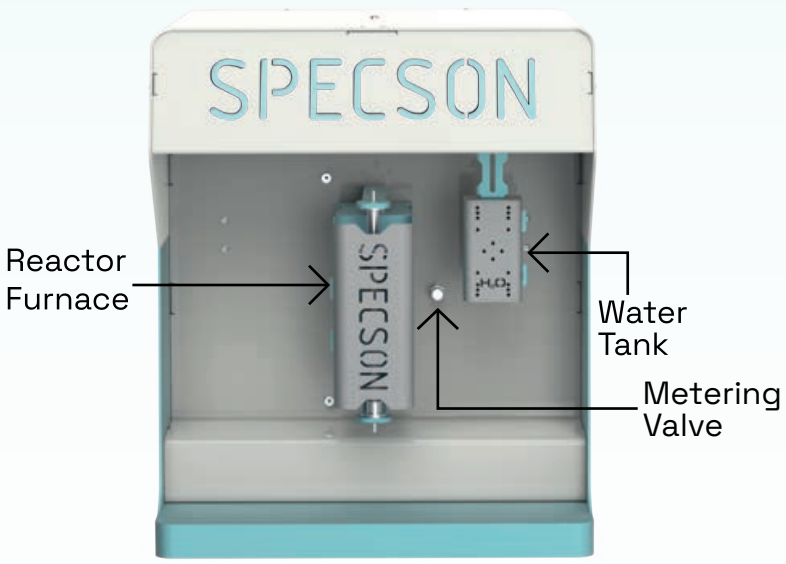
CCUS-1

CO_2 Capture and Utilization
Smart Unit for Catalyst Testing: Enabling a Greener Future

High pressure reactor for another custom project.

CCUS-1

CCUS-1 is a lab-scale, fully automated and compact reactor system designed for Industrial R&D and university research groups, capable of conducting CO_2 capture/utilization and a wide range of catalytic and gas-phase experiments (Dry Reforming of Methane, Steam Reforming of Methane, Reverse Water-Gas Shift, CO oxidation, ICC DRM, etc.) under precisely controlled conditions of temperature (up to ~900 °C), pressure, gas composition, flow rate and relative humidity (0–70 % RH).



This smart unit can be operated manually or fully automatically with using recipes for unattended runs via the Specson WorkFlow Manager software. Powdered sorbent or catalyst samples are loaded into a tubular reactor, enabling performance analyses based on dynamic breakthrough curves, time-on-stream tests, thermal programmed desorption experiments (CO_2-TPD) and aging tests.

Features

Mass Flow Controllers (MFCs)

In its basic configuration, the CCSU-1 includes 3 Vögtlin mass flow controllers. For more complex gas-mixing requirements, the system can be expanded to accommodate up to 7 MFCs.

Gas Analyzer & NDIR Sensors

The standard system is equipped with Edinburgh Sensors CO_2 and CH_4 NDIR sensors for deliver real-time, high-accuracy concentration measurements, and it can optionally be fitted with additional Edinburgh sensors for CH_4, CO, N_2O and C_3H_8 gases. For advanced gas analysis, the CCSU-1 can also interface with an external gaschromatograph (GC) and a mass spectrometer.

Pressure Control

Pressure regulation is managed by an internal needle valve as the standard method, allowing manual control of reactor pressures in quartz vessels up to 2.6 barG and in stainless-steel reactors up to 50 barG. For applications requiring independent downstream pressure management, an optional back-pressure regulator (BPR) can be fitted as a automatic pressure control solution.

Humidity Control (Steam Generator)

In its optional configuration, the CCSU-1 can be equipped with a steam generator and SUTO RH sensor to provide closed-loop control (PID Control) of relative humidity from 0% to 70% RH, making it straightforward to perform humidified reaction studies under precisely maintained conditions.

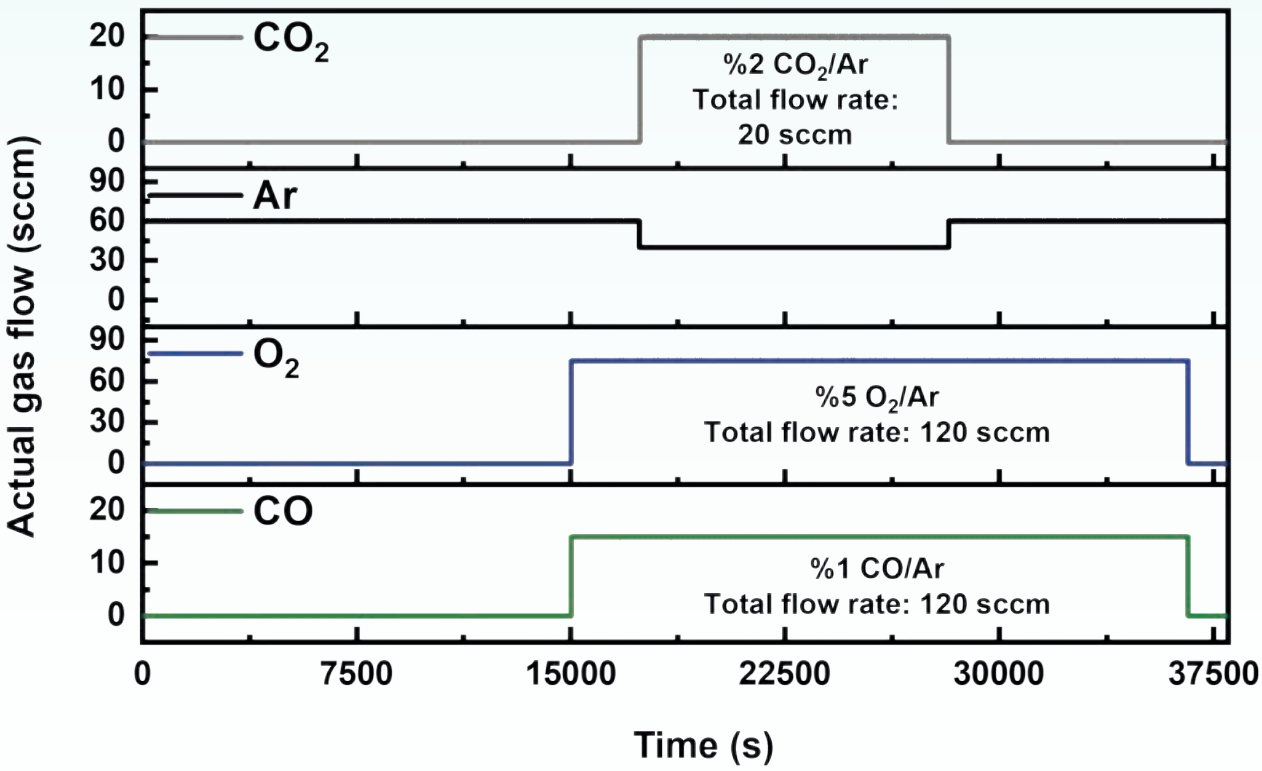
Temperature Control

The integrated furnace can be programmed up to 900 °C, with fully customizable linear ramp profiles ideal for CO_2-TPD, reverse water-gas shift, steam reforming, and other thermal-programmed experiments.

