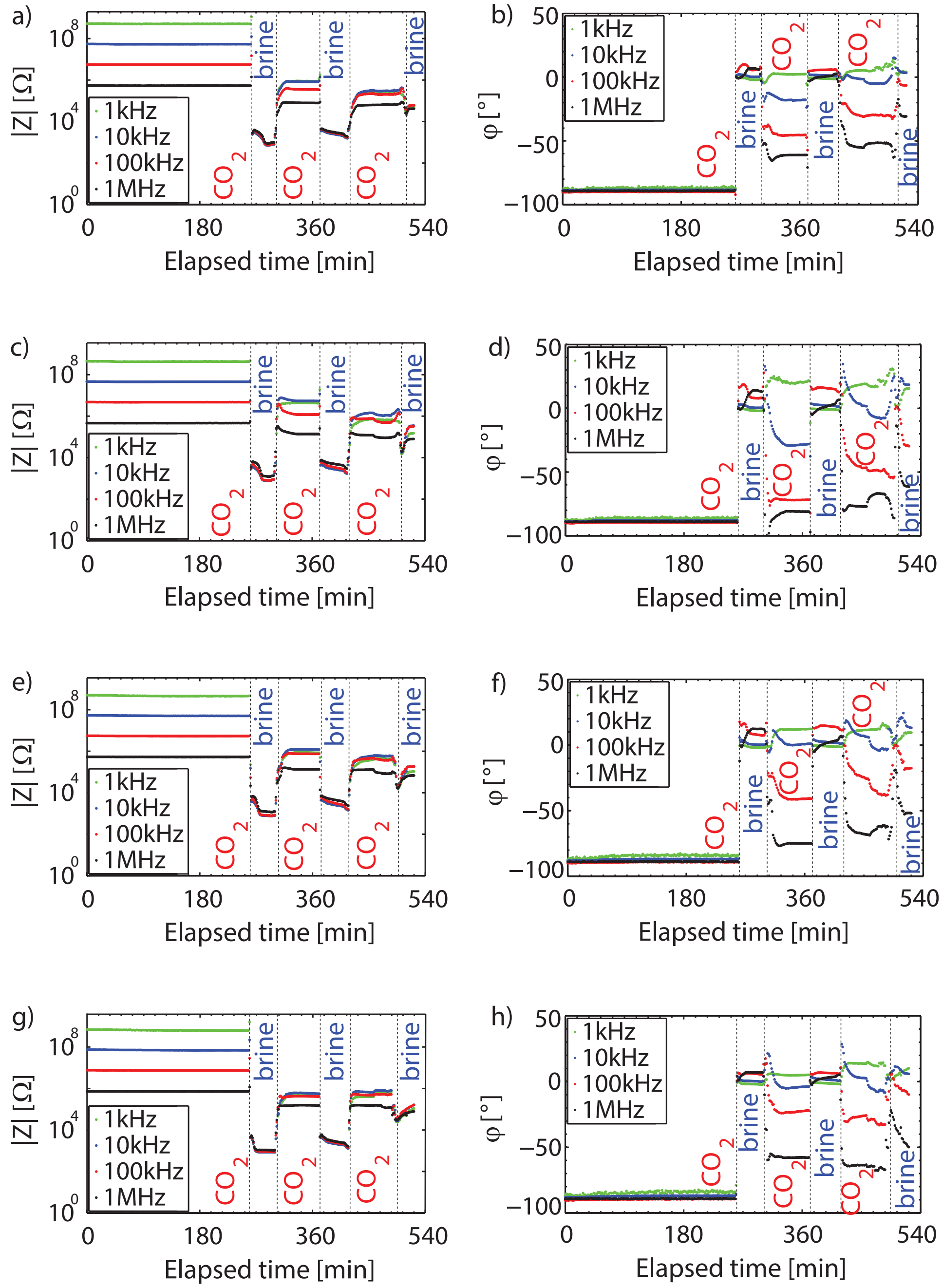

Figure 2: The changes in amplitude $|Z|$ and phase ϕ of the complex electrical impedance during brine-CO_2-brine displacement. The horizontal axes depict the elapsed time from the beginning of the experiment. The panels represent the top-to-bottom sequence of the electrode-pairs along the length of the core (see Figure 1), i.e. panels (g) and (h) represent the farthest electrode pair from the CO_2 injector and panels (a) and (b) show the closest ones. The green, blue, red and black dots show frequencies of 1 kHz, 10 kHz, 100 kHz and 1 MHz, respectively.

