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Early design of new experimental setup for joint elastic, electrical and CT monitoring of CO_2 injection

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Summary

Laboratory-scale measurements of CO_2 injection and monitoring are essentially milli to micro-scale investigations of the interaction between fluid-fluid and rock-fluid interfaces. These measurements are crucial to understand the capabilities of the monitoring techniques and to validate the models that simulate plume distributions. The reliability and the accuracy of the laboratory measurement depends on design aspects of the measurement of the experiment and of the apparatus used. Appropriate measurement must be put in place in order to quantify the fluid displacement before and during sample flooding. In this paper, we present an overview of important design factors that were identified during the initial design of our elastic-electrical measurement system.

Introduction

Anthropogenic sources of CO_2 are known as the main cause of greenhouse gas emissions (IEA-Green House Gas, 2008). Carbon Capture and Storage (CCS) is one of the proposed mitigation method for reducing carbon emission (CCS) (IPCC, 2013). In order for CCS technology to be successfully implemented, suitable reservoirs for safe and long-term storage of CO_2 must be identified. Geophysical imaging can provide a qualitative and quantitative verification of the containment performance of reservoir throughout its life, however, the influence of CO_2 on the physical properties must be properly understood.

Laboratory measurements provide a means to acquire this information and to make a detailed assessment of rock samples from reservoirs where CO_2 is to be injected. These measurements are useful for the interpretation of field observations and to simulate imaging scenarios that could be envisaged (e.g. leak detection). Core-scale experiments are the most prevalent and are used to characterize and quantify micro-scale phenomena (Mukherjee & Misra, 2018) in order to assess the validity of theoretical models and assumptions.

The introduction of CO_2 within host pore network perturbs the geophysical signal. The chemical features of the pore fluid, pressure, temperature and the state of injected CO_2 (gaseous, supercritical or liquid) can all have an effect on the physical properties measured. Core-scale laboratory experiments are therefore important to understand the influence of each factor on the monitored response. The results from multi-phase flooding experiments are also a critical piece of information to establish a robust carbon capture reservoir model and to create a velocity-saturation model for given reservoir conditions.

Although different aspects of making laboratory measurements related to CO_2 sequestration have been reviewed in the literature, such as CO_2 storage mechanisms, monitoring and modeling techniques (Zahid *et al.*, 2011), caprock interaction with CO_2-brine system (Liu *et al.*, 2012), geochemical monitoring of injection (Humez *et al.*, 2014), experimental and numerical model studies in CO_2-brine-carbonate rock system (Siqueira *et al.*, 2017) and Laboratory monitoring of CO_2 sequestration in coal bed methane (Mukherjee & Misra, 2018), up to authors' knowledge and until the time of gathering the data, no comprehensive paper regarding the effective parameters on acquired data (acoustic and electrical resistivity) during CO_2 injection by time-lapse geophysical methods were published. In this work, we report our progress on the design, Figure 1, and assembly of our combinatorial laboratory apparatus for monitoring acoustic, electrical and fluid flow using CT scan imagery. Figure 1 is a schematic of a general combinatorial rig for joint interpretation of elastic-electrical data integrated with CT images. Interaction between pore structure and different forces (viscous, capillary and gravitational) between immiscible fluids (CO_2 and brine) yields different and complex flow regimes. These saturation regimes can be plotted by CT images. The scope of this project is to understand the geophysical responses of different saturation regimes by using joint acquisition of elastic-acoustic data. Combinatorial rig assemblage increases the design and construction complexity of the measurement system but on the other hand it circumvents limitations of individual measurements as discussed by (Lumley, 2010). In the following section, the design requirements of combinatorial measurement system required to monitor CO_2 saturation will be discussed. Measurement hurdles are discussed and potential solutions are proposed.

Material and Methods

Electrical resistivity is retained as a monitoring technology for this combinatorial rig to monitor the plume variation and allows for a precise resistivity-saturation model. This approach will reduce the impact of sample heterogeneity (axial to radial differences). Longitudinal ER measurements will provide information with regards to the resistivity variations observed during different injection scenarios.

