Design, economics, and parameter uncertainty in dynamic operation of post-combustion CO$_2$ capture using piperazine (PZ) and MEA solvents

Jozsef Gaspar$^1$, Luis Ricardez Sandoval$^2$, John Bagterp Jørgensen$^3$, Philip Loldrup Fosbøl$^1$

$^1$Technical University of Denmark, Department of Chemical Engineering, Center for Energy Resource Engineering (CERE), Lyngby, Denmark
$^2$University of Waterloo, Department of Chemical Engineering, Waterloo, Ontario, Canada
$^3$Technical University of Denmark, Department of Applied Mathematics and Computer Science, Lyngby, Denmark

Abstract

Despite the efforts and recent advances in renewable energy sources, the energy infrastructure is currently not ready to replace the fossil-fuel fired power plants with renewables. Thermal power plants represent the main energy supply and they are expected to dominate the market in the coming decades, especially in developing countries\(^1\). However, the growing focus on CO$_2$ emissions mitigation requires integration of fossil-fuel fired power plant with CO$_2$ capture units. Post-combustion CO$_2$ capture (PCC) has emerged as one of the main alternatives for CO$_2$ capture and it is moving towards industrial deployment. PCC is a mature technology that can be implemented in existing power plants and it is also suitable for other sectors, e.g. the steel industry, cement production, petroleum refining, and the biochemical industry.

Most of the research on CO$_2$ capture has been focused on steady-state optimization, design and techno-economic evaluation, generally applied for the baseline MEA solvent\(^2\). Consequently, dynamics of the plant is considered only after the design specifications and operating variables, e.g. packing height, solvent flow rate, heat demand, have been determined from the steady-state analysis. However, a PCC plant must be able to handle fluctuations resulting from various sources, such as peak in energy demands, raw material heterogeneity, malfunctioning of equipment, increasing share of renewable energy sources, etc.

The aim of this work is to quantify the impact of design decisions and uncertainties on the dynamic operation and economics of a CO$_2$ capture plant using piperazine (PZ), compared to the benchmark MEA solvent. This will be exemplified through dynamic model calculations.

Design, dynamics and uncertainties

Flexibility is particularly crucial from an economic and operational point of view. Plants must balance the power production and the electricity demand on a daily basis\(^3\). Therefore, the sequential steady-state design and controllability analysis approach may result in a dynamically inoperable capture plant since the design of the plant imposes a limitation on the process dynamics and therefore on the flexibility of the plant. To develop a flexible and economically efficient post-combustion unit, these should be designed considering the transient evolution of the plant and not only the steady-state behaviour\(^4,5\). Furthermore, there is a gap of knowledge in the dynamics and controllability of novel-low energy solvents since most of the research have focused on the benchmark MEA capture process. An example of a promising solvent is the 5 molal piperazine solution which offers higher CO$_2$ capacity and an energy improvement of approximately 20% compared to MEA\(^6\). However, rate-based models using novel solvents are less reliable due to
insufficient kinetic and physico-chemical data; thus, uncertainties must be accounted for when designing and evaluating the controllability of a CO2 capture plant.

**Objectives and Results**

The aim of this work is to investigate the effect of design variables, i.e. packing height, capacity of buffer tanks and sumps, sizing of the lean–rich cross heat exchanger, on the transient evolution of a CO2 capture plant using the low energy piperazine (PZ) and compared to the benchmark MEA solvents. Figure 1 shows the importance of design specifications on the process dynamics. This figure illustrates that the CO2 capture efficiency and the specific heat demand, i.e. amount of heat needed to regenerate 1 ton of CO2, present different transients when using buffer tanks of different capacities. This suggests the importance of design on the controllability of these plants. Furthermore, this analysis is coupled with an evaluation of the process economics. Thus, this work shows how design variables affect the dynamics of the absorber and stripper towers but also the cost of flue gas cleaning, considering the capital cost, the operational cost and the dynamic variability cost. The focus of the study is on the innovative low energy PZ solvent. The dynamic variability cost refers to the cost of CO2 avoided using a tax of carbon of $30 per tons of CO2 captured. The equipment and utility cost have been estimated using empirical correlations from literature. However, in general models are not perfect and a key aspect in assessing the dynamic techno-economic performance of a plant is quantification of expected uncertainties. Accordingly, this work includes uncertainties related to kinetics, mass transfer and hydraulic capacities in the dynamics and economics of the capture process.

The results of this work were developed using the dynamic CAPCO2 (dCAPCO2) in-house DTU model for CO2 absorption and desorption. The complete capture process has been implemented in Matlab. This model uses the extended UNIQUAC thermodynamic model and the general method (GM) enhancement factor for mass transfer rate calculation.

**References**

Figure 1. Effect of the capacity of the lean solvent tank on the MEA plants dynamics for a 10% step change in the lean flow rate: (A) CO$_2$ removal efficiency and (B) specific reboiler heat duty.