Upgrading of Biogas to Biomethane via Vacuum Pressure Swing Adsorption: Integrated Experimental and Modeling Study for Sustainable Energy Production

Esther Pancione [a], Francesco La Motta [b], Amedeo Lancia[a] & Alessandro Erto [a]

[a] Department of Chemical, Materials and Production Engineering, University of Naples Federico II (Naples, Italy)
[b] Oiltech S.r.l. (Milan, Italy)

E-mail: esther.pancione@unina.it

The upgrading of biogas to biomethane has emerged as a strategic approach to support decarbonization and European goals for climate neutrality, also encouraging sustainable energy production. Biogas contains 60-70% CH_4, 30-40% CO_2, and minor impurities; thus, upgrading is essential to obtain biomethane fully equivalent to fossil natural gas. Vacuum Pressure Swing Adsorption (VPSA) distinctly stands out among the available technologies, due to its efficiency, operational flexibility, and environmental benefits. VPSA technology relies on selective adsorption of CO_2 over CH_4 under high pressure in fixed-bed columns packed with porous adsorbents. The adsorbent bed is regenerated by reducing pressure, ensuring continuous operation and purified biomethane production. It captures CO_2 from non-fossil sources, contributing to climate mitigation, and promotes waste management and circular economy. Furthermore, the captured CO_2 can be valorized industrially, improving overall process sustainability and economic viability. Interest in VPSA-based biogas upgrading is rapidly growing, both academically and industrially. Nonetheless, to make this technology fully competitive, it remains crucial to improve methane recovery (> 95%) while ensuring high product purity (> 97%).

This research aims to develop and optimize a VPSA process capable of producing high purity biomethane with elevated methane recovery, productivity, and energy efficiency. To achieve this goal, a multidisciplinary approach was adopted, integrating adsorbent material characterization, VPSA cycle design, and mathematical modeling.

The experimental campaign was conducted on a lab-scale VPSA unit composed of five stainless steel fixed-bed columns. Synthetic biogas mixtures were introduced at pressures ranging from 1 to 10 bar for the adsorption step, with desorption performed under vacuum (< 0.1 bar). Adsorbents tested included a commercial CMS CT-350 and two innovative UTSA-type MOFs. Breakthrough and desorption tests were used to evaluate adsorption capacity, CO_2/CH_4 selectivity, kinetics, and regenerability. A dynamic model was developed in MATLAB to fit breakthrough data and extract mass transfer coefficients, which were then used in Aspen Adsorption™ to simulate the full VPSA cycle.

Among the tested adsorbents, CMS CT-350 exhibited excellent kinetic selectivity and regeneration properties, enabling a six-step VPSA cycle to reach 92% methane recovery with a minimum purity of 97%. The UTSA-type MOF showed higher CO_2 adsorption capacity but slower desorption kinetics, which may hinder its performance under cyclic VPSA conditions. This integrated methodology enables the design of advanced cycle configurations not yet experimentally feasible and supports efficient process optimization.

Future work includes model refinement, extended validation, and techno-economic analysis to evaluate the industrial scalability and feasibility of VPSA technology for commercial biogas upgrading.

Keywords: Biogas upgrading; VPSA; Adsorbents; Modeling; Methane recovery; Sustainable energy.