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Development of a Circular CO_2 Capture and Reuse System for Small and Medium-Sized Industrial Applications

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Abstract

The growing emphasis on sustainable industrial processes, aligned with circular economy principles, has heightened awareness of the significant CO_2 emissions generated by various industries. Addressing this challenge, GasN2, in collaboration with IQS, aims to develop a reusable CO_2 capture technology specifically designed for small and medium-sized enterprises (SMEs). This in-situ solution enables businesses to capture and repurpose CO_2 for their own operations, with applications in wastewater treatment, brewing, meat processing, food packaging and other industrial sectors.

The Spanish Ministry of Agriculture, Fisheries, and Food reports that between 55 to 58 million pigs are slaughtered annually in Spain, with approximately 85–95% undergoing CO_2 stunning. Current industry practices estimate a CO_2 consumption of approximately 400 g per pig, amounting to an annual usage of nearly 20,000 tons of CO_2 exclusively for stunning procedures in Spain. Additionally, 2.5 million cattle, 8 million sheep, and 2 million goats and poultry are processed annually, although CO_2 stunning is not universally applied across these species. Despite its regulatory compliance and widespread adoption, CO_2 stunning presents environmental and welfare concerns. This study explores an innovative approach to reducing the carbon footprint of slaughterhouses by integrating a circular economy model, wherein CO_2 emissions from industrial sources are captured and directly reinjected into the stunning process. This strategy eliminates the need for external CO_2 supply and transportation, thereby significantly reducing the sector's carbon footprint. In addition, this CO_2 system can adjust the purity of the captured CO_2, allowing it to be tailored to animal welfare requirements, resulting in reduced distress during stunning. Existing literature highlights the welfare implications of CO_2 stunning, indicating that high CO_2 concentrations (>80%) induce nociceptive responses, including mucosal irritation and breathlessness, which may contribute to aversion and distress. Conversely, controlled reductions in CO_2 concentration have been associated with decreased aversive reactions while maintaining stunning efficacy. This study aims to evaluate the feasibility of CO_2 capture and recirculation into slaughterhouses. By integrating gas purity adjustments with CO_2 emission capture technologies, this approach presents a viable strategy to reduce commercial CO_2 dependence while enhancing compliance with ethical slaughtering practices and sustainability goals.

The industrial CO_2 capture system operates in three main stages, as it can be seen in figure 1: pre-treatment, treatment via Vacuum Swing Adsorption (VSA) technology, and post-treatment with final Application. The pre-treatment phase

involves the flue gas conduction from the chimney of an industrial boiler towards the CO_2 capture plant. The flue gas stream is cooled and conditioned to remove water and other impurities such as particulates. This is achieved through a series of heat exchangers, demisters and filters, which allow condensation of water vapor and filtration of residual solids prior to CO_2 capture. The treatment stage is based on VSA technology and consists of two independent sets of adsorption columns. The first set is dedicated to flue gas drying, employing a solid desiccant to remove residual moisture. The second set is designed for CO_2 separation, using a solid adsorbent as the selective adsorbent. These VSA cycles operate alternately under vacuum and pressurization to maximize separation efficiency. The VSA cycle employed in this setup is a five-step process encompassing pressurization, adsorption, depressurization, equalization, and regeneration. The main parameters can be checked in Table 1. The post-treatment section includes a vacuum pump, a compressor, and a low-pressure and high-pressure storage tanks. These are followed by a dedicated application system, which in this case is configured to supply CO_2 at controlled concentrations to a stunning cage for livestock processing. This final delivery system integrates a series of valves and pressure regulators to ensure the stability and accuracy of CO_2 concentration over time inside the stunning cage. Throughout the entire process, the system is instrumented with multiple sensors for real-time monitoring of pressure, temperature, CO_2 concentration, and dew point, ensuring robust process control and operational safety under industrial conditions.

