CCUS: 4173977

Acoustic-Based Injectivity Monitoring at the Perforation Scale

Joseph Ma*[1], Glenn Wilson[1], Rory DeHart[2], Jacob McGregor[2], Mikko Jaaskelainen[1]

1. Halliburton, Houston, TX, USA
2. Jet Research Center, Alvarado, TX, USA

This paper was prepared for presentation at the Carbon Capture, Utilization, and Storage conference held in Houston, TX, 03-05 March.

Abstract

We describe perforation laboratory experiments to acoustically characterize supercritical fluid injection into permeable rock formations at reservoir conditions. The experiments mimic carbon dioxide (CO2) injection typical of carbon capture and storage (CCS) operations. We measured acoustic signals during controlled flow experiments at various injection pressures with a hydrophone. Analysis of the spectral content revealed distinct characteristics in specific acoustic bands, indicating the potential for passive acoustic monitoring to quantify injectivity at the scale of the perforation interval. In practice, that passive acoustic monitoring would be achieved via distributed acoustic sensing (DAS) of permanently installed fiber optic cables. We acknowledge the need for further research and development to subsequently derive an equivalent DAS response for quantifying CO2 injection rates at the individual perforation level to improve understanding of CO2 injectivity.

Introduction

Carbon capture and storage (CCS) is recognized as a critical technology to directly reduce greenhouse gas emissions. The injection and geological storage of supercritical CO2 presents unique challenges in terms of measurement, monitoring, and verification (MMV) required to satisfy long-term geological integrity of the storage facility. Ensuring the integrity of the storage site, tracking the movement of injected CO2, and detecting any potential leakages are crucial aspects of CCS operations. Like plug-and-perf unconventional wells, CCS wells are typically cased and perforated across the injection interval, with permanent downhole monitoring via fiber optic cables installed behind casing and injection and tubing pressure and temperature gauges installed on tubing. Inspired by Stokely (2016) and Shen et al. (2017), this suggests that distributed acoustic sensing (DAS) is a potential diagnostic for the real-time quantification of supercritical CO2 injectivity at individual perforation levels to improve understanding of well injectivity.

Following Schaeffer et al. (2024), the development of a quantitative DAS injectivity metric requires a priori quantification of the acoustic response under controlled injection conditions. It is reasonably expected that the DAS response of CO2 injection will be a function of the perforation charge, and reservoir contact, permeability, and pressure. For CO2 injection, we can design such controlled conditions by instrumenting a perforation laboratory (Grove et al., 2021) with acoustic sensors. This enables us to design and run experiments that flow supercritical fluids across a perforated casing into a permeable rock at quasi-reservoir conditions. Acoustic responses are measured using hydrophones during fluid injection, under controlled flow rates, injection pressures, and thus pore pressures. This paper aims to present and provide a preliminary analysis of the measured acoustic signals, and that as a tool for characterizing and monitoring carbon injection in CCS projects.

Methodologies

We establish laboratory flow conditions to mimic subsurface injection flow through perforated casing into rock formation (Ma et al., 2024), by creating a pressure chamber with a 12” × 16” cylindrical steel container where a permeable rock formation is contained and enclosed exterior from below (Fig. 1a). At the opposite end of the container, a 3” diameter outlet is present, where a Teledyne-4037 hydrophone is mounted on the separate steel cover and directed at outlet. We consider injection flow through a standard 0.75” perforation by installing a steel plate of corresponding hole size onto the outlet (Fig 1a). In this experiment, we consider a well permeable condition conducting the flow through a Saltwash Red sandstone core with approximately 1 Darcy permeability (Fig. 1b). It is appreciated that the choice of perforation and formation used in this pilot was arbitrary and can be designed to any specific CCS formation. The formation core itself is unperforated throughout the experiment. This hydrophone is rated to a maximum 3,500 psi pressure, thus limiting the upper bound we can currently test. However, for initial experiments intended to validate our hypothesis of a pressure-dependent acoustic response, this is sufficiently within expected CO2 storage reservoir pressures (Bump and Hovorka, 2024).