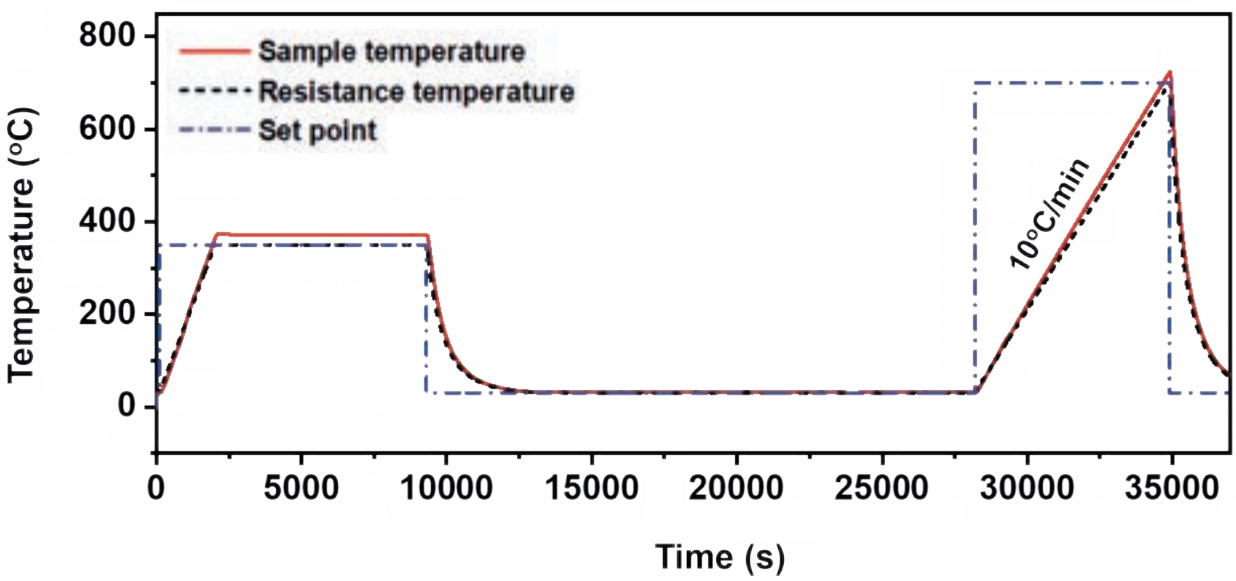
SPECSON
INSTRUMENTS

Performance Analysis

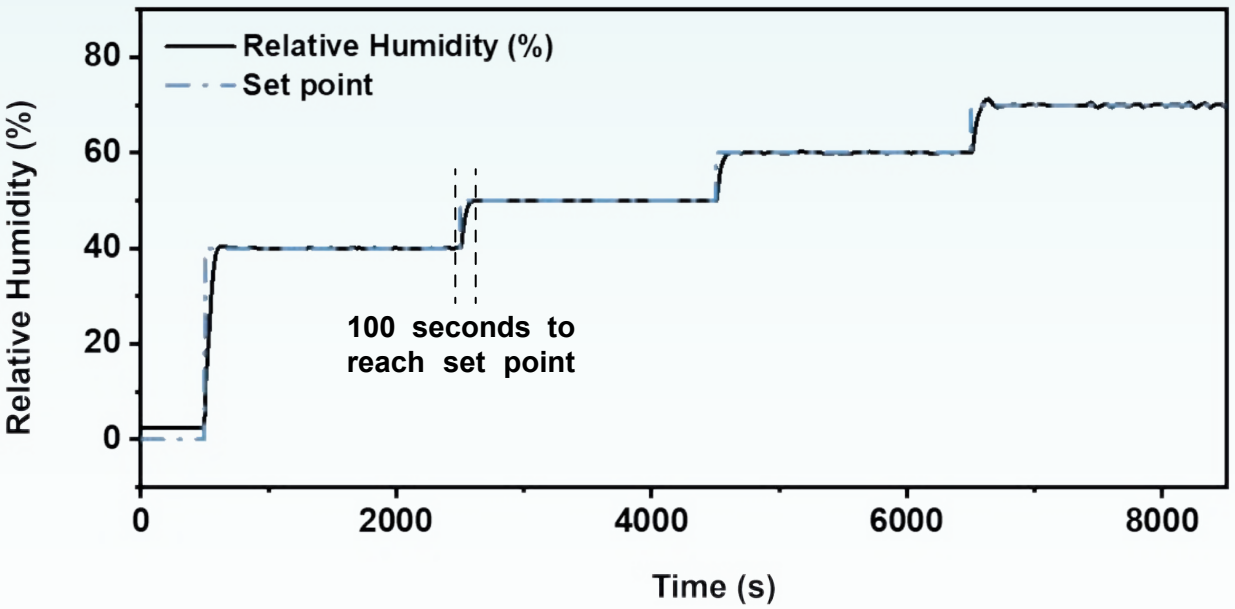
All gases flow at constant flow rates corresponding to the specified set point.



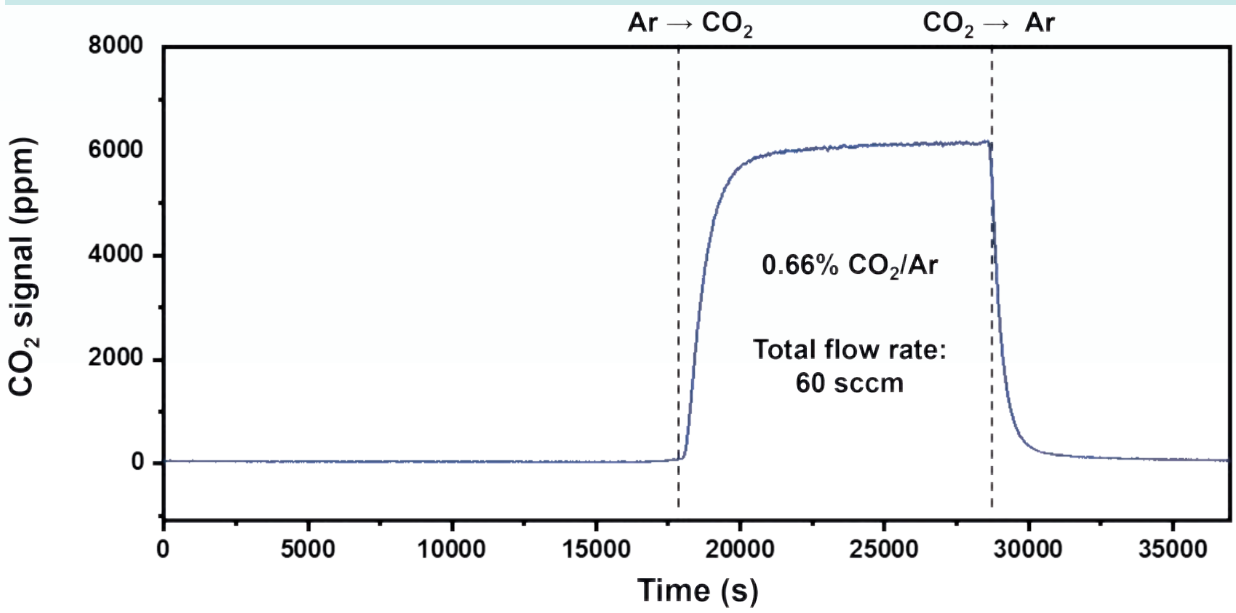
A linear temperature ramp was applied, with
continuous monitoring of the sample and resistance temperature.



