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Demonstration of economic nonlinear model predictive control of CO_2 capture plant with CESAR1

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Abstract

A nonlinear model predictive control (NMPC) strategy is successfully demonstrated for the Tiller CO2Lab (SINTEF AS) amine-based post-combustion CO_2 capture pilot using the CESAR1 solvent. The dynamic pilot plant model is validated against experimental results with good agreement. Building on previous experience with testing this type of controller, a particular focus has been to combine day-to-day economic optimization with supervisory control of the plant performance. Such control structure consists of two hierarchical layers, an underlying NMPC layer for supervisory control subject to varying operational process conditions, and a dynamic real-time optimizer (DRTO) on top of the NMPC whose role is to account for slower, day-to-day variability. Specifically, reboiler energy input and solvent flow rate are manipulated to control the CO_2 capture rate in the absorber and the specific reboiler duty (SRD), while the economic optimization is connected to varying price of electricity and CO_2 tax. The total operational cost is minimized over the 24-hour horizon to maintain an average CO_2 capture rate of 92% or higher. Since this kind of automatic control under varying operating regimes is able to optimize multiple variables simultaneously, it enables considerable cost savings compared to manual control. This flexibility is especially significant as energy variability (both in terms of cost and availability) is expected to increase as a result of the introduction of renewables to the energy mix. Not only can the energy usage and costs related to CO_2 tax be reduced, but with a control structure as demonstrated here, the plant operation will also be less labor intensive.

Keyw words: Post combustion carbon capture; amine based CO_2 absorption; CESAR1 Solvent; nonlinear model predictive control; optimal control; OPEX reduction; flexible operation

1. Introduction

Many large-scale capture plants will need to be operated in a flexible and dynamic manner to cope with varying flow rates and/or CO_2 concentration in the flue gas from the host plant. Under such circumstances, careful design of the capture plant is required, as well as proper process control to ensure the operating- and product specifications are met. These specifications mainly concern the CO_2 capture rate, amine emission limits, and CO_2 quality, but other requirements like minimising utility consumption (energy, process- and cooling water) and loss of solvent are also

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important. Valuable insight into the aspects contributing to the most optimal plant design and operation is achieved from pilot testing combined with simulations. Despite the extensive testing over the last 20-30 years in a number of pilots of different sizes and at different locations, the focus on dynamic testing has been limited, particularly when the operating conditions approach the limits of the pilot plant. However, this is an important part of the ongoing EU-funded project AURORA (https://aurora-heu.eu/).

The overarching aim of the AURORA project is to qualify the CESAR1 solvent for commercial deployment. This is done through a dedicated qualification procedure[1], which ensures that important knowledge gaps are identified based on results from previous projects (*e.g.*, CESAR, ALIGN-CCUS, and SCOPE). Furthermore, the gaps are closed through extensive pilot testing, solvent and process modelling, and concept studies. Particularly, the Cybernetica CENIT software based on non-linear model predictive control (NMPC) testing at both SINTEF's CO_2 laboratory (hereafter referred to as the Tiller pilot) and the Technology Centre Mongstad (TCM) pilot is part of the AURORA project. Though this tool has been successfully demonstrated in these pilots earlier, both with MEA and CESAR1 as solvent (see e.g. Mejdell et al. 2022[2] and Kvamsdal et al. 2018[3]), the tests revealed the necessity of continued improvement of the underlying first principle dynamic model used in the NMPC, but also improvement of the controller performance. Additionally, the focus of the motivating business model has somewhat shifted since what was demonstrated in Kvamsdal et al. 2018[3]. An increasing fraction of renewables into the energy mix is expected to result in hour-to-hour variability in energy price and availability, necessitating dynamic real-time optimization to achieve truly optimal plant performance.

CENIT NMPC and CENIT DRTO interact in a hierarchal two-level structure. While the CENIT NMPC application interacts with certain elements of the basic control system layer of the pilot plant (e.g. existing stabilizing PI(D), the DRTO functionality is to optimize a certain economic based objective function to establish time-varying set-point trajectories sent to the NMPC (Skogestad 2004[4]). In the Tiller pilot demonstration, the DRTO minimises the cost of electricity used for the reboiler (electric reboiler) and maximises CO_2 capture. The application minimizes the sum of electricity consumption and costs related to CO_2 tax, subject to a constraint on minimum capture rate. The DRTO objective function thus looks like

$$\min_u f = \int_{t=0h}^{t=24h} \left(c_{elec} \cdot Duty_{reboiler} + c_{CO2tax} \cdot w_{CO2,released}\right) dt \qquad (1)$$
$$\text{subject to} \quad \begin{matrix} CR_{average,24h} > 92\% \\ g(u) = 0 \end{matrix}$$

