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On-going development of five geochemical monitoring technologies for onshore CCS.

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Abstract

A critical aspect of Carbon Capture and Storage (CCS) will be the ability to adequately monitor the injection site, both to ensure public and environmental safety and for "carbon credit auditing". In the unlikely event of a leakage in the near-surface environment, the study of natural CO_2 emanations in volcanic and geothermal environments have shown that the gas will tend to migrate along the path of least resistance and create spatially restricted "hotspot" leaks at the ground surface that can be challenging to find and quantify. For this reason, innovative technologies are required to improve our ability to detect, locate and characterize such features. To address this need our group is developing geochemical monitoring tools that confront the significant challenges associated with spatial, analytical and temporal resolution and sensitivity. Here we describe on-going work focused on increasing the Technology Readiness Level (TRL) of five prototypes and concepts developed by the Tectonics and Fluid Chemistry Lab (TFCL) at Sapienza University of Rome: the GasPro, Mapper, Multipla, Well-Star, and SWiM systems.

Keywords: CCS; monitoring; geochemistry; near-surface; gas; water.

1. Introduction

Carbon Capture and Storage (CCS) is the process of capturing CO_2 produced by large point sources and storing it within deep geological formations. CCS is considered one of the decisive technologies for reducing anthropogenic emissions of greenhouse gases and for achieving the objectives of the Paris Agreement. A critical component of CCS will be the ability to adequately monitor the injection site, both to ensure public and environmental safety and for "carbon credit auditing". While deep methods, like 4D seismic, are mature technologies, there is a great need to develop and improve new near-surface methods due to the significant technical challenges associated with spatial, analytical and temporal resolution.

It is well known, from the study of volcanic and geothermal environments, that if CO_2 leaks it tends to migrate along the path of least resistance and create spatially restricted "hotspot" leaks at the ground surface [1] that can be challenging to find and quantify. For this reason, innovative technologies and integrated site monitoring protocols are needed to increase the potential to find small CO_2 leaks and also demonstrate to the public, government authorities, and stakeholders that tools exist that ensure the safety of CCS. To address these issues we are conducting

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research to increase the Technology Readiness Level (TRL) of five prototypes developed by our group, each of which address technological gaps in our ability to guarantee the safety and integrity of onshore Carbon Capture and Storage sites. As explained in more detail below, these tools are focused on monitoring different environments, each having different requirements regarding sensitivity, spatial or temporal resolution, and robustness.

For the case of low TRL tools the strategy is to construct simple prototypes and perform initial feasibility testing in the laboratory. In contrast, higher TRL tools will be made more robust and user-friendly and will be large-scale tested at natural sites where geological CO_2 leaks at the surface or at man-made test sites where CO_2 is intentionally released under controlled conditions.

2. Tools under development

2.1. GasPro

The unsaturated soil horizon above the water table is a key monitoring target, as leaking CO_2 can accumulate in this interval and produce anomalous concentrations prior to its release to the atmosphere. While manual soil gas sampling is a valid approach, it addresses spatial distribution and not temporal variability. Instead, continuous monitoring of individual, high-risk areas, such as abandoned wells or faults, can potentially give early warning of a potential leak. While commercial sensors have been tested for CCS applications [2], they tend to require burial and subsequent retrieval for data download and battery substitution.

The GasPro (Fig. 1a) is an autonomous, sensitive CO_2 probe for soil gas monitoring that is based on a Non-Dispersive Infrared (NDIR) sensor behind a gas permeable Teflon-AF membrane. In its present form it distinguishes itself from commercial units by the fact that control electronics, data logger, batteries and WiFi antenna are all located near the surface (wider tube on probes in Fig. 1a); this means that batteries can be changed and some maintenance can be performed without removal of the probe and that data can be transferred to a central server in real-time. On-going development of the GasPro includes multiple-unit deployments together with the creation of sensor mesh networks; the conversion of the sensors into network nodes will reduce transmission power requirements and the number of access points required for data transmission to the server. It will also increase the potential distance between a given probe and the central Wi-Fi antenna, given that transmission distance will probe-to-probe instead of probe-to-hotspot. Presently at TRL6, planned large-scale testing at natural and/or controlled release sites should bring the GasPro to TRL8.

Fig. 1. Photographs showing: (a) various GasPro sensors ready for deployment at different depths in the unsaturated soil horizon (note that the sensor is located in the bottom end while batteries, control electronics and Wi-Fi antenna are housed in the wider, upper tube); (b) the Ground CO_2 Mapper; and (c) the Multipla groundwater monitoring probe.

2.2. Ground CO_2 Mapper

The ground-atmosphere interface is a monitoring target with great potential for two reasons. First because CO_2 can accumulate in this zone prior to atmospheric dilution, due both to its greater density relative to air and the fact that wind velocities (and thus mixing) approach zero at the ground surface due to friction effects. Second because concentration measurements at this interface can be made more rapidly than point flux methods, thus allowing for much greater spatial resolution. Originally proposed by Annunziatellis et al. [3], subsequent CCS-related research in this field focused on the use of expensive sensors [4, 5] and sample inlets at a height of at least 10 cm to protect the sensor; it is known, however, that significant dilution already occurs at this height [6]. Instead the Ground CO_2 Mapper prototype, designed and developed by the TFCL, overcomes this problem by using a modified and optimized low-cost sensor that allows for direct sampling at the interface [6].