Figure 1. *3D isometric plan of CO_2 capture plant and photos, including boiler, chimney, heat exchangers, dryer and CO_2 capture units, blower, vacuum pump, compressor, intermediate low-pressure deposit and high-pressure final product deposit.*

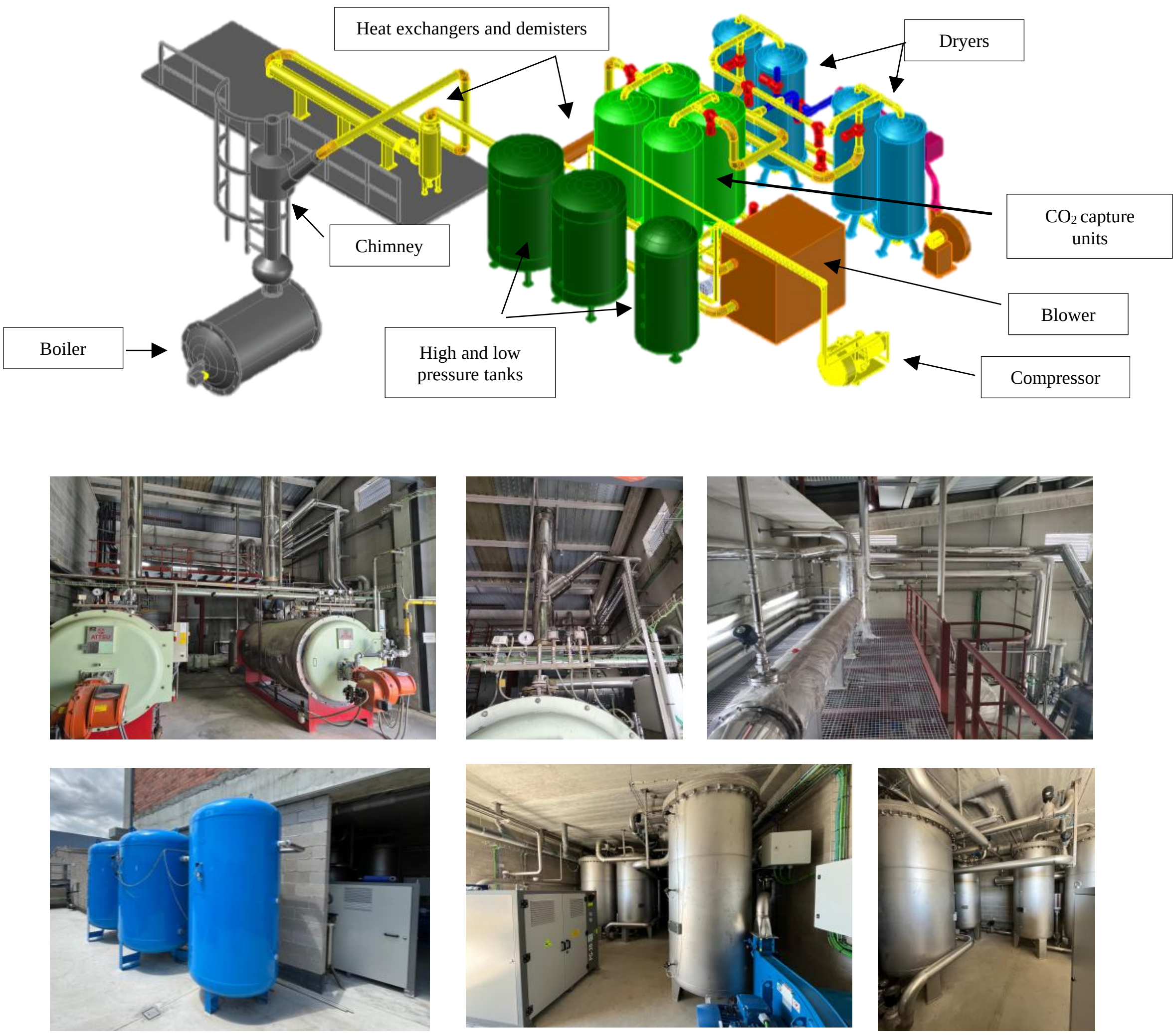

Figure 2. *Simplified diagram of the CO_2 capture plant.*

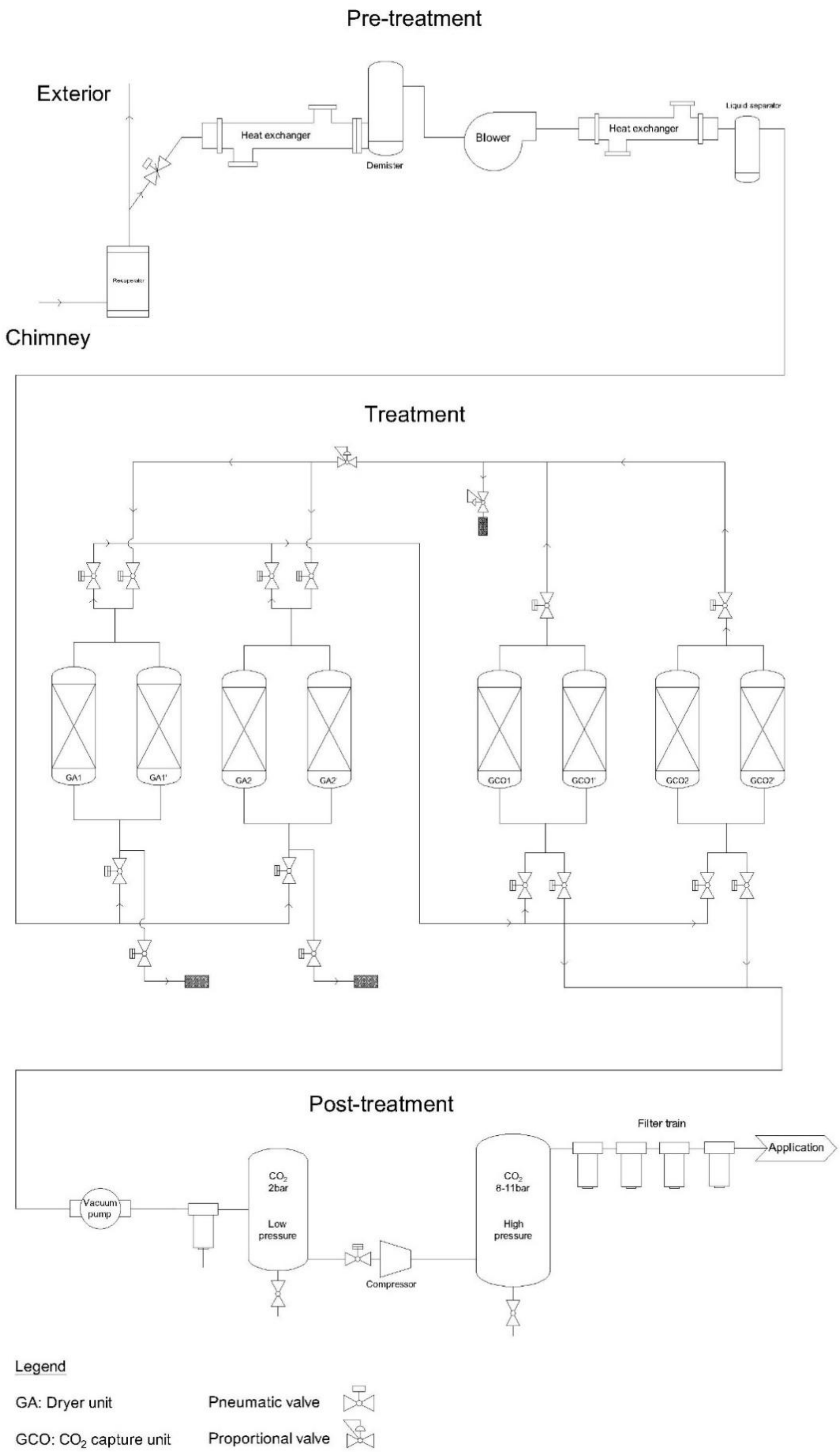

Table 1. *Industrial specifications and conditions*

Dryer		CO_2 capture unit	
Column height (mm)	2000	Column height (mm)	2100
Column diameter (mm)	1000	Column diameter (mm)	1100
Adsorbent quantity (kg)	1450	Adsorbent quantity (kg)	1178
Flow (Nm^3/h)	850	Flow (Nm^3/h)	820
Nº of columns	4	Nº of columns	4
CO_2 (v/v) inlet	4-9	CO_2 (v/v) inlet	4-9
Adsorption pressure (barg)	0.5	Adsorption pressure (barg)	0.4-0.45
Adsorption temperature (ºC)	20-25	Adsorption temperature (ºC)	25-30

