PILOT-SCALE TESTING OF ALUMINIUM METAL ORGANIC FRAMEWORKS FOR POST-COMBUSTION CO_2 CAPTURE AT TECHNOLOGY CENTRE MONGSTAD (TCM)

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Topics: Projects – Pilots and demos; Pre- and post-combustion capture – Adsorption

Keywords: *Pilot; Adsorption; MOF; Experiments; Simulations*

ABSTRACT

The accelerating frequency and severity of extreme weather events, driven by rising anthropogenic greenhouse gas emissions, highlight the urgent need for effective decarbonization strategies to achieve climate neutrality. Carbon Capture and Storage (CCS) or Use (CCU) has emerged as a leading approach for CO_2 mitigation, particularly in carbon-intensive, post-combustion industrial processes. Among various CCUS technology, adsorption is a promising technology that can potentially reduce energy consumption and environmental impacts as solvent loss or toxicity of amine absorption process. The use of metal-organic frameworks (MOFs) has an important potential due to the high CO_2 adsorption capacity, selectivity, and efficient regeneration capabilities of these materials. Although extensive lab-scale studies highlight the potential of MOFs for CO_2 capture, industrial-scale application remains limited, and the effects of real operational conditions on factors like productivity, purity, and energy consumption are not yet fully understood.

Addressing the issue, a consortium of 14 partners from 8 different countries has collaborated to establish the MOF4AIR project. The initiative aims to develop and demonstrate the performance of promising MOF materials in post-combustion CO_2 capture contexts. Technology Centre Mongstad (TCM) is one of the three selected demonstration sites to test the MOF-based CO_2 capture technology at industrial scale as part of the MOF4AIR project.

Following evaluations across various scales—including working capacity, CO_2/N_2 selectivity stability tests with impurities, binder selection for shaping, green synthesis, cost and lab-scale pilot testing, MIL-160(Al) (formula: $Al(OH)(O_2CC_4H_2OCO_2)$) (A. Cadiau et al, 2015; D. Damasceno Borges et al., 2017) emerged as a promising MOF candidate for scaling up to pilot demonstration (60 kg) using a vacuum pressure swing adsorption (VPSA) process for carbon capture. MIL-

160(Al) features an inorganic aluminum chain linked by five-membered 2,5-furan dicarboxylate rings, forming helical chains with interactive sites that selectively adsorb CO_2 (or H_2O) over N_2. With an adsorption enthalpy of -33 kJ/mol for CO_2, this MOF allows efficient regeneration. MIL-160(Al) was synthesized through a mechanochemical process and shaped by extrusion at MOFTECH facilities, where process optimizations were made to meet the required crushing strength (minimum 10 N) while minimizing porosity losses. The demonstration pilot setup at TCM (Figure 1) is designed to treat 50 to 100 Nm^3/h of flue gas coming from a residual fluid catalytic cracking unit (RFCC) or from a steam boiler (Mongstad heat plant (MHP)). The pilot includes (i) a scrubber, (ii) a water removal unit, (iii) a contaminant removal unit, and (iv) the MOF section, which comprises three 41 L columns filled with pelletized MOF material. The pilot operates a 6-step cycle composed of an adsorption step, heavy reflux, co-current evacuation, counter-current evacuation, light reflux and light product pressurization (Figure 2) (M. Khurana et al., 2016).

This demonstration unit was firstly optimized with a simulation model developed with the results obtained with the laboratory scale VPSA pilot using an aliquot of the 60kg of MIL-160(Al) (Henrotin et al. 2024). Breakthrough curves measured on the TCM pilot were used to adjust the heat transfer coefficients of the adsorption bed, and validate the simulation model at this scale. A design of experiments (DOE) was constructed to create a surrogate model including (i) adsorption time, (ii) light reflux time, (iii) co-current evacuation time, (iv) feed flow rate, (v) light reflux flow rate, and (vi) feed CO_2 concentration. Results obtained from the DOE were used to fit an artificial neural network giving a value of R^2 >99.9% for recovery, purity and energy consumption. Optimization of the unit using a genetic algorithm (NSGA-II) was performed with the surrogate model to maximize purity and recovery while minimizing energy consumption. From simulation, the demonstration unit is able to reach purity and recovery higher than 90% for CO_2 concentration ranging from 5 to 15% at 50 Nm^3/h of flue gas. If the flowrate increases the recovery and the purity decrease (Figure 3). The optimization procedure made through the simulation enabled optimum conditions to be found for each concentration of gas to be treated, defining test conditions for the demonstration unit.

After MOF loading in the TCM demonstration unit, breakthrough tests were conducted to understand material activation and compare with simulation results. Performance tests were carried out based on an experimental plan derived from VPSA simulations. Various VPSA configurations were tested to improve CO_2 recovery and purity. During the test campaign at TCM, parameters such as co-current evacuation time, co-current flow rate, and counter-current flow rate were found to significantly influence the adsorption process. However, achieving the target levels for CO_2 capture and purity has been challenging, with fine-tuning hindered by the process's inherent complexity.
The VPSA unit was extensively modified to enhance performance. Optimization efforts have been focused on reducing flow and pressure in the co-current evacuation step, as well as reducing light reflux flow rate. After more one year of tests and improvements, current results indicate solid overall performance of both the VPSA system and the plant's operational flow. The maximum CO_2 purity achieved was 95.6 ± 3.6 % with a recovery of 91.1 ± 0.3 % and with an energy consumption of 743 ± 12.2 kWh/ton. These data are calculated based on a 2-hour operating period representing 35 consecutive cycles.

