Advancing systematic assessment of leakage from CO_2 geological storage through a novel experimental setup

Introduction

Geological storage of CO_2 in deep sedimentary formations (e.g. saline aquifers, depleted hydrocarbon reservoirs) is increasingly viewed as a cornerstone of large-scale decarbonization. Ensuring containment over operational and post-closure timescales requires an integrated understanding of storage capacity and trapping processes, but also potential leakage pathways and its impact on surroundings (Benson & Cole, 2008; Celia et al., 2015) (. Benson and Cole, 2008; Celia et al., 2015).
In contrast with short-lived transport accidents, storage-related releases are intrinsically coupled to the subsurface architecture: potential pathways include engineered conduits (e.g. legacy/abandoned wells) and natural features (e.g. faults, fractures and caprock hydro-fractures). These pathways may also be active in natural CO2 systems, where long-term seepage provides analog evidence on migration, dissolution, and surface expression (Oldenburg & Zhang, 2022; Tamburini et al., 2024) (Oldenburg, 2007; Tamburini et al., 2024).
For quantitative risk assessment and monitoring design, a persistent knowledge gap concerns the source term, specifically in relation to boundary conditions (phase state, flux, intermittency, geometry) that govern releases from the subsurface to the near-surface environment or to the water column. While mature consequence models exist for atmospheric and subsea dispersion, validated source-term datasets spanning relevant regimes remain scarce and fragmented, limiting systematic calibration and cross-comparison of models. These data are always limited to specific field experiments (Dewar et al., 2015; Gros et al., 2021; Sellami et al., 2015), linking them to target conditions such as local acidity, salinity, depth and leakage flow rate, undermining their usage for structured analyses.
Building on prior work on controlled subsea releases, this extended abstract reframes experimental source-term research in the broader context of geological storage integrity and natural/induced releases. The objective is to outline a reproducible laboratory-based strategy to generate model-ready datasets for leakage characterization, supporting (i) storage-site screening, (ii) monitoring and early-warning design, and (iii) environmental consequences assessment.

Methods and Theory

The proposed setup, named Simulated Subsea CO_2 Release Equipment (S_2CO^2RE), allows to combine various boundary conditions, to simulate a broad range of scenarios that may be encountered in geological storage and subsea CO_2 transport and injection, such as: depth, leakage pore equivalent diameter, environmental salinity, mass flow rate of the leakage (up to ~10^{-2} kg/s).
Capacity and containment are framed using established geological criteria (e.g. depth, seal thickness and capillary entry pressure, permeability/porosity, well inventory) and practical storage metrics, including specific sequestration volume (SSV) to relate point-source emissions to required subsurface volumes under representative reservoir conditions (Benson & Cole, 2008; Brennan & Burruss, n.d.).
Controlled experiments are based on a pressurized, optically accessible vessel enabling hydrostatic-equivalent pressures up to 9 bar (≈90 m water depth) and interchangeable nozzle geometries, designed to deliver repeatable gaseous CO_2 releases, at a maximum pressure of 11 bar, representative of shallow offshore leak boundary conditions. High-speed imaging and synchronized diagnostics target: (1) initial jet breakup and bubble-size distribution, (2) near-field plume evolution (velocity decay, entrainment, plume width), and (3) far-field bubbly-plume development and dissolution-driven shrinkage. A set of dissolved CO_2, pH and temperature sensors are placed along the water column, to keep track of the environmental changes near the CO_2 flux during and after the leakage experiment. Seawater upwelling can also be simulated alongside CO_2 dispersion, thanks to dedicated pumps.
The results coming from this experimental setup are easily confronted with on-field experiments present in literature.

Examples

The controlled-release dataset is expected to enable systematic validation of competing external-dispersion models under CO_2-specific mass transfer and breakup regimes, reducing reliance on non-CO_2 multiphase spill analogs: in particular, CO_2 solubility, which drives part of its environmental impact, can be precisely assess and linked to plume source term.
From a storage-integrity perspective, structured source-term priors improve the credibility of QRA and monitoring design by constraining plausible leakage-rate distributions for pathways such as legacy wells or faults. Natural seepage analogs can be used to contextualize laboratory-derived regimes (e.g. persistent low-flux seepage versus episodic higher-flux releases), while the laboratory provides repeatability and controlled geometry that field analogs cannot guarantee. Figure 1 summarizes the leakage pathway from reservoir to marine sediment for subsea stored CO_2, comparing it with different features of the experimental setup referred in the present work.