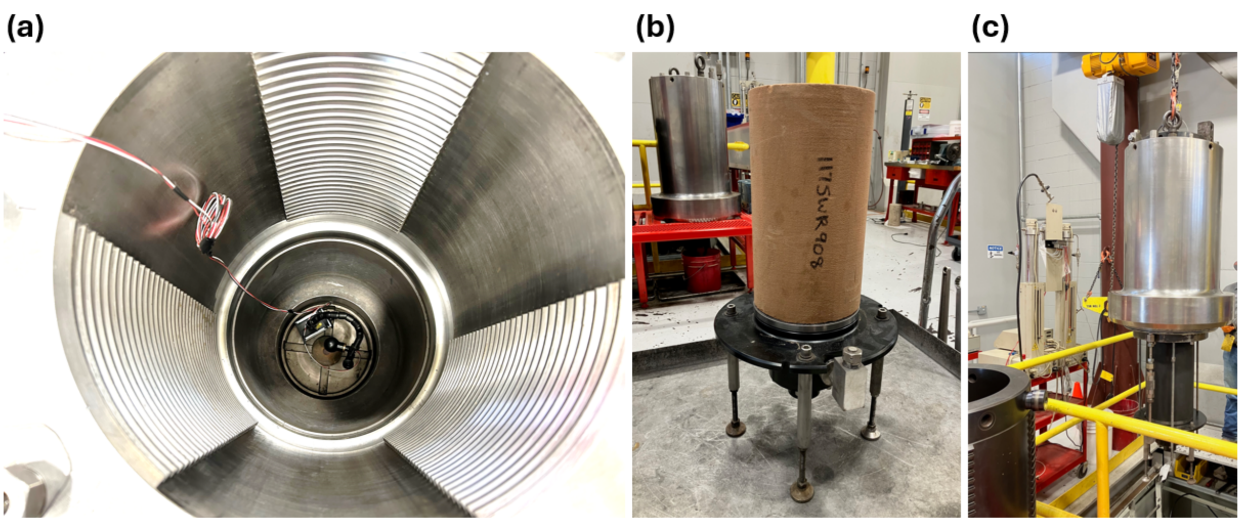

Figure 1. Experimental equipment: (a) pressure chamber with a mounted hydrophone directed at perforation hole, (b) high permeability Saltwash Red sandstone core, and (c) the assembly set up which is to be submerged into a water-filled downhole for flow experiments.

The system (Fig. 1c) is submerged to form a water-filled initial condition. An overburden pressure is applied. The injection system possesses accurate monitoring and control of the supercritical fluid injection rate. We also monitor the temperature and pore pressure in the containment. In initial experiments, supercritical nitrogen (rather than CO2) is used as the injectant. Dynamic acoustic pressure, inside the containment, is sensed by the hydrophone and electronically transmitted to and recorded by an acquisition system. Prior to any injection, we record the background acoustic noise of the system. Subsequently, we gradually increase the injection pressure of supercritical nitrogen until an approximately a steady injection rate, injection pressure, and pore pressure are all achieved. Figure 2 shows an image of the experimental setting in the perforating laboratory.

Nitrogen is injected at ambient temperature (~70ºF, or 21ºC). We acquire the acoustic signals generated from both steady-state and dynamic flows. For steady-state flows, the corresponding injection pressure is maintained, and acoustic signature are recorded for 10 minutes. The experiment is repeated at four different pressure levels. For dynamic flows, we define a starting pressure, and a target pressure change rate. And we record the acoustic signals generate from the evolving flow rates as a result of the changing injection pressure.

Results

Figure 2 shows the averaged power spectrum of the acoustic signals of background environment, and signals from injection flow under the different injection pressure. The downhole environment is rather robust to surface and operating machinery noises. Most signals recorded are only electronic noise and its aliasing. In steady-state conditions, the injection flow rate is proportional to wellbore pressure. We observe several characteristic modes of decent signal levels in 1500-6000Hz frequency range, which is related to the flow activities. In particular, approximately 17.5% frequency increment for the modes are observed compared between injection at 3000 psi and 1000 psi. For instance, a flow-noise related peak at 1912 Hz migrates to 2244 Hz, and another changes from 4674Hz to 5526Hz.