Resistivity measurements are sensitive to the presence of CO_2, brine saturation and the salinity of these brines. Temperature of the brine also plays an important role,/? as temperature increases results in greater ion mobility and hence lower resistivity. Sustained t/emperature increases can also promote evaporation and reduce water saturation within the samples and thus increase measurement uncertainty.

In order to acquire electrical resistivity data in the laboratory, two types of electrodes are often employed $Cu/CuSO_4$ and Ag/AgCl. Copper and silver based electrodes are both photo-sensitive, hence ambient light can induce undesirable potential to the electrodes. The magnitude of the light impact on Ag/AgCl electrodes is usually less than $Cu/CuSO_4$ electrodes (Ansuini & Dimond, 1994). In this regard, shielding the electrodes from ambient noise increases the accuracy of the measurements. Zhang *et al.* (2015) used Ag/AgCl ring electrodes to acquire non-polarized electrical resistivity measurement. Minimizing contact resistance of electrodes at the surface of the sample is important because small variations during loading and unloading of the sample can alter the measurements and increase the uncertainty of the measured data.

Ultrasonic measurements are done using piezoelectric transducers. These transducers can be used as single element, pulse echo, (Rabbani *et al.*, 2014) or be stacked to form dual element transducers, pulse transmission (Yurikov *et al.*, 2018). There are two potential configurations for these acoustic measurements:

1- Specific area measurement, by mounting the piezo-transducers on each side of the sample, involves a harder setup (to make a perfect coupling between transducer and the surface of the sample) and more complex data processing. However, the outcome is a more representative estimate. Due to their reduced size, the sampled regions of interest (ROI) exhibits less variation of the pore structure, in comparison with longitudinal variation of heterogeneity. Also, by this procedure, the investigation of dissolution and precipitation at specific areas such as the inlet and outlet are feasible, as was shown by Zhang *et al.* (2014). This configuration reduces the uncertainties due to pore structure heterogeneity and focus on the impact of saturation patterns on acoustic data. The main limitation of such procedure, to be conducted at reservoir condition, relates to core holder, to have enough space to mount the transducers.

2- Whole sample measurements are achieved by mounting the piezo-transducers at the ends of the core sample. These measurements are easy to setup and interpret, but since the pore structure heterogeneity along the sample is higher, it makes the interpretation of the acoustic data to saturation-pattern more difficult.