The results from the TCM site demonstration reach to project objectives with a recovery higher than 90% and a purity higher than 95% and demonstrates the feasibility of using MOFs in a post-combustion CO2 capture process.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 831975 (MOF4AIR project).
The authors would like to thank MOFTECH for supplying the MIL-160(Al).

REFERENCES

A. Cadiau et al., "Design of Hydrophilic Metal Organic Framework Water Adsorbents for Heat Reallocation," Adv. Mater. 2015, 27(32), 4775–4780.
D. Damasceno Borges et al., "Gas Adsorption and Separation by the Al-Based Metal–Organic Framework MIL-160," J. Phys. Chem. C. 2017, 121 (48), 26822–26832.
M. Khurana and S. Farooq, "Simulation and optimization of a 6-step dual-reflux VSA cycle for post-combustion CO_2 capture," Chem. Eng. Sci., vol. 152, pp. 507–515, 2016.
A. Henrotin et al., "Lab-scale pilot for CO_2 capture vacuum pressure swing adsorption: MIL-160(Al) vs zeolite 13X," Carbon Capture Sci. Technol., vol. 12, p. 100224, 2024.

FIGURES

Figure 1: Pictures of the TCM MOF4AIR pilot

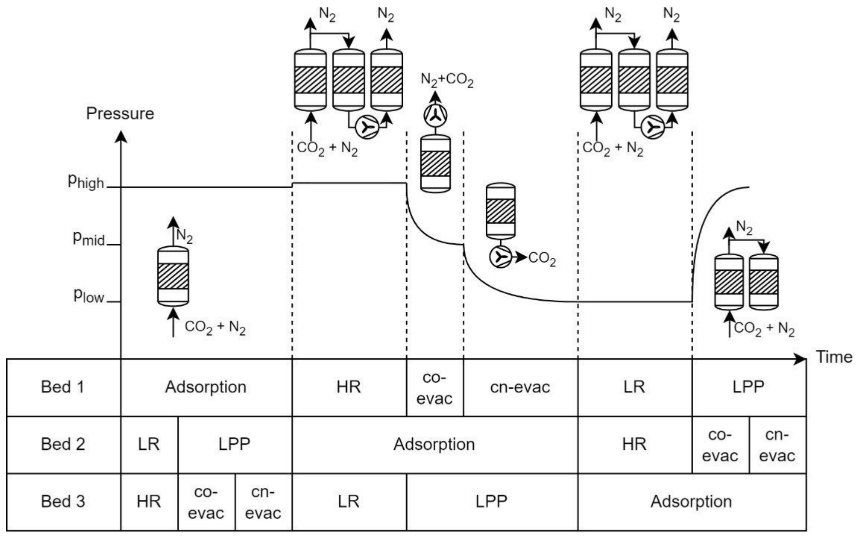

Figure 2. Cycle configuration of the 3-bed 6-step cycle with pressure level representation of bed 1 (HR: heavy reflux, co-evac: co-current evacuation, cn-evac: counter-current evacuation, LR: light reflux, LPP: light product pressurization). The size of the blocks is not representative of the duration of the steps.

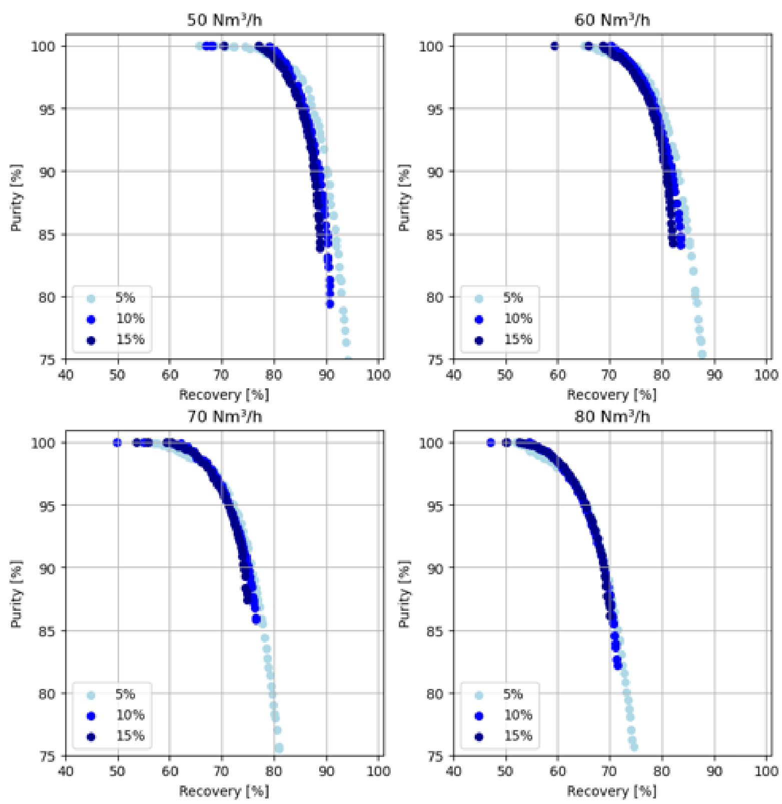

Figure 3. VPSA pilot with 3-columns - 6-step cycle was simulated with Aspen Adsorption© V14 software using the unibed approach by saving and replaying the flow, temperature, composition and pressure of the streams for light and heavy reflux steps, and light product pressurization step.