The Mapper (Fig. 1b) is a mobile tool that yields very high spatial resolution along track (20-30 cm) thanks to a 4 Hz sampling frequency, is extremely sensitive due to reduced sensor noise, and has limited memory effects and anomaly smearing due to the use of a small volume sensor and efficient wash-out design, as shown in controlled release testing and mapping of natural leakage sites. Work is underway to further reduce sensor noise and to implement real-time mapping graphics to aid in survey decision making, as well as to combine primary, high-precision, low-resolution point flux measurements with secondary, moderate-precision, high-resolution Mapper data to reduce the uncertainty of leakage quantification estimates. The Mapper is also at TRL6, with the goal of increasing it to TRL8 via planned large-scale testing at natural and controlled release sites.

2.3. Multipla

Groundwater monitoring in wells is another environment where continuous measurements are required to ensure early warning of any potential CO_2 leak, preferably by analyzing multiple parameters to help in data interpretation [7]. Although commercial units do exist that measure pH, dissolved oxygen, and electrical conductivity, they are limited by the fact that they do not measure dissolved CO_2 (i.e., pCO_2). Instead, the Multipla's ability to also measure pCO_2 means that the carbonate system can be monitored more completely, which is critical for recognizing leakage-related anomalies in both carbonate or silicate aquifers [8]. The Multipla (Fig. 1c) is a multi-parameter probe developed for autonomous, continuous monitoring of groundwater chemistry in shallow wells and real-time data transfer to a central server. At present these units measure pCO_2, pH, temperature, pressure, and electrical conductivity. On-going development includes incorporation of dissolved oxygen and redox sensors, improving control electronics and real-time data transfer, and increasing probe robustness. The Multipla is presently at TRL4, with the goal of increasing this to TRL6 with field testing of the updated and improved version.

2.4. Well-Star

Techniques tested for well-head monitoring in the atmosphere include open path infrared lasers (OPIRL) and multiple point sensors (MPS). With OPIRL, a transmitted laser light beam is reflected back to a sensor and any decrease in the returned signal, caused by CO_2 absorption, is used to quantify CO_2 present along the path length. While very sensitive, as shown during testing at industrial sites [9, 10], these systems are expensive, complex and require a constant line-of-sight between transmitter and reflector. In contrast, MPS has the potential to be less expense, thanks to the recent improvement of small, low-cost Non Dispersive Infra-Red (NDIR) sensors, and to be more flexible, due to their inherent modular, point-measurement design. Jenkins et al. [11] conducted tests with the deployment of 8 commercial sensors at 2 m height up to 500 m away from a large release of CO_2. This work showed that the sensors were able to recognize and locate the leak, however the very large flow rate (8 t/d) and large deployment distances mean that it is difficult to assess sensitivity. More recently, Honeycutt et al. [12] described the development of a network approach to MPS, with inexpensive NDIR CO_2 sensors integrated in a communication and data transfer mesh for real-time spatial monitoring. Long term monitoring of background atmospheric CO_2 showed the viability of the system, however no controlled release test was conducted and thus, again, it is not possible to assess sensitivity.

The Well-Star concept looks to provide detailed and sensitive monitoring of well-heads above a storage complex. Still in the concept stage (TRL1) the Well-Star will build on experience gained using low-cost NDIR sensors for the GasPro and Mapper, with the goal being to provide a less expensive, simpler alternative to open path infrared lasers. It involves deploying multiple GasPro units in a star pattern around the well-head for CO_2 concentrations and a single sonic anemometer for wind speed and direction, with real-time data transfer and basic automated data analysis capabilities. Controlled release experiments are proposed to bring the Well-Star concept to TRL5 (technology validated in relevant environment). Considering that much of the hardware and some of the software has already been created during GasPro development, the principle unknown related to Well-Star functionality and capabilities is linked to sensitivity. Broad questions relate to the smallest leak that may be recognized above background and instrumental variability, considering also the impact of leakage height (i.e., ground level or higher), atmospheric conditions like wind (on CO_2 dilution) and solar radiation (on the heating of system electronics), and sensor deployment positions (e.g., distance from source, height above ground). If possible, both passive and pumped sensors will be tested, depending on availability and power supply.

2.5. SWiM

Finally, the contact between surface water and the atmosphere, like the ground-atmosphere interface, represents another potential monitoring environment where rapid, detailed, spatially distributed samples can be collected while in motion. For example, the so-called equilibrator technique, which involves constantly drawing water from the near-surface and equilibrating it with a gas volume to allow for continual, on-the-fly measurements of dissolved gases, has been tested to find anomalies caused by sub-sea CO_2 leakage [13]. On fresh-water bodies, on the other hand, attempts have been made to integrate surface water sensors with an Unmanned Surface Vehicle (USV) to map river water quality parameters [14]. While CCS applications for fresh water bodies have not yet been undertaken, the work of Nicholson et al. [14] shows that this a potentially valid approach. While such surface water bodies above CCS sites may be less common, where they occur they can represent sensitive ecosystems that require protecting.

SWiM, which stands for Surface Water mobIle Monitoring, is presently at the concept stage (TRL1) but with the goal of reaching TRL3. This system will integrate a commercial Unmanned Surface Vehicle (USV) capable of following pre-programed grid patterns with various chemical sensors to map surface water quality of small lakes or open water wetlands that may occur above a storage reservoir, especially given the sensitivity of such ecosystems. Chemical sensors, measuring continuously from a depth of about 15 cm while the drone moves, will include commercial units for electrical conductivity, temperature and pH, as well as ad hoc developed probes for the rapid and sensitive analysis of pCO_2, pCH_4, and pO_2.

3. Summary

Geochemical monitoring of the near surface environment has the potential not only to play an important role in monitoring and confirming the integrity of terrestrial CCS sites, it is also an important tool to demonstrate to local stakeholders that the local environment, biosphere and groundwater is safe. In the future, the development of innovative approaches that increase spatial resolution or which gives complementary information that improves data interpretation will help make CCS more secure and socially acceptable. It is hoped that the on-going research described here will contribute to this evolution of ideas and technologies.

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