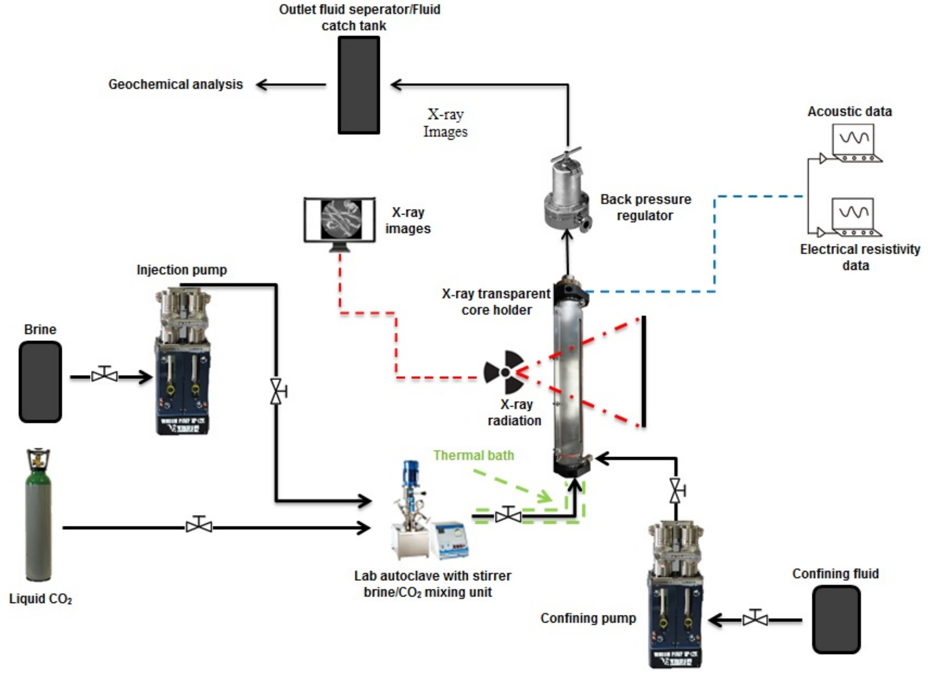

Figure 1. An example of a combinatorial rig to geophysical monitor of CO_2 injection.

Acoustic measurements are usually done using a pulser unit and a transducer that generate acoustic signals between 300 kHz and 1 MHz and a receiver, mainly oscilloscope. The time of the first arrivals, the amplitude of the measured signal and the length of the sample are used to compute the seismic velocities (P and S) and the attenuation. Inaccurate time picking of first arrival, which is in order of microseconds, may be problematic, since mis-picking of even 0.1 microseconds can cause velocity variation in order of tens of m/s. Attenuation studies are sensitive to the applied axial pressure, since the transducers are a part of applied stress, so it is important to have accurate strain gauges in place.

In acoustic investigations, the precision relies on the frequency of propagated wave and homogeneity of the medium, which includes the pore fluid and the rock matrix. To map the velocity distribution alongside the sample, the frequency of propagated wave must be higher than the ratio of patch size to the length of fluid diffusion (Lebedev *et al.*, 2009). This ratio is dependent on the fluid-fluid/rock interaction (dissolution and precipitation of minerals) and heterogeneity of the rock matrix. In this regard, however, the heterogeneity of the matrix and rock-fluid interaction is an intrinsic feature of rock cores. Steady injection of CO_2/brine is achievable if the injection rate is properly chosen and a stable fluid front is applied at the inlet. This can be achieved by using high-precision syringe pumps to expose the sample to a precise and constant amount of fluid. This is especially important during the injection of CO_2 in order to simulate real conditions distal from the well. A stable injection rate is crucial to these experiments because of its impact on the rate of progression of the plume front and hence the CO_2 saturation pattern. It is also important to note that too high injection values in a brittle matrix may induce micro cracks at the inlet and alter the inherent characteristic of the sample. Based on the scenarios of injections (phase of CO_2), pumps must have the capability of providing different pressure ranges for all three phases of CO_2. Fluid pressure at outlet can be controlled by a pump or a backpressure regulator. The temperature requirement can be provided by an autoclave and sustained by thermal bath before the core holder. Sample can be sealed from the confining fluid by providing an adequate sealing. Polyetheretherketone (PEEK) and rubber sleeve are among the popular X-ray transparent sealer for CO_2 monitoring rig.

Testing and monitoring samples exposed to CO_2 utilizing a (micro)CT scanner at high-pressure, high temperature (HPHT) conditions involves employing a transparent uniaxial/triaxial core holder (cell) to X-ray emissions, which is a key component of the combinatorial rig (Figure 1). The core holder must be able to sustain the applied pressure and temperature. As such appropriate selection of core holder materials should be based on X-ray compatibility (trade-off between scan quality and thickness of the cell wall), HPHT tolerance. Machinability of the material, without significant derating of the core holder should also be considered since modifications can be required (Glatz *et al.*, 2018).

Conclusion

Joint interpretation of elastic-electrical data combined with CT images has the potential to reveal new aspects of fluid-rock interaction. The quality of the data acquired is highly dependent on the data acquisition procedure and the reliability of the laboratory apparatus. At this early stage in the design of this combinatorial laboratory apparatus, we have identified aspects that could reduce the quality of our measurements and taken these into account during the design process. The performance of this apparatus should be documented in future publications.

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