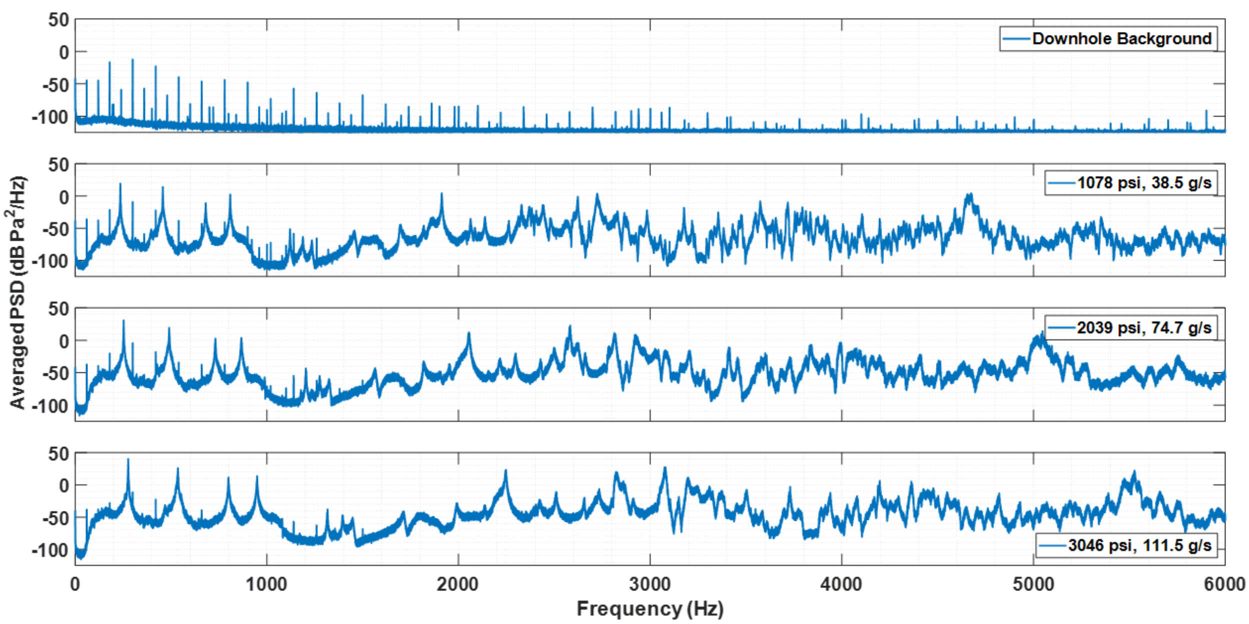

Figure 2. The averaged power spectral density of the 10-minutes hydrophone recordings of the downhole background and under steady-state Nitrogen injection of various wellbore pressure and flow rates respectively.

Viewing the acoustic signals obtained under a dynamic flow condition offers a more comprehensive insight on the potential spontaneity between flow rate and acoustic frequency. In this run, we slowly pressure up the wellbore to 3500 psi with an increment rate of 10 psi per second. Fig 3a shows the log of wellbore pressure and injection flow rate across the 10-minute acquisition. From the corresponding flow noise hydrophone recording (Fig. 3b), we first observe the superb correlation between flow rate and acoustic signa, especially from the fluctuations induced from the flow PID controller. From the time-frequency spectrum of the acquired signal (Fig. 3c), it is encouraging to witness the instantaneous reactance on flow noise frequencies to flow rates. These results demonstrate that in additional to noise levels, we might use characteristic acoustic frequencies towards real-time injection flow monitoring in downhole environment.

