DOCPCC - Demonstration of Optimal Control of Post-Combustion Capture processes

Testing of advanced control system at the Tiller and TCM pilots

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Outline

- Project overview
- Background and motivation for dynamic modelling and Nonlinear Model Predictive Control (NMPC)
- NMPC in general and in DOCPCC
- Some results from the Tiller testing
- Some results from the TCM testing
- Conclusions and further work

National project DOCPCC

- Demonstration project
- Coordinator: SINTEF MC (Dr. Hanne Kvamsdal)
- Partners:
  - ✓SINTEF, NTNU, Cybernetica, TCM
- Duration:
  - ✓March 2016 - September 2017
- Budget:
  - ✓16.7 MNOK (10.7 MNOK from the CLIMIT demo program)

Project objectives

Main objective:

To demonstrate reduced energy cost (3-5 % reduction) by introducing advanced control (NMPC) compared to manual operation of absorption based CO_2 capture processes.

Secondary objectives:

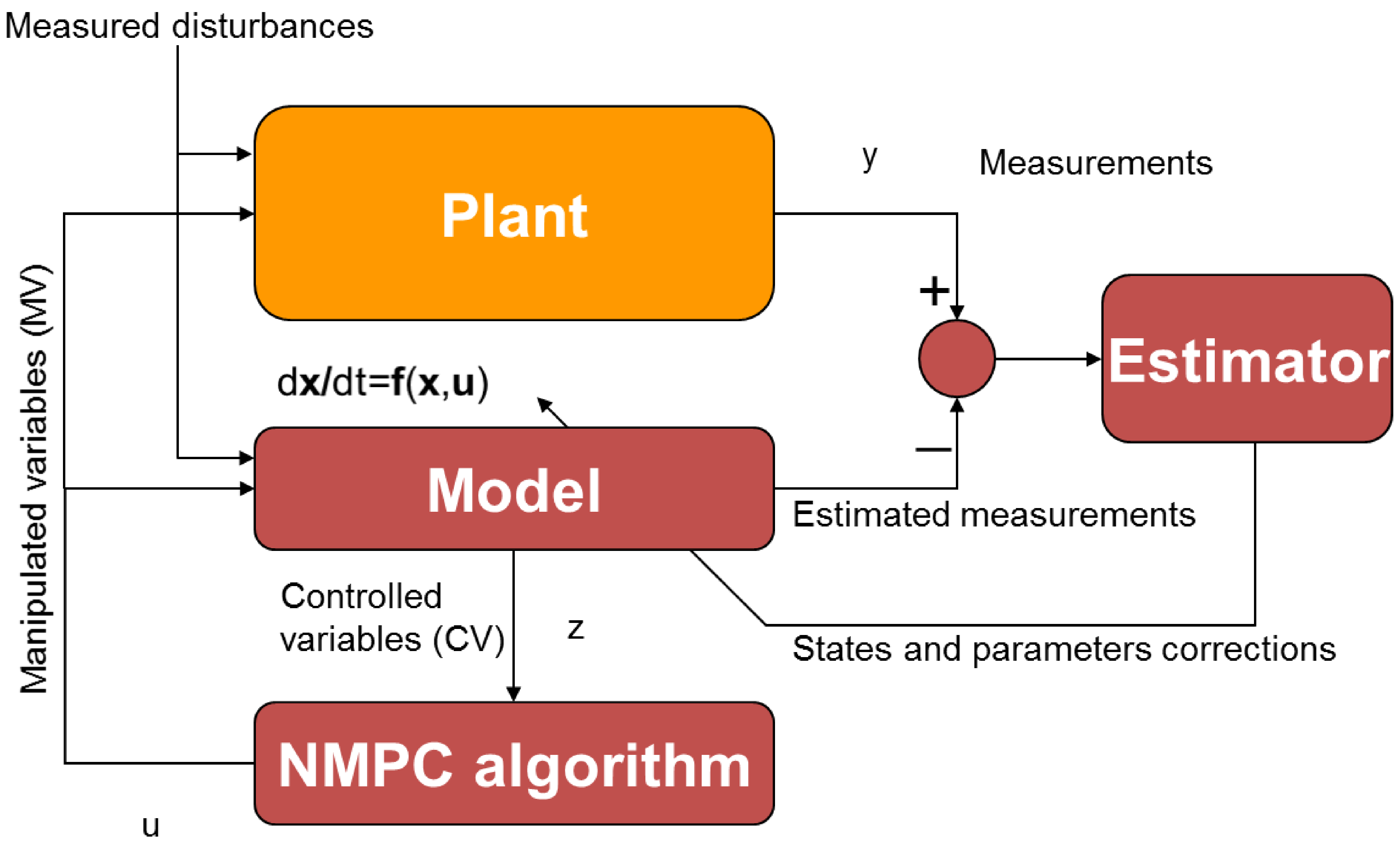
- Achieve hands-on experience with dynamics, control actions, operational procedures (start-up, shutdown, change of operating conditions) and challenges in a capture process plant
- Develop control solutions suitable for flexible CCS plant operation, including:
  - ✓ Optimal base level - and plant-wide control structures for absorption/desorption processes
  - ✓ A model to be used in an NMPC unit for installation and testing at Tiller and TCM
  - ✓ Check possible cost savings (both energy and time-wise) from inclusion of NMPC.
- Demonstrate various flexibility scenarios, at all time maintaining the design specification of 90% capture at the average over some time horizon

