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CONTINUOUS TEMPERATURE SWING ADSORPTION FOR CARBON DIOXIDE CAPTURE IN INDUSTRY

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1 ABSTRACT

Continuous temperature swing adsorption (TSA) with circulating solid sorbents offers an alternative to monoethanolamine (MEA) scrubbing for CO_2 capture, avoiding corrosion, solvent degradation and amine-related emissions. A pilot-scale continuous TSA plant (250 kg CO_2/d) for biogenic CO_2 from wood-chip combustion was experimentally evaluated and used to validate a process model for industrial scale-up. With 4–5 stages on adsorber and desorber, capture efficiencies above 95 % and CO_2 purities above 98 vol% (dry) are achieved, implying industrial contactor heights of 6-8 m. No degradation of the amine-functionalised sorbent (Lewatit® VP OC 1065) was observed, and no decomposition products were detected in the off-gas; besides CO_2, the product gas contains only H_2O and N_2 used as fluidising agent. Scale-up simulations and techno-economic assessment indicate capture costs of 125-190 €/t CO_2 (i.e., 139 – 219 \$/tCO_2) at a footprint of 30-50 kg CO_2-eq/tCO_2 under biomass heat and low-carbon electricity. These costs exceed the small-scale MEA benchmark of 87–103 \$/tCO_2 and purities of 99.6-99.9 vol% CO_2 but lie at the lower end of the MEA regeneration energy range [1], [2]. At its current TRL of 5-6, continuous TSA shows strong potential for CO_2 capture in hard-to-abate industries and biomass-derived streams, with full competitiveness expected at a TRL comparable to mature MEA processes.

Keywords: Carbon Capture and Utilization/Storage; Temperature Swing Adsorption; Solid sorbent

2 INTRODUCTION

Industrial CO_2 capture for utilisation or storage requires energy- and cost-efficient post-combustion technologies. MEA scrubbing is the current benchmark, reaching 99.6-99.9 vol% CO_2 product purity at capture costs of 87–103 \$/t CO_2 for small-scale (≈100 kt CO_2/a) energy-from-waste and lime kiln applications [1], [2], but suffers from high regeneration heat demand, large columns, solvent degradation, amine and nitrosamine emissions, corrosion and carry-over of degradation products into the CO_2 product that must be removed for food-grade use [3].

Continuous TSA with solid sorbents, as developed in the ViennaGreenCO_2 project, captures CO_2 from flue gas at 40-50 °C in a multi-stage adsorber and regenerates the sorbent at 105-115 °C [4], [5]. This desorption temperature is essentially the same as the ≈120 °C reboiler temperature in MEA regeneration, so TSA's advantage lies in avoiding a large aqueous solvent inventory and in the absence of solvent degradation, corrosion and amine emissions [1], [3], [6]. The reference case is biogenic CO_2 capture for the food and beverage industry, which demands high purity; similar operating conditions apply when biogenic CO_2 is permanently stored to obtain carbon removal certificates under the carbon removal certification framework (CRCF). This paper presents pilot-scale evaluation of the continuous TSA process together with validated process simulations for industrial scale-up and techno-economic performance relative to MEA scrubbing.

3 MATERIALS AND METHODS:

The methodology comprised three consecutive steps. First, experimental data from a pilot-scale continuous TSA plant (250 kg CO_2/d) capturing biogenic CO_2 from wood-chip combustion flue gas were obtained to evaluate process performance, optimize operation and assess product gas quality. Second, these data were used to validate a process model implemented in IPSEpro. Third, the validated model was applied to a simulative scale-up adapted to the specifications of three industrial stakeholders; the reported performance ranges span these three use cases. Capture costs were defined as the sum of total capital investment, energy costs, material-related operating costs and certification costs for EIGA food/beverage-grade standard verification. Energy prices of 52 €/MWh (thermal) and 120 €/MWh (electric) were assumed, together with a sorbent price of 69 €/kg for Lewatit® VP OC 1065 at the measured replacement rate. The CO_2 footprint was calculated from emission factors of 19 g CO_2-eq/kWh (thermal) and 83 g CO_2-eq/kWh (electric), 2.49 t CO_2-eq/ t for steel amortized over 20 a, and 4.93 kg CO_2-eq/kg for the sorbent.

4 RESULTS AND DISCUSSION

Pilot-scale experiments and validated simulations confirmed the technical feasibility and scalability of the continuous TSA process. Low stage numbers of 4-5 on both adsorber and desorber sides are sufficient to reach capture efficiencies above 95 % and CO_2 purities above 98 vol% (dry), so total contactor heights of 6-8 m are expected to suffice at industrial scale.

CO_2 purity is presently limited by the N_2 used as fluidizing agent, i.e. by an operating constraint rather than an intrinsic process limit; aside from CO_2, the product gas contains only H_2O, which is removed by condensation. No sorbent decomposition products were detected in the off-gas or product stream, and no mechanical degradation or loss of working capacity was observed under the tested conditions. The functionalized amine groups are chemically bound within the cross-linked polymer matrix and cannot be stripped, in contrast to MEA where degradation products can enter the CO_2 stream. Significant O_2-induced degradation of amine-functionalized polymers is measured above 70-80 °C, so adsorption is kept below 50 °C and the desorber operated essentially free of O_2 to protect sorbent lifetime. The current configuration does not meet the EIGA specification of ≥99.9 vol% CO_2 and ≤30 ppmv O_2; the plant is therefore being rebuilt for steam-only fluidization, after which food-grade purity is expected without additional purification [7].

From the scale-up simulations validated with pilot adsorber data, capture costs of 125-190 €/t CO_2 comprise roughly equal shares of investment, sorbent and energy costs, making sorbent price and replacement rate key cost drivers. The optimised thermal energy demand of 0.80-0.90 MWh/t CO_2 (2.9-3.2 GJ/t CO_2) lies at the lower end of the MEA range, with electrical demand of 0.04-0.17 MWh/t CO_2. The CO_2 footprint of 30-50 kg CO_2-eq/t CO_2 is dominated by thermal energy and presupposes biomass heat and low-carbon electricity. The CO_2 product leaves the process gaseous at 20 bar and 10 °C; liquefaction to typical food-grade delivery conditions of −20 °C and 15-20 bar would add approximately 90-96 kWh/t CO_2 [8].

5 CONCLUSION

Continuous TSA has demonstrated its potential as an alternative to conventional MEA scrubbing for industrial CO_2 capture. Pilot-scale investigations and validated process simulations confirmed high capture efficiencies (>95 %) and product purities (>98 vol% CO_2, dry) without detectable sorbent degradation under appropriately oxygen-limited conditions. The techno-economic assessment identified thermal energy demand and sorbent-related costs (price, replacement rate and oxidative stability) as main contributors to capture costs, indicating that heat integration and improved sorbent materials are key levers for further optimization. Given its current performance and development status, continuous TSA represents a promising option for biogenic CO_2 utilization and for biomass-based carbon dioxide removal pathways, with the potential to become competitive with established MEA technologies as scale-up and sorbent optimization proceed.

6 References

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