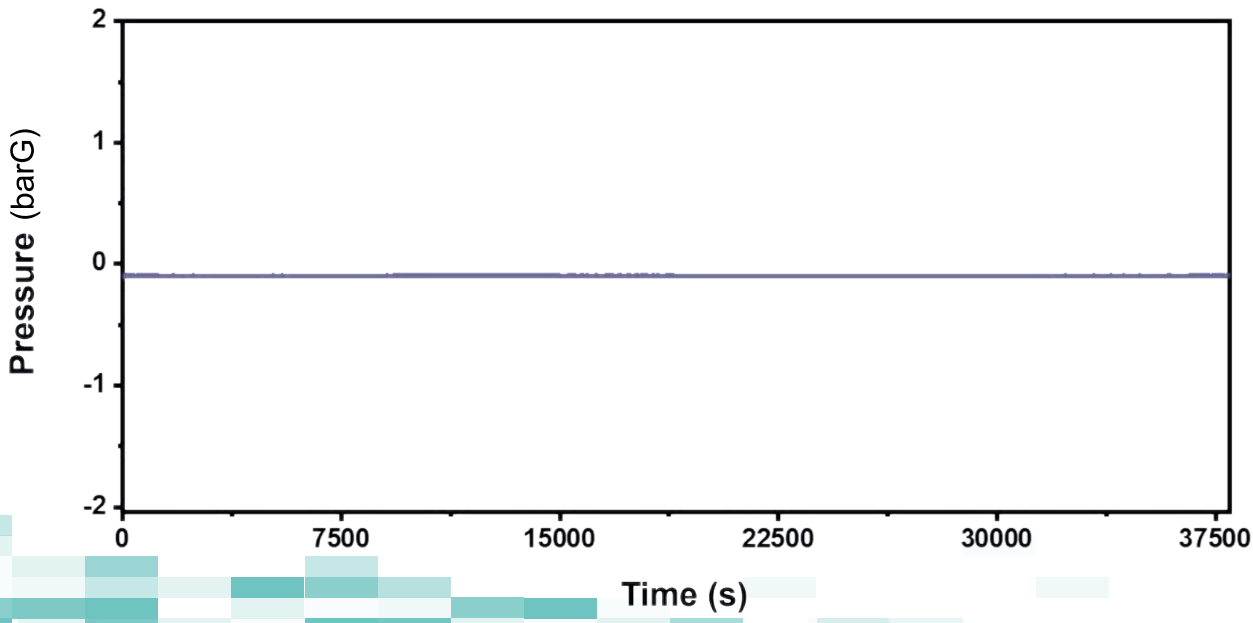
Reactor relative humidity was controlled and monitored at levels up to 70% RH (300 sccm gas mixture of CO_2 + Ar)



The CO_2 concentration was measured using a non-dispersive infrared (NDIR) detector (60 sccm gas flow in 0.66%CO_2 | CO_2 capture experiment with 13X zeolite sample)

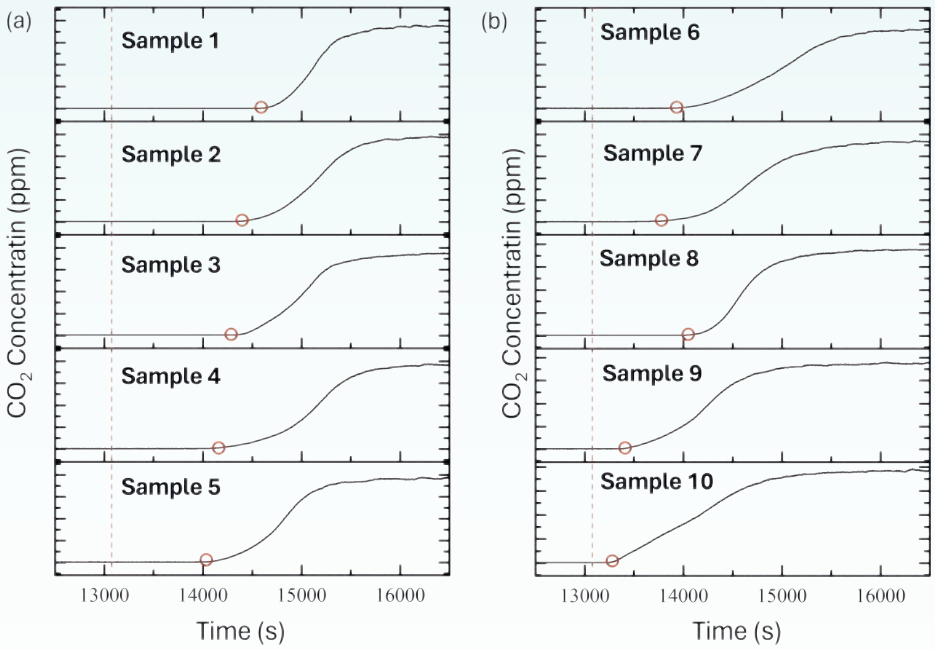


Real-time reactor pressure monitoring.