Motivation and background for the project

- **Advanced control systems are requested for the foreseen future operational challenges**
  - ✓ More flexible operation of the power plants will be required with inclusion of power from wind, solar, and other more unstable energy sources in the grid.
  - ✓ Biomass and coal fueled power plants will exhibit large variations in flue-gas CO_2 content and challenging amine emission counteractions during load changes.
  - ✓ The process industry are facing large variations in CO_2 content in the gases that may be applicable for CO_2 capture.
- **Background**
  - ✓ NMPC effectively controls the process and may ensure a more optimal operation
  - ✓ At NTNU and SINTEF dynamic models of post-combustion CO_2 capture have been developed and verified against three pilot plants
  - ✓ Cybernetica is a software company specialised in NMPC for application in various types of chemical processes

Nonlinear Model Predictive Control (NMPC)

- ❑ Utilization of a nonlinear process model to optimize the plant performance over a given time horizon
- ❑ Based on the response of the controlled variables the model is used at each sampling interval to calculate future scenarios of the manipulated variables so as to minimize an objective function.
- ❑ As the model is not accurate, the model needs to be frequently updated based on the online plant measurements
- ❑ Since the measurements are not exactly either, the model parameters are updated based on filtering the deviations (through the "Estimator")



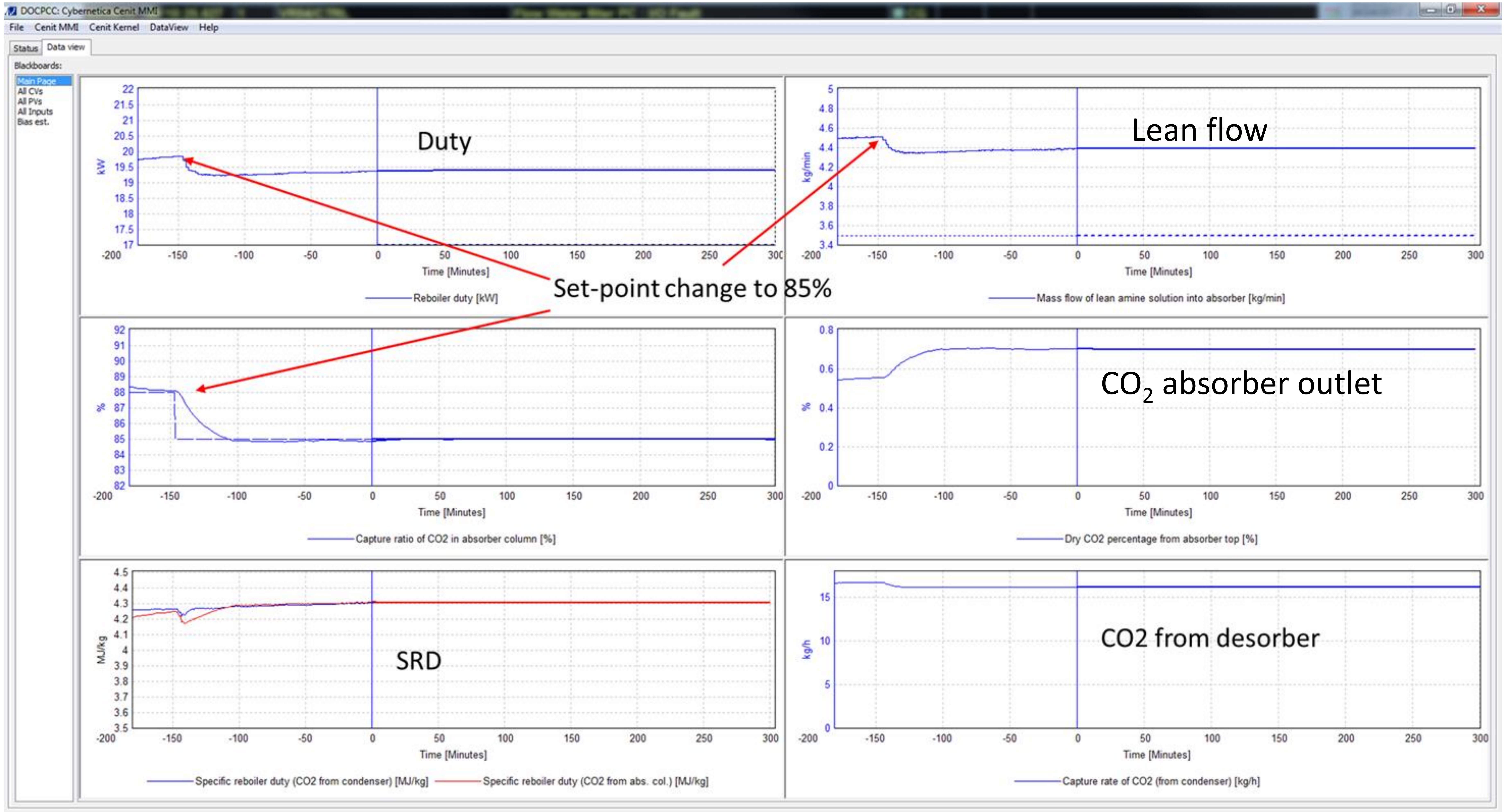
NMPC in DOCPCC

- ❑ The process model was implemented in Matlab and converted to C to be integrated with the CENIT software
  - ✓ The thermodynamics an physical properties only for 30wt% MEA implemented in the model