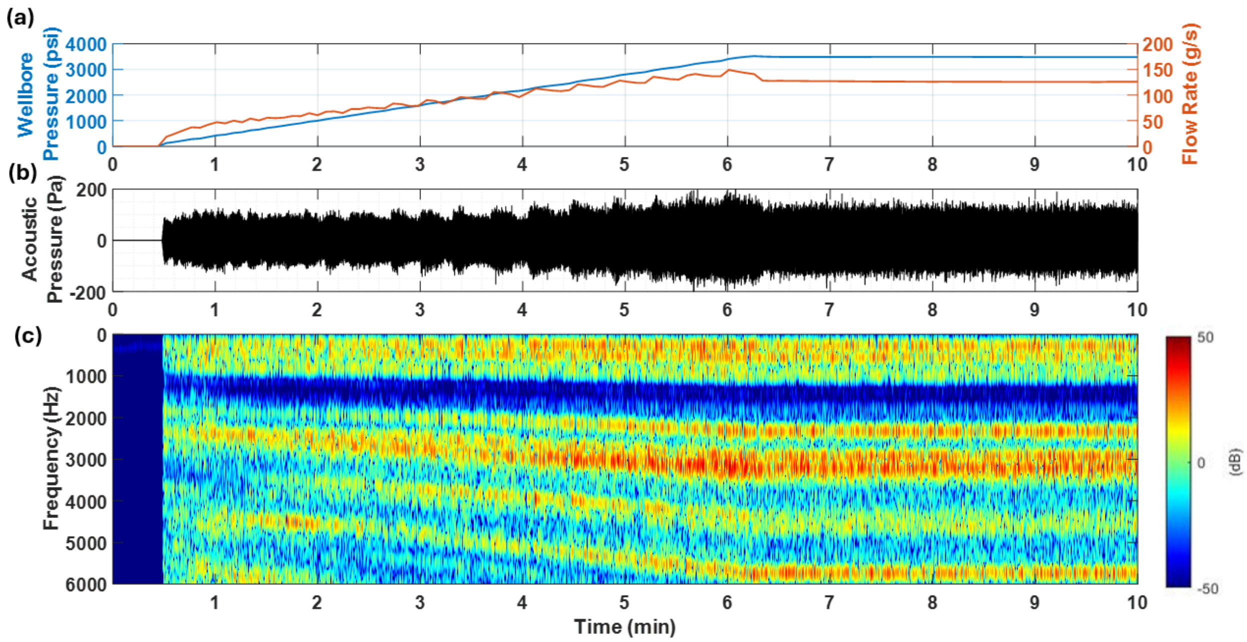

Figure 3. (a) The laboratory log of wellbore pressure and injection flow rate under a ramp of system pressure from o to 3500 psi, and (b) the corresponding acoustic recording on flow through perforation, and (c) and its time-frequency spectrum.

Discussion

The injection of supercritical CO2 from wellbore to formation is typically in the order of 3000 psi. In the laboratory environment, we are able to increase injection pressure to 3500 psi. This allows us to acquire more comprehensive acoustic characteristics and responses in related to expected operating conditions. We will also be performing acoustic measurement using hydrophones in tighter formations. Eventual goal is to understand the signal response of CO2 injection flows in fiber optic distributed acoustic sensing. However, we then need to apply a transfer function that converts our point acoustic measurements to expected distributed acoustic measurements that we would reasonably expect to measure with DAS at a given gauge length and noise floor. The transfer function itself is derived from independent flow loop experiments (Stokely, 2016). The expected DAS measurements are then the basis for real-time quantification of CO2 injection at each perf level and is analogous to the application of DAS to hydraulic fracturing by Shen et al. (2017).

Conclusions

We have designed a perforating laboratory experiment that can quantify the acoustic responses of supercritical fluid injection through perforations and porous formations. The apparatus can be configured for any casing/perforation/formation combination; implying CCS project-specific perforation and reservoir responses can be acquired to establish expected DAS responses for CO2 injection, and thus quantify CO2 injection per perforation level in CCS injector wells.

References

A. P. Bump and S. D. Hovorka, 2024, Pressure space: The key subsurface commodity for CCS: International Journal of Greenhouse Gas Control, 136, 104174, https://doi.org/10.1016/j.ijggc.2024.104174.

B. Grove, J. McGregor, R. DeHart, R. Dusterhoft, N. Stegent, and A. Grader, 2021, Frac charge performance at downhole conditions: Assessments and implications: Presented at SPE Hydraulic Fracturing Technology Conference and Exhibition, Virtual, https://doi.org/10.2118/204204-MS.

J.H.Y. Ma, G. Wilson, R. Dehart, J. McGregor, B. Grove, D. Barlow, and M. and Jaaskelainen, 2024, Characterizing Acoustic-Based Reservoir Injectivity Monitoring with Perforation Laboratory Testing: Presented in SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana. https://doi.org/10.2118/221081-MS

B. Schaeffer, M. Grubert, S. Jugdaw, C. Allen, G. C. Cortez, M. Jaaskelainen, R. Satti, A. Ellmauthaler, J. Maida, P. McPhail, and G. Wilson, 2024, Distributed acoustic sensing of passive and active inflow control technology and quantification of flow rates for reservoir surveillance: Presented at SPE Annual Technology Conference and Exhibition, New Orleans, Louisiana. https://doi.org/10.2118/220968-MS

Y. Shen, E. Holley, and M. Jaaskelainen, 2017, Quantitative real-time DAS analysis for plug-and-perf completion operation: Presented at SPE/AAPG/SEG Unconventional Resources Technology Conference, Austin, Texas, USA, https://doi.org/10.15530/URTEC-2017-2668525.

C. Stokely, 2016, Acoustics-based flow monitoring during hydraulic fracturing: Presented at the SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, USA, https://doi.org/10.2118/179151-MS.