Productivity, purity, and recovery obtained are reported in Table 2, with a CO_2 output of 60 kg/h, product purity ranging from 90% to 95%, and recovery rates between 60% and 65%.
Figure 2 shows the evolution of CO_2 concentration at five key points of the system over time during steady state, the inlet to the dryer (%CO_2 dryer inlet), the inlet to the capture unit (%CO_2 inlet), the CO_2 that scapes during adsorption (%CO_2 upper column out), the CO_2 captured (%CO_2 out) and the collected CO_2 captured (%CO_2 final product). The data reflect the system's capacity to progressively purify the gas stream, from initial low CO_2 levels at the dryer inlet to high concentrations at the final product outlet. Fluctuations observed in the outlet of column (%CO_2 out), are consistent with the cyclic operation of the adsorption system, where a less pure stream comes out the column the first five minutes. These transients are effectively smoothed in the final product line (%CO_2 final product), where final purity remains stable, indicating good buffer control and gas homogenization.

Figure 2. *CO_2 concentration profiles and pressure during VSA cycle operation.*

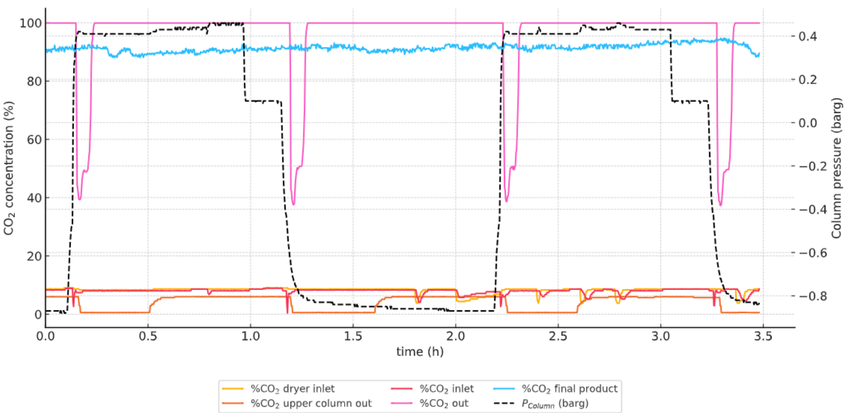

Table 2. *Key parameters including productivity, recovery and purity*

Productivity (kg/h)	60
Purity (kg)	90-95%
Recovery (%)	60-65%

These results demonstrate the feasibility of a modular VSA-based CO_2 capture system tailored for SMEs. By enabling on-site capture and direct reuse of CO_2, the industry would minimize dependence on external CO_2 supply chains and it would also support environmentally and circular responsible practices. Overall, it offers a scalable solution which integrates circular carbon strategies in industrial sectors.

Keywords: Vacuum Swing Adsorption (VSA); Carbon Capture Use and storage (CCUS); Small and Medium Businesses; Industrial Plant; Solid adsorbent; Circular economy; High purity CO_2.