- ❑ It has been simplified to cope with real time requirement of the controller
- ❑ The model has been validated against dynamic data for both Tiller and TCM applications
- ❑ The CENIT software has been integrated with the basic control system at each plant
- ❑ The CENIT software use a Kalman filter for the model updates based on the pilot plant online measurements
- ❑The objective has been to minimize the specific reboiler duty and keep the cumulative capture rate on setpoint (which can vary).
- ❑ The manipulated variables include solvent flow rate and energy input to the reboiler.

Test cases at both TCM and Tiller

Test #	Activity description	Purpose	Variable to be changed manually	Set-point range	Objective function for NMPC
1	Initial set-point changes in CO_2 capture rate	Initial check to observe manipulative variable (solvent flow-rate and reboiler duty). Verify changes and response time.	Capture rate set point	90, 92.5, 95	Keep capture rate at specific value while minimising reboiler duty
2	Determination of SRD at base case conditions	Determine minimum SRD for constant base case conditions (gas flow rate and concentration).	none	none	Keep capture rate at 90% while minimising reboiler duty
3	Set-point changes in CO_2 capture rate	Check that minimum SRD is achieved for each capture rate	Capture rate	90, 88, 85	Keep capture rate at specific value while minimising reboiler duty
4	Changes in flue gas flow-rate	Check that specific capture rate and minimum SRD is achieved for each flue gas flow-rate	Flue gas flow-rate	100, 90, 80, 70 % load	Keep capture rate at 90% while minimising reboiler duty
5	Changes in flue gas CO_2 concentration	Check that specific capture rate and minimum SRD is achieved for each CO_2 gas concentration	Flue gas CO_2 inlet concen-tration	4.5, 7, 10, 13.5	Keep capture rate at 90% while minimising reboiler duty