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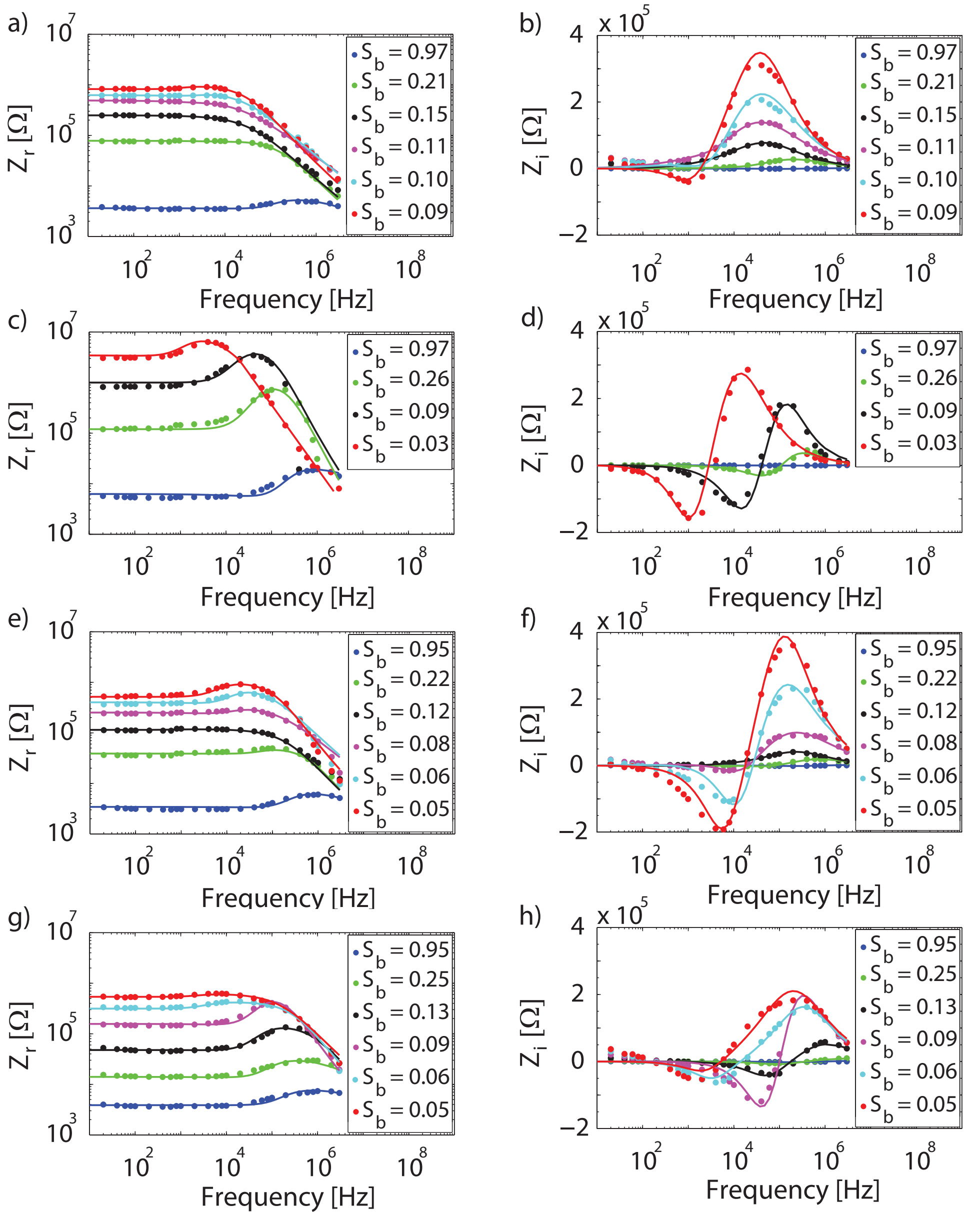

Figure 3: The changes in real Z_r and imaginary Z_i components of the complex electrical impedance during CO_2-brine substitution for the frequency range between 20 Hz and 3 MHz. The panels represent the top-to-bottom sequence of the electrode-pairs along the length of the core, i.e. panels (g) and (h) represent the farthest electrode pair from the CO_2 injector and panels (a) and (b) show the closest ones. Circles show the data for different saturation levels and solid lines depict the relaxation model predictions.

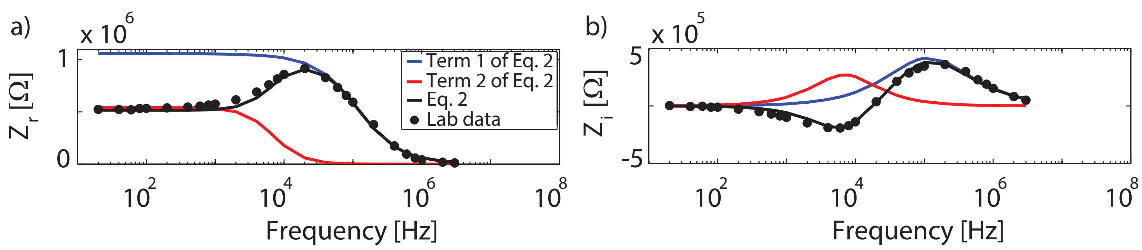

Figure 4: (a) Real and (b) imaginary parts of the complex electrical impedance: lab data for a of the CO_2-brine system (circles); CO_2 equivalent circuit (blue line); mineral-brine equivalent circuit (red line). Superposition of these two mechanisms is given by the black line.

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EDITED REFERENCES

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