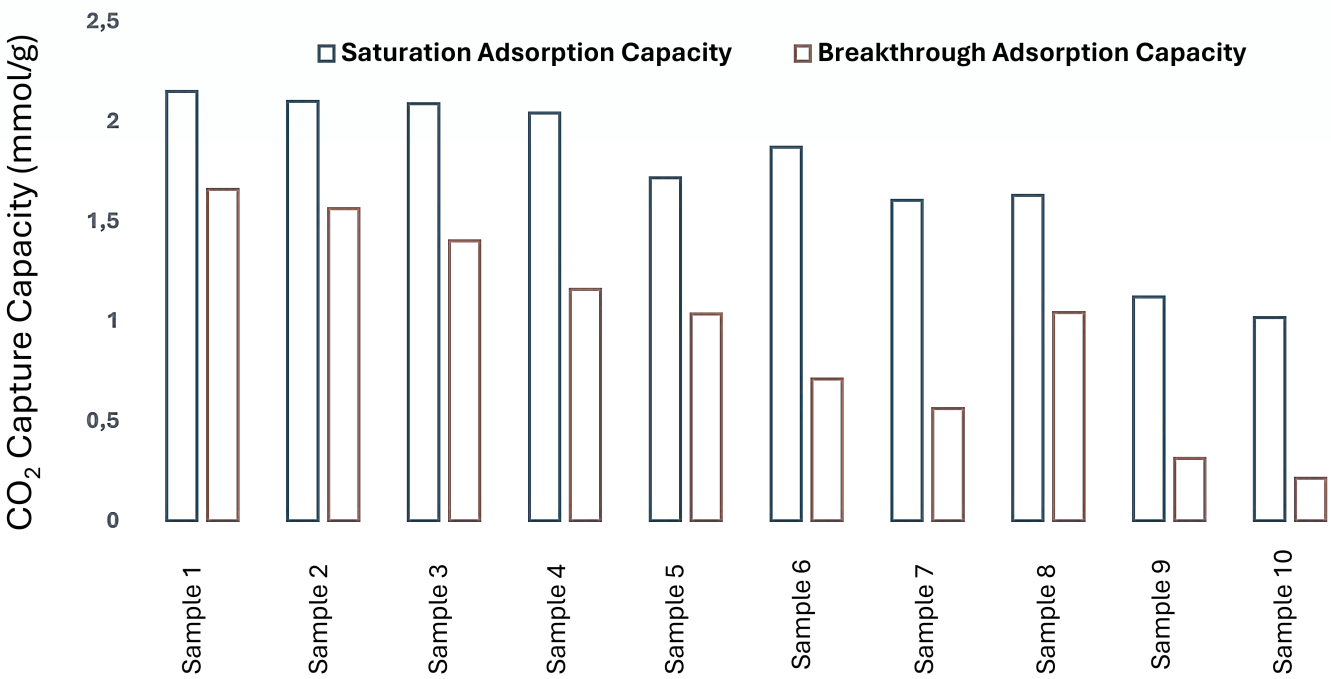
Applications

Dynamic CO_2 Breakthrough Analysis



Dynamic CO_2 breakthrough curves of CO_2 signal recorded by NDIR CO_2 Sensor under continuous 20 sccm 0.2% CO_2 gas flow of ten different test samples. Red dashed-line vertical to the x axis corresponds to gas switch onset point from Ar to 0.2% CO_2. Red circles pinned on CO_2 curve represents the point where CO_2 signal rise up.

Calculated CO_2 Capture Capacities (mmol/g) of Corresponding Sorbent Materials



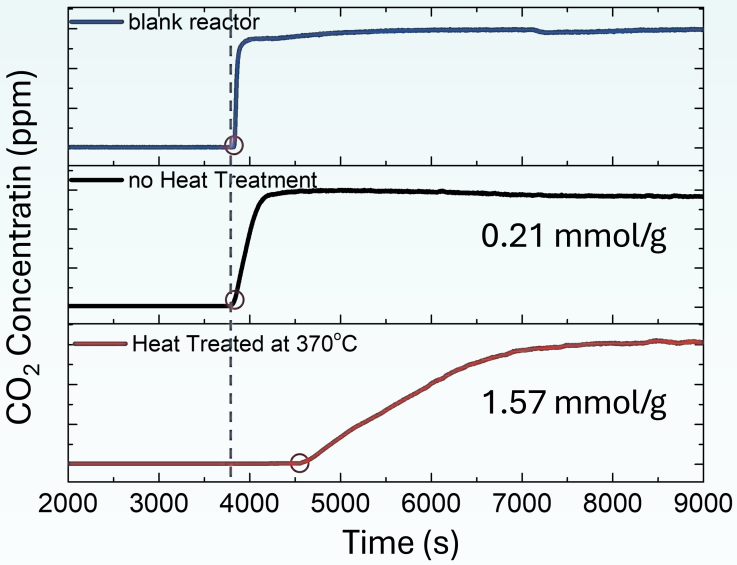
Published Results

Solar-driven calcination of clays for sustainable zeolite production: CO2 capture performance at ambient conditions

Pelin Pasabeyoglu, Erdem Deniz, Gkiokchan Moumin, Zafer Say, Burcu Akata

Journal of Cleaner Production, 477, 2024, 143838

Effect of Pre-treatment on Dynamic CO_2 Breakthrough Curves and CO_2 Capture Capacity



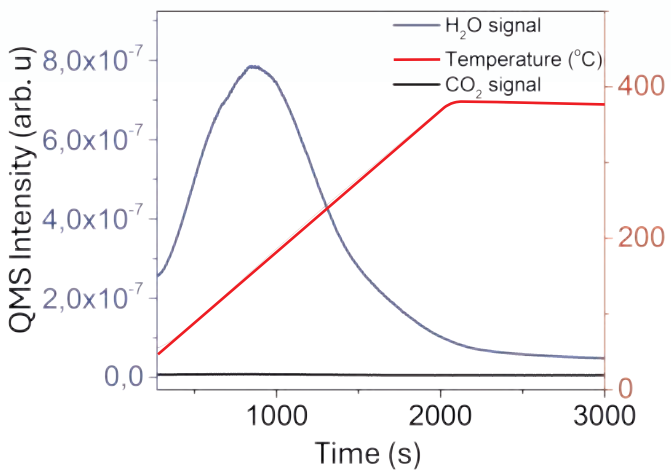
Dynamic CO_2 Breakthrough Curves of blank reactor(blue), 13X zeolite without(black) and with (red) heat-treatment. Gray dashed-line exhibitst the gas switch from Ar to CO_2. The red circles on each curve indicate the points where the first CO_2 signal was detected by the NDIR Sensor.

The time interval between the dashed line and the red circle, during which no CO_2 signal is detected, demonstrates the filling of the available pore volume of each porous sorbent material. This interval reflects the CO_2 capture capacity and efficiency of the different zeolite samples.

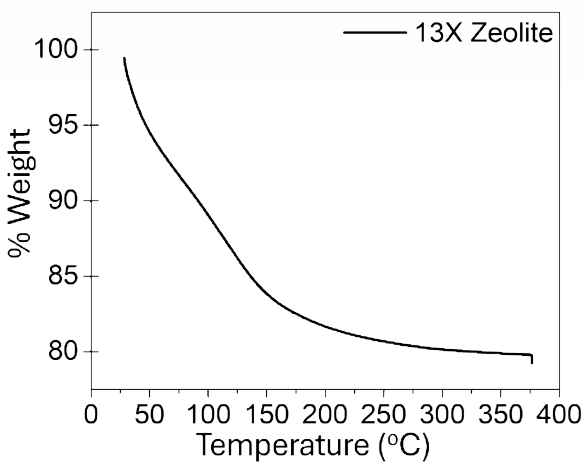
If no pre-treatment applied, all the pores and internal cages remain occupied by ambient water and other gases. Therefore, no rooms for CO_2 capture.