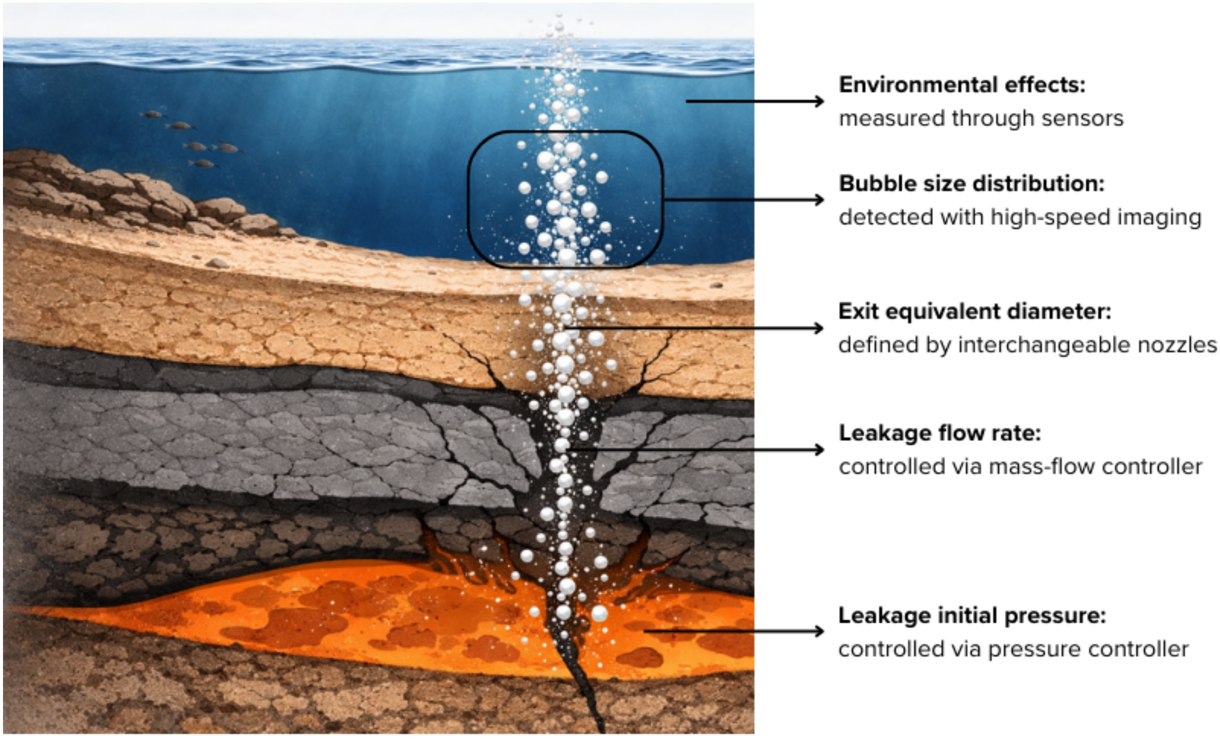

Figure 1 *Conceptual leakage pathway from geological CO2 storage, compared with capabilities of presented experimental setup. This figure is colorblind-friendly.*

In parallel, capacity framing via SSV provides a practical bridge between regional storage assessments and infrastructure scale-up: translating annual point-source emissions into required reservoir volumes highlights the importance of porosity, residual water saturation, and CO_2 phase behavior in defining storage efficiency.
The same observations, mainly focusing on subsea storage here, can be transported to saline aquifers, where simply higher salinity is required inside the equipment.

Conclusions

Geological CO2 storage safety depends on both subsurface containment (seals, traps, wells) and credible characterization of leakage source terms across engineered and natural pathways. Controlled release experiments with repeatable boundary conditions can fill a key data gap by providing model-ready datasets for CO2-specific breakup, dissolution, and plume dispersion. Integrating experimental source terms with scenario taxonomies supports monitoring and remediation design, including fracture sealing options (Rahman et al., 2024; Song et al., 2022). Practical capacity framing (e.g., SSV) supports scale-up reasoning and highlights sensitivity of storage efficiency to CO2 phase behavior and residual water saturation. In a scale-up perspective, measurements of dissolved CO_2 and pH near-field shall be linked to impact metrics such as acidification, to quantitatively assess ecological risk of not only large-scale release scenarios, but first and foremost continuous and extensive seepage from wide storage fields.

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