Techno-economic assessment of post-combustion CO₂ capture using aqueous piperazine at different flue gas compositions and flowrates via a general optimization methodology

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Abstract

The optimal operating conditions of solvent-based (also referred to as absorption-based hereinafter) capture processes depend on the CO₂ concentration in the inlet flue gas (FG), on the rate of CO₂ capture achieved by the capture plant, and on the flowrate of FG treated. While the CO₂ concentration in the exhausted FG produced in natural gas- and coal-fired power plants is approximately 4 vol% and 13.5 vol%, respectively, the concentration of CO₂ in the FG generated from industrial activities, e.g. cement manufacturing, steelwork facilities, refineries, etc., will vary in most cases between 4 and 33 vol%. However, most techno-economic studies available in literature on absorption-based capture processes applied to industrial CO₂ point sources use optimal operating conditions imported from the gas- and coal-fired power plant application, instead of carrying out a dedicated process optimization. Moreover, there is no literature discussing the selection of operating conditions of the capture plant for small and large-scale, in operation or planned, industrial projects in steel and iron production (Al Reyadh CCUS project and Japan’s COURSE50 Project), cement manufacturing (Norcem plant in Norway), fertilizers production (Enid plant in the United States) or waste-to-energy plants (Fortum Oslo Varme plant in Norway).

This work [1] aims at analyzing and studying CO₂ capture using aqueous piperazine (PZ) as absorbent to capture up to 99% of the CO₂ contained in flue gases with a broad range of flowrates and CO₂ concentrations, which include the features of the diverse flue gases produced in the majority of industrial CO₂ point sources that exist. We do this by developing and applying a methodology that is general for aqeous amine solutions and that allows for the overall techno-economic assessment of solvent-based CO₂ capture processes using computer-aided process modelling, simulation and optimization. The techno-economic assessment is based on a rigorous multi-objective technical optimization in which the energy consumption of the capture process is minimized and the volume-based productivity maximized for different combinations of FG compositions and CO₂ capture efficiencies. As a result of this technical optimization, increasing minimum specific reboiler duties between 2.4 and 2.9 MJ/kg CO₂ captured are obtained for decreasing FG CO₂ concentrations between 33 and 4 vol%, on a dry basis, with absorber packing heights below 10 m. Multi-objective technical optimizations are preferred to single-objective cost optimizations because technical performance indicators: (i) are based on first principles of thermodynamics and mass transfer and are thus general, while cost optimization requires many case specific assumptions; and, (ii) are scale-independent, while a cost optimization problem should be solved not only for each combination of FG composition and CO₂ capture efficiencies, as the technical optimization, but also for each FG flowrate value. Subsequently, costs are computed for a range of FG flowrates only for the minimum energy-maximum productivity sets obtained for each FG composition and capture efficiency combination. Although rigorously minimum costs are not determined, this approach allows to obtain close-to-minimum costs as a function of the flowrate of FG treated by the capture plant, of the CO₂ concentration in the inlet FG and of the CO₂ capture rate, without compromising the computational demands of the overall techno-economic assessment. In addition, a technical-driven optimization allows for a better understanding of the process fundamentals thus provides insightful knowledge for further process improvements and optimization. As a result, cost contour plots and response

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surfaces are obtained as a function of the flowrate of FG treated, of the CO₂ concentration in the inlet FG and/or of the CO₂ capture efficiency. The cost analysis is carried out for different scenarios of energy prices and carbon footprint, and of access to capital, and also considers excess heat availability at the industrial CO₂ point source and different carbon prices, using different cost metrics such as cost of CO₂ captured, cost of CO₂ avoided and cost of CO₂ generated by the point source. The corresponding maps for the associated optimal operating conditions and equipment designs are also obtained. Our computer-aided modelling, simulation and optimization of solvent-based capture processes includes: (i) the use of a reliable model that has been validated with results from pilot tests, (ii) the performance of rate-based simulations using rigorous models that not only allow to compute the energy requirements of the process, but also the sizing of the absorption column for a broad range of operating conditions; (iii) the use of an advanced configuration of the capture process that allows to obtain competitive energy consumptions and absorber sizes, thus capture costs, representative of the solvent system with minimal impact on the process complexity; (iv) the inclusion of the CO₂ post-conditioning section in order to account for the effect of different operating pressures in the CO₂ desorber; and, (v) a process optimization strategy that considers all operating variables that affect significantly the performance of the capture process, as well as their possible inter-dependencies.

Although aqueous monoethanolamine (MEA) solutions have been considered historically as the standard solvent system for absorption-based post-combustion CO₂ capture processes, aqueous PZ solutions in concentrations up to ca. 40 wt% have taken over in the recent years as the new benchmark solvent system. With respect to MEA, PZ is less volatile, and more resistant to oxidative and thermal degradation, which allows for higher maximum operating temperature for solvent regeneration. Additionally, aqueous PZ solutions present two to three times faster CO₂ absorption rate than aqueous MEA solutions, greater CO₂ absorption capacity and similar viscosity. Consequently, absorption-based CO₂ capture processes using aqueous PZ as solvent require smaller absorber and FG water-wash packings and lower steam demands for solvent regeneration than aqueous MEA. Therefore, the results of this work also aim at providing a reference for the comparison of the techno-economic performance of other solvent systems or capture technologies.

*Keywords*: CO₂ capture; aqueous piperazine; model-based process optimization; techno-economic assessment; industrial CO₂ point sources