The delay between dashed line and red circle can be attributed to a larger pore volume, which allows more CO_2 to be adsorbed before it becomes detectable by the NDIR Sensor, and a stronger capture affinity, whereby CO_2 molecules are more effectively captured by the zeolite active sites.

Supporting Figure for water desorption during heat treatment.



(18 amu signal is recorded by SRS RGA200. Quartz reactor is heated up to 370°C with a 10°C/min ramp.)



(TG-MS results of 13X zeolite (a) % weight loss during heating under N_2 up to 400°C. (b) MS data recorded by Specson portable RGA 200 gas analyzer. Heating ramp of 10°C/min.)

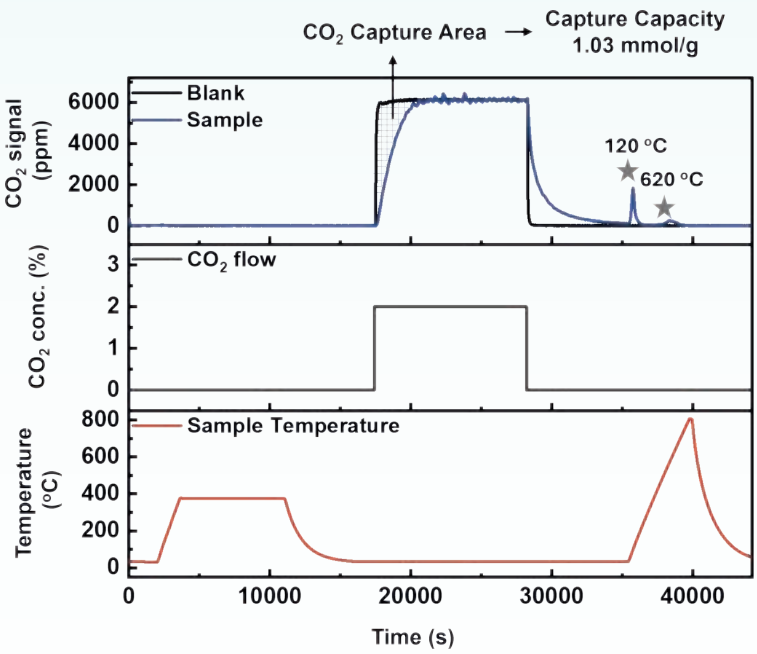
One should always keep in mind the possible weight loss during heat treatment. In this specific example, 13X zeolite looses its 20% of initial weight. This is very important to calculate CO_2 capture capacity by unit mass.

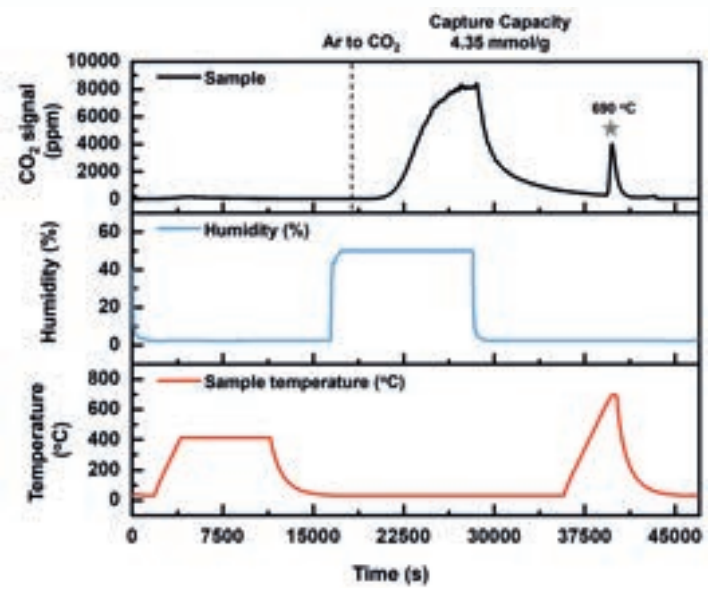
Water desorption has started around 100°C, exhibited a peak maxima around 180°C, and continues around 20 min up to 370°C. Ease of outgassing depends on the sample nature.

CO_2 Capture Breakthrough Curve Analysis in Dry and Humid Environment

The CO_2 capture performance of 13X zeolite was investigated under dry and humid conditions by recording breakthrough curves, with simultaneous monitoring of CO_2 concentration, controlled moisture, and sample temperature to quantify capture capacity and evaluate the impact of humidity on sorbent behavior.

Breakthrough experiments were conducted under a dry CO_2 gas stream at ambient temperature. Prior to analysis, the 13X zeolite was thermally pretreated under an Ar flow to eliminate adsorbed water and residual surface species. Subsequently,CO_2temperature-programmed desorption (CO_2-TPD) was performed under Ar with a linear heating ramp up to 800 °C. The desorption profile revealed two prominent CO_2 release peaks centered at approximately 120 °C and 620 °C.



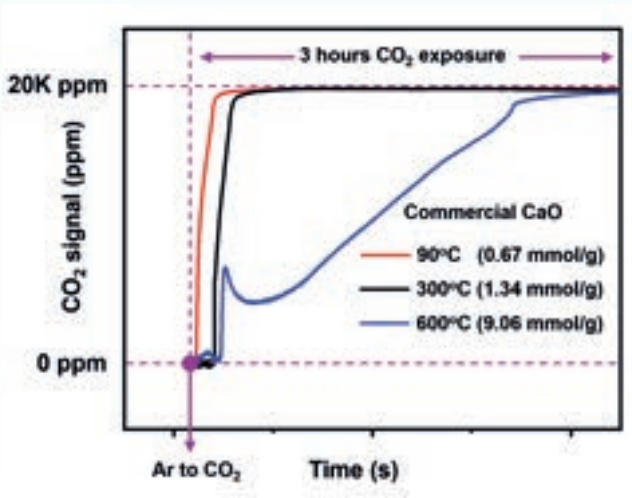


Analogous breakthrough measurements were carried out under a humid atmosphere (50% relative humidity). In contrast to the dry CO_2 stream, the resulting breakthrough profile exhibited a markedly different character. The presence of water vapor led to a substantial enhancement in CO_2 uptake, with the capture capacity increasing to 4.36 mmol g^{-1} cat, compared to 1.04 mmol g^{-1} cat under dry conditions. In addition to this, the humid environment significantly altered the adsorption mechanism, suggesting the cooperative role of water molecules in promoting the formation of bicarbonate- or carbonate-type species on the zeolite surface. This synergistic effect accounts for the enhanced CO_2 capture capacity observed under humid conditions. This interpretation is further supported by the CO_2-TPD profile obtained under humid conditions, which exhibited a pronounced desorption peak at ~690 °C, while the low-temperature desorption feature was completely absent. This shift indicates the stabilization of more strongly bound CO_2 species in the presence of water vapor, consistent with the formation of bicarbonate/carbonate-type intermediates.