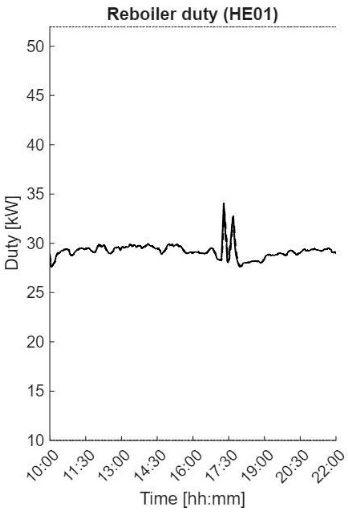
, where *u* are the inputs (i.e. the capture rate setpoint to the NMPC), c_{elec} are the day-ahead electricity prices for the Trondheim, Norway (NO3) area from NORD POOL[5], which are fetched automatically by the application at regular intervals, c_{CO2tax} is the cost of emissions per ton of CO_2 (assumed to be 900 €/ton for the sake of demonstration, although this could also be fetched and adjusted in real-time). *g(u)* is a simplified representation of the nonlinear process model. In typical textbook DRTO fashion, the first input is implemented (that is: sent to the NMPC), before the whole optimization problem is re-optimized at the next sample to be able to account with changes in the plant.

The controlled variables for the NMPC level were the absorber CO_2 capture rate and temperature profile in the desorber (an analogue for the specific reboiler duty, i.e. the efficiency of the capture process), while the manipulated variables were the lean solvent flow-rate and the reboiler electric input. Although there are some minor differences in the problem formulation and the underlying process model, for the sake of brevity, the reader is referred to Mejdell et al. 2022[2] for a more in-depth description of the NMPC formulation.

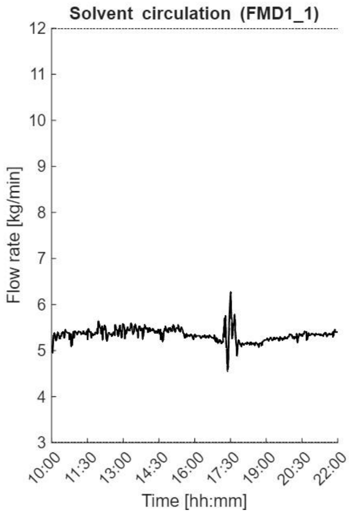
2. Results

The described two-layer control structure was implemented in the Cybernetica CENIT software and tested at the Tiller pilot plant during February of 2025. Figures 1-4 show the results of the test. Due to time restrictions, the economic optimization was only run for a 13-hour period, but the obtained results are promising and serve well to explain the proposed methodology.

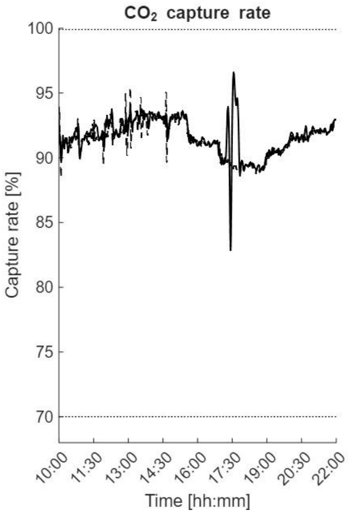
In Figure 4 we see the electricity prices for that particular day and the next. The DRTO has a prediction horizon of a little over 24 hours. Since day-ahead-prices are not published for the next day until sometime around 13:00-14:00, the DRTO assumes that the following days' prices are identical to the current day. Consequently, the optimal solution may change somewhat when the new prices are published. The corresponding optimal capture rate setpoints are shown in Figure 3. As expected, the optimal capture rate is adapting to account for varying electricity prices. When electricity is cheap in the evening, more CO_2 is captured. When electricity is expensive, the capture rate is lowered, at the expense of increased emission costs. Due to the time limitations, we changed the average capture constraint in Equation (1) to be evaluated at midnight, and not after the full 24 hours. As expected, the average CO_2 capture rate over the course of the 13-hour period where the DRTO / NMPC was running, was 92%, i.e. the minimum requirement. Note that a somewhat large external disturbance hit the plant at around 17:30-18:00. The NMPC correctly rejected the disturbance before returning to the desired setpoint.



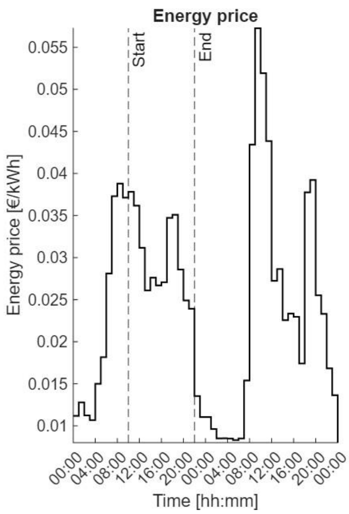
1:Reboiler duty [kW], as controlled by the NMPC



2: Solvent circulation rate [kg/min], as controlled by the NMPC



3:Capture rate setpoint [%], as controlled by the DRTO and read by the NMPC



4: Energy prices [€/kWh] for a 48-hour period, as read by the DRTO

The economical saving for that particular day of operations is difficult to quantify, due to the lack of a comparison. It is possible to attempt to compare the energy consumption and CO_2 emissions to a day with a constant 92% capture rate setpoint. However, due to inherent variability of real-life process plants, the disturbance profile will not be identical, and it would thus not be an apples-to-apples comparison. Nonetheless, simulation studies have shown that the economical savings are typically in the range of 3-10%, depending on the variability of the flue gas and the electricity price profile.

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