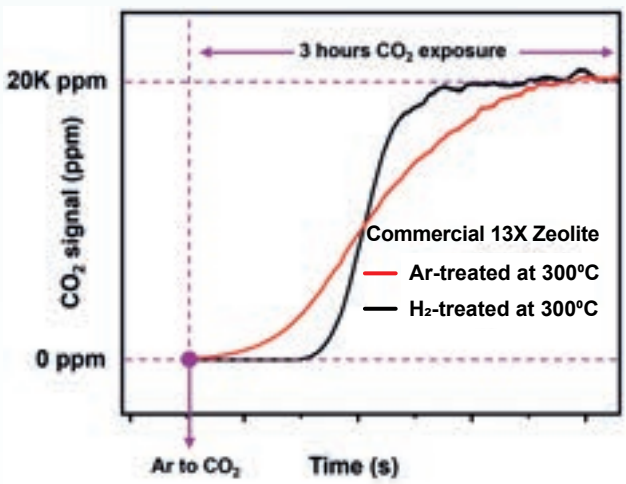
Effect of Temperature and Pre-treatment Conditions on CO_2 Capture Capacity

The system enables evaluation of sorbent performance and CO_2 capture capacity under varying temperatures, as demonstrated with commercial CaO. Temperature-dependent CO_2 capture behavior is a key parameter in selecting suitable materials for specific capture–utilization processes, since operational temperature strongly influences both capacity and regeneration efficiency.

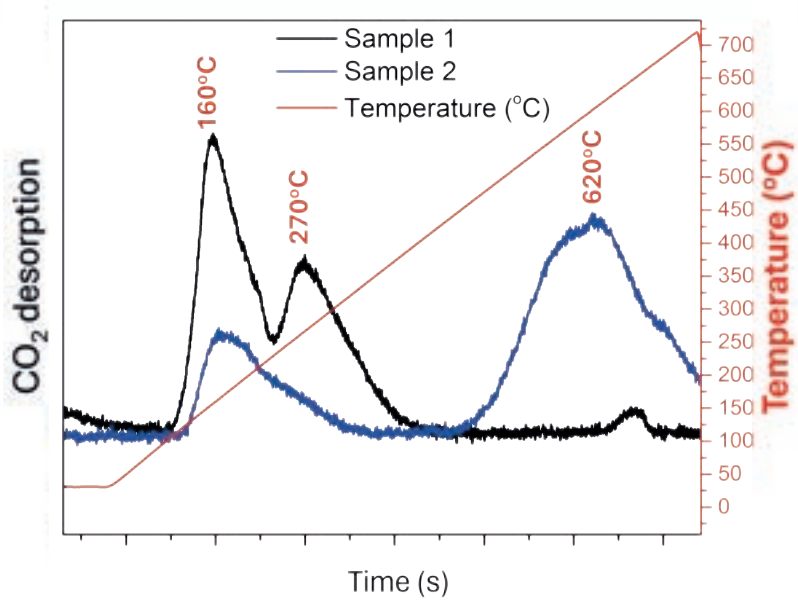
Effect of Temperature



Effect of Pre-Treatment Conditions



Temperature Dependent CO_2 Desorption Analysis

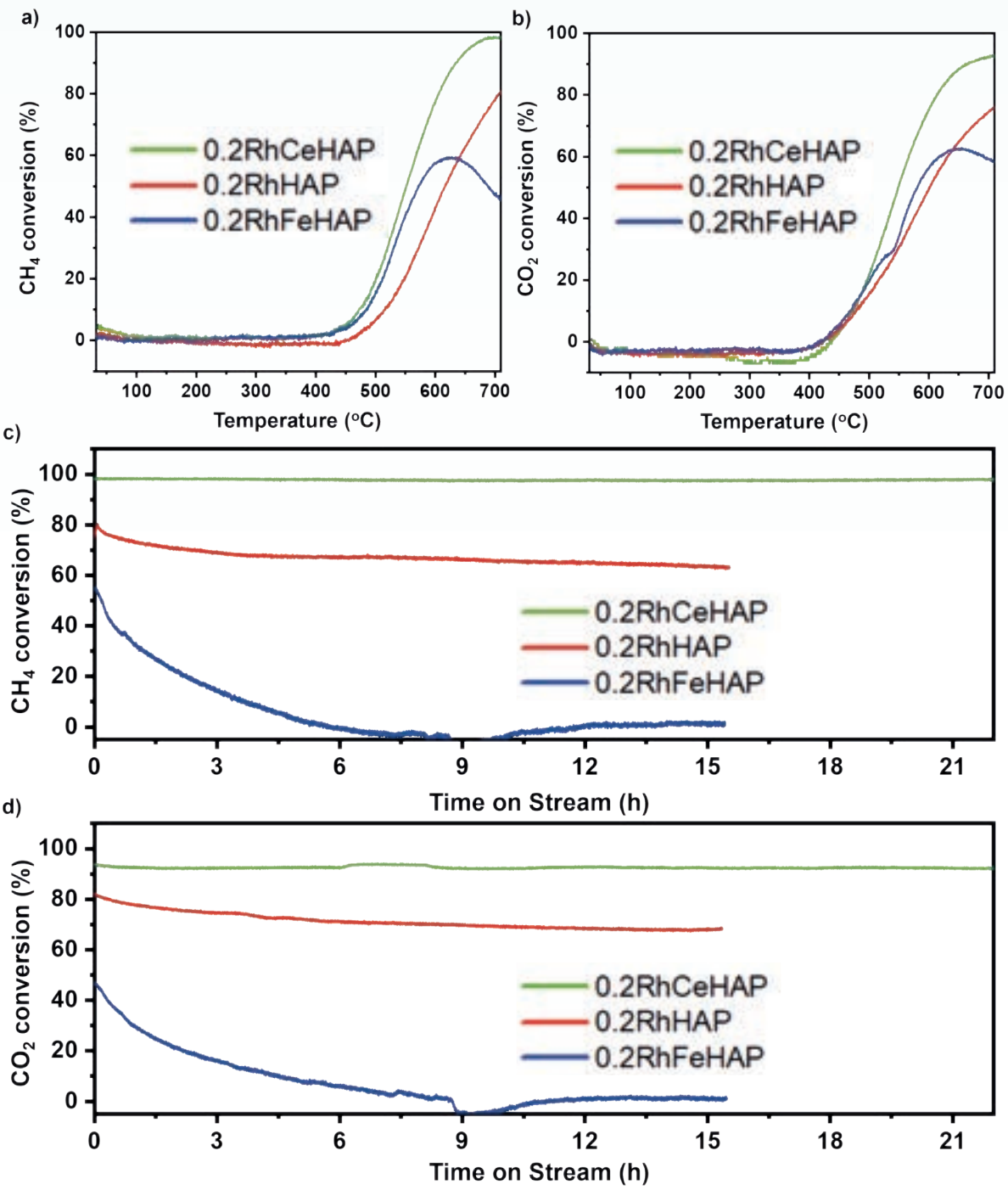


CO_2 desorption analysis during heating the solid samples in Argon flow up to 720°C with 10°C/min heating rate. This analysis can be also performed in O_2-rich gas atmosphere for combustion tests.

Recently, two additional samples were evaluated, both exhibiting comparable CO_2 capture capacities. However, subsequent analysis revealed significant differences in their regeneration behavior, which directly affects their potential commercial applicability. For instance, Sample 1 could be almost completely regenerated by heating to ~270 °C under an Ar flow, whereas the second material required thermal treatment above 620 °C for effective regeneration. These contrasting regeneration profiles highlight the importance of thermal stability and energy requirements in assessing the practical viability of CO_2 sorbents.

Dry Reforming of Methane: Temperature Resolved Activity & Time on Stream Experiment

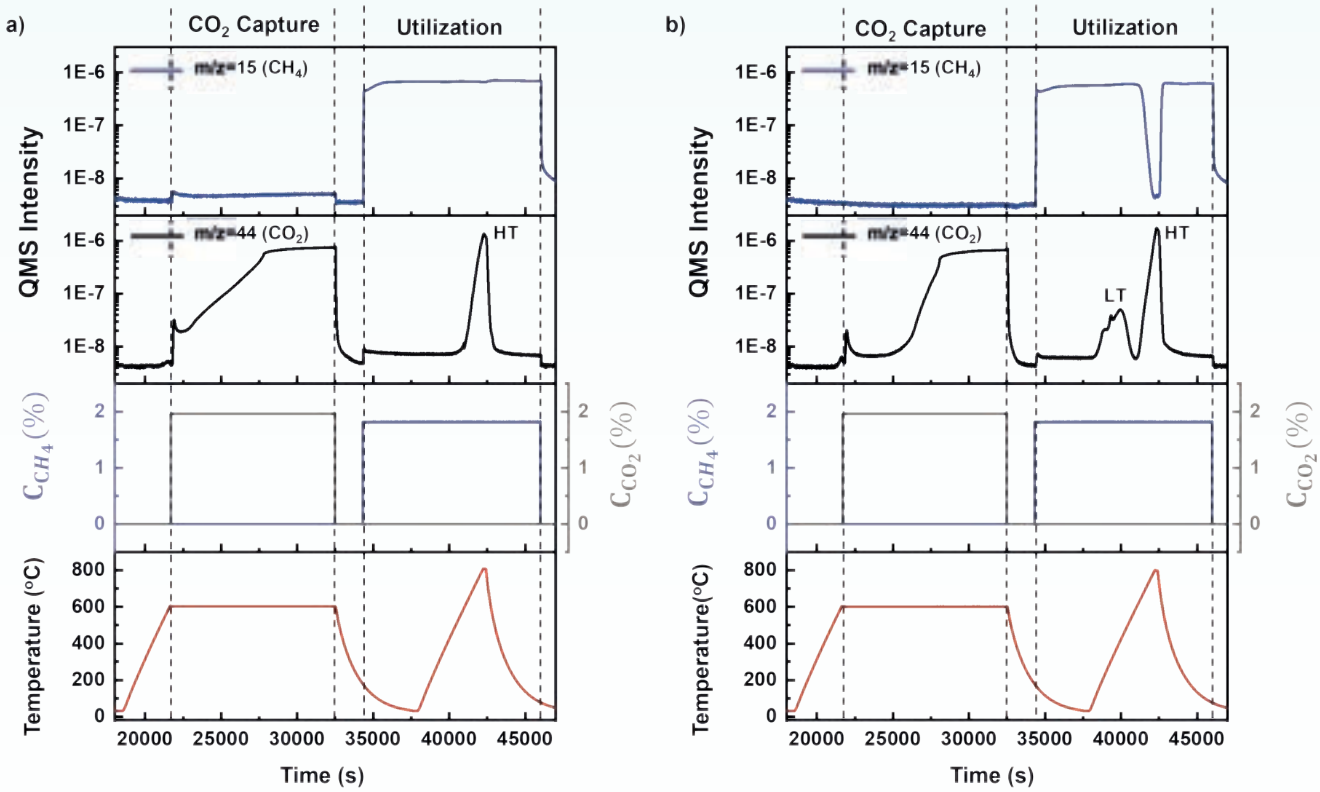
Dry reforming of methane ($CH_4 + CO_2 \rightarrow 2H_2 + 2CO$) is a critical reaction for both environmental and industrial reasons. It simultaneously converts two potent greenhouse gases—methane and carbon dioxide—into syngas, a valuable feedstock for chemical synthesis (e.g., Fischer–Tropsch processes, methanol production). Studying temperature-resolved activity allows researchers to determine the optimal operating conditions for maximum reactant conversion and syngas selectivity. Meanwhile, time-on-stream experiments provide insights into catalyst stability, deactivation mechanisms (e.g., coking or sintering), and regeneration potential under prolonged operation. Together, these experiments are essential for designing efficient, durable catalysts capable of sustainable CO_2 utilization and methane valorization.



Temperature-dependent (a) CH_4 and (b) CO_2 conversion performances of Rh-based catalysts. (c) CH_4 and (d) CO_2 conversions during TOS at 700 °C under a 0.4% CH_4 + 0.4% CO_2 gas mixture in Ar with a total flow rate of 100mL/min.

CO_2 Capture and Dry Reforming of Methane (ICC-DRM)

The integration of carbon capture and utilization (ICCU) with DRM offers a practical pathway to reduce greenhouse gas emissions. By capturing CO_2 from external processes and reusing it as a feedstock in DRM, this approach creates a closed-loop system with enhanced environmental and operational benefits.

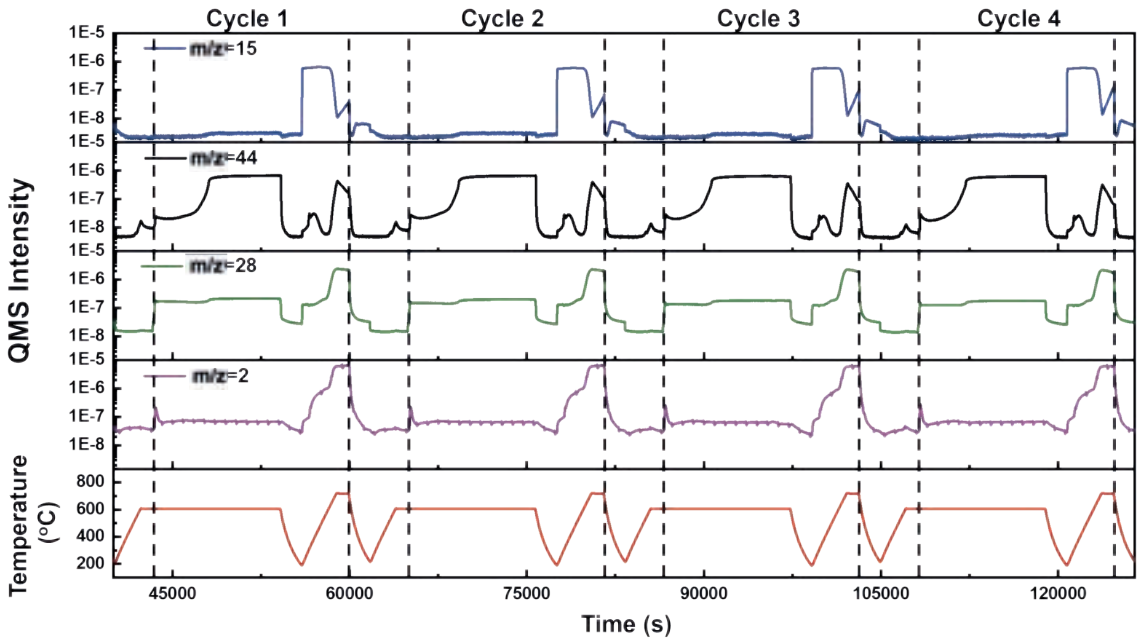


Time-dependent CH_4 and CO_2 QMS signals, gas concentrations, and temperature profiles for (a) CaO adsorbent and (b) dual-functional material (RhCeHAP + CaO)

The ICC-DRM represents one of the most recent experimental capabilities within the CCUS-1 setup. In this procedure, materials are initially exposed to a continuous CO_2 flow until equilibrium saturation is reached at the target temperature. The CO_2 capture process is monitored via the breakthrough curve, allowing quantitative determination of the CO_2 uptake in mmol per gram of sorbent (Step 1). Subsequently, the sample is heated to 800 °C at a linear ramp rate of 10 °C min^{-1} under a constant 2% CH_4 flow (Step 2). During this stage, the captured CO_2 is released and reacts with CH_4 to generate syngas.

Figure A shows ICC-DRM testing of CaO in the absence of a catalyst. In Step 1, CaO captures CO_2 effectively at ~600 °C, followed by desorption at approximately the same temperature, with a pronounced peak near 700 °C in Step 2. Although this temperature range is suitable for dry reforming of methane (DRM), the absence of a catalyst prevents CH_4 conversion. In contrast, the introduction of a Rh catalyst to CaO, as shown in Figure B, enables simultaneous CO_2 desorption and CH_4 consumption at ~700 °C, highlighting the catalyst's essential role in promoting the DRM reaction under these conditions..

Integrated CO_2 Capture and Dry Reforming of Methane: Multicycle Run



Excellent reproducibility of gas switches and temperature heating/cooling cycles during 36 hours of continuous flow.

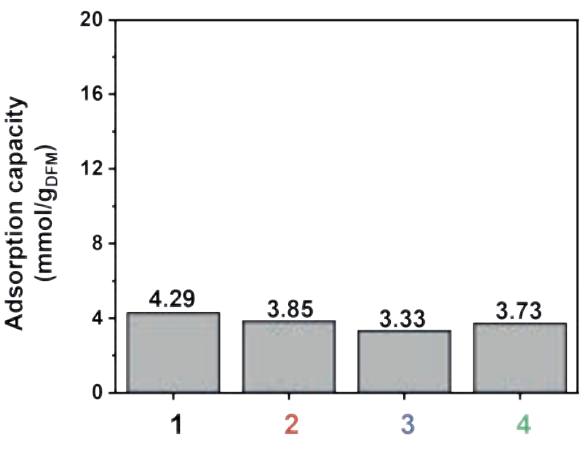
Test: Cyclic ICC-DRM experiments were performed to evaluate the long-term stability of the dual-function material (DFM) in a tubular quartz reactor under atmospheric pressure.

Pretreatment: The sample was heated to 600 °C in a 5% H_2/Ar flow and maintained at this temperature for 2 h, followed by cooling to room temperature in the same reducing environment.

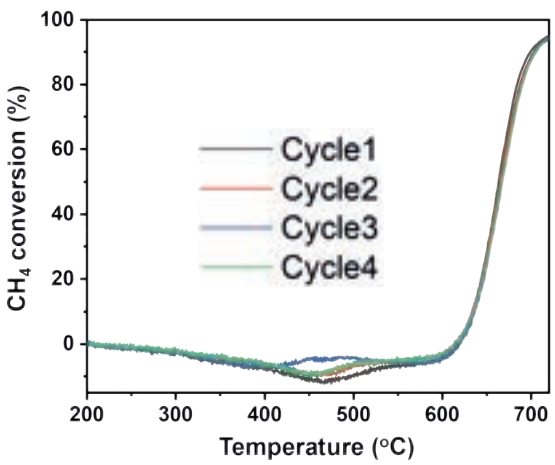
Cycle: Each cycle consisted of (i) CO_2 capture at 600 °C in a 2% CO_2/Ar stream (20 mL min^{-1}) for 3 h, (ii) cooling to room temperature under Ar, and (iii) dry reforming of methane (DRM) at 700 °C in a 2% CH_4/Ar stream (50 mL min^{-1}) for 4500 s.

Monitoring: Gas-phase products were monitored online using a quadrupole mass spectrometer (QMS), tracking CO_2 (m/z = 44), CH_4 (m/z = 15), CO, and H_2. Dashed lines in the data plots indicate the beginning and end of each cycle.

Evaluation: The CO_2 uptake and CH_4 conversion were quantified on a per-cycle basis to assess adsorption–conversion efficiency and durability over repeated operation.



Calculated CO_2 Capture Capacity



Calculated % CH_4 Conversion

Specson Prototyping Atelier

2 x CNC Vertical Machining Center with 4th Axis

-10,000-rpm inline direct-drive spindle
-30+1 side-mount tool changer
-High-Speed Machining control option
-X/Y/Z : 762/406/508 mm

-HRT210 Platter Diameter 210 mm
-Max Speed 100°/sec
-Backlash 30 arc-sec
-Resolution: 0.001 °

CNC LATHE

-One piece 30° slant bed
-Large swing diameter 600 mm
-8" Power chuck / 4200 rpm
-Z-axis travel:
400 mm (Vturn-S20/40)
600 mm (Vturn-S20/60)

-Shortened belt driven spindle
-High rapid feed 20/24 m/min (X/Z)
-Machine width 2300mm only (for Vturn-20/40 with rear disposal chip conveyor

With our expertise in both large-scale production and prototype manufacturing, we will be pleased to offer tailored solutions to your startup's needs.

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