Results Tiller Case 3: Setpoint changes in capture rate



- Capture rate 88 to 85%
- Solvent flow-rate reduced
- SRD unchanged

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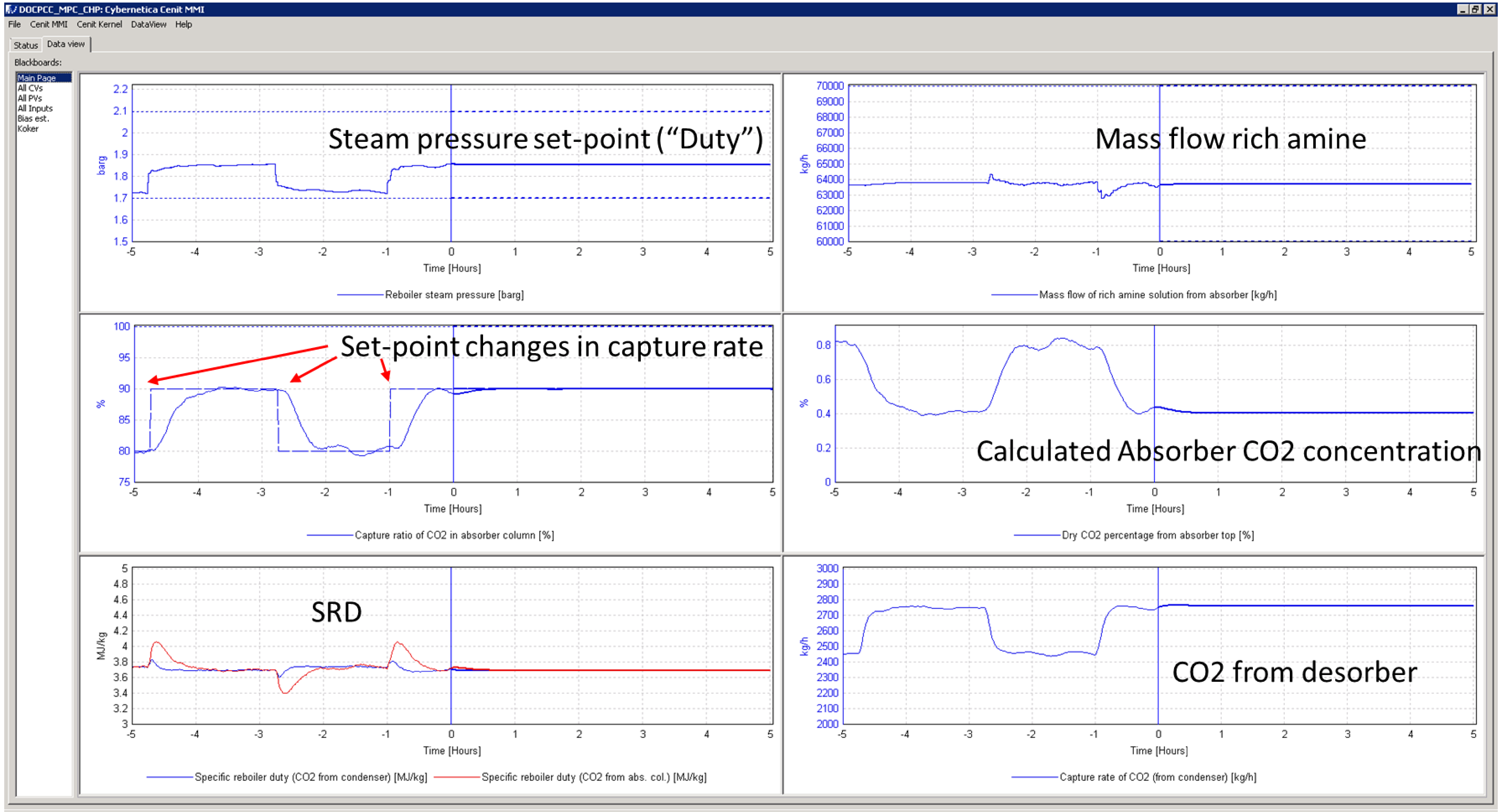
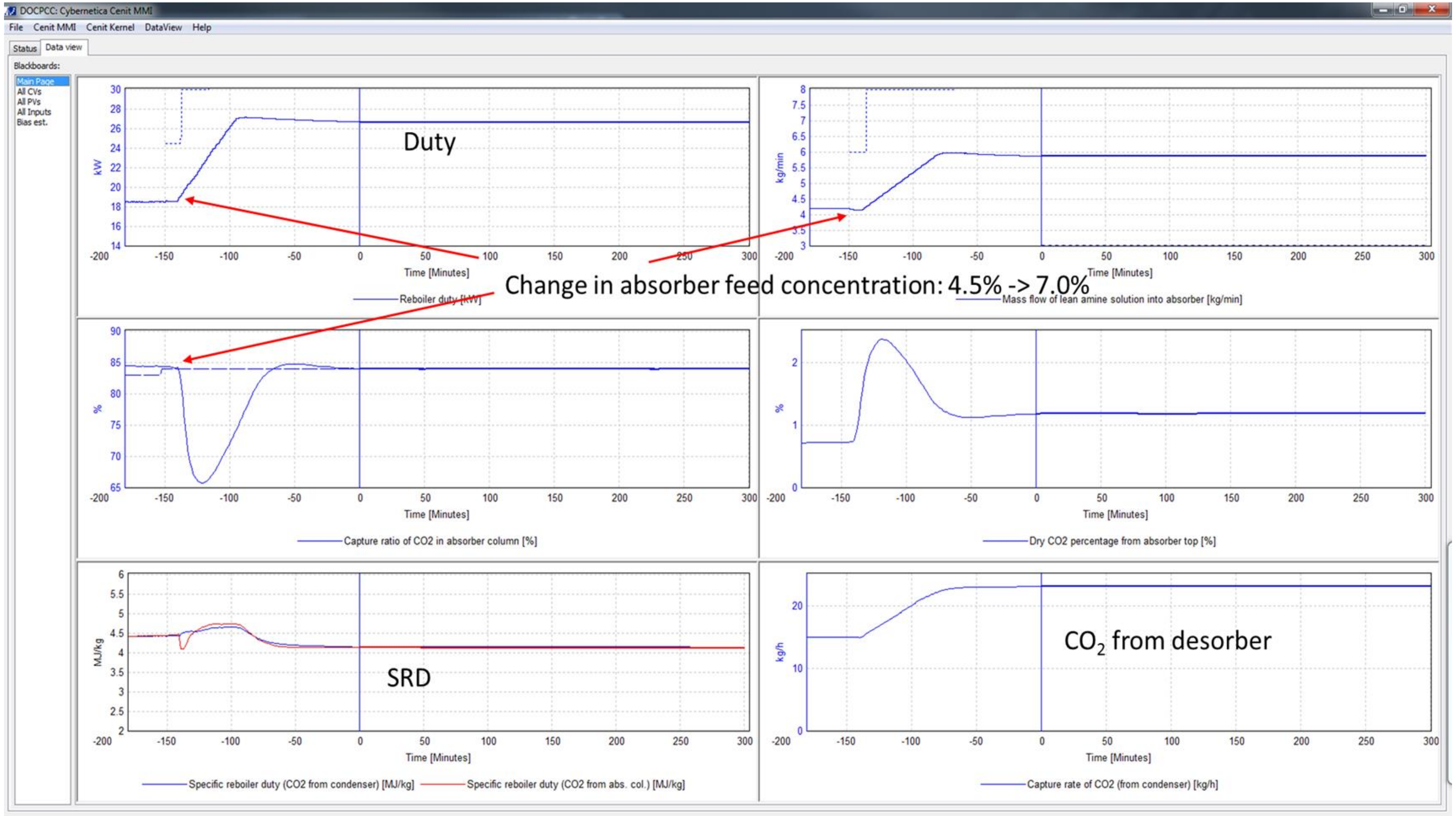
Results TCM Case 3: Setpoint changes in capture rate



- Capture rate 80 to 90%
- Solvent flow-rate is changing
- SRD unchanged

Results Tiller Case 5: Changes in CO_2 flue gas concentration



- Set-point Capture rate 90%
- Solvent flow-rate increased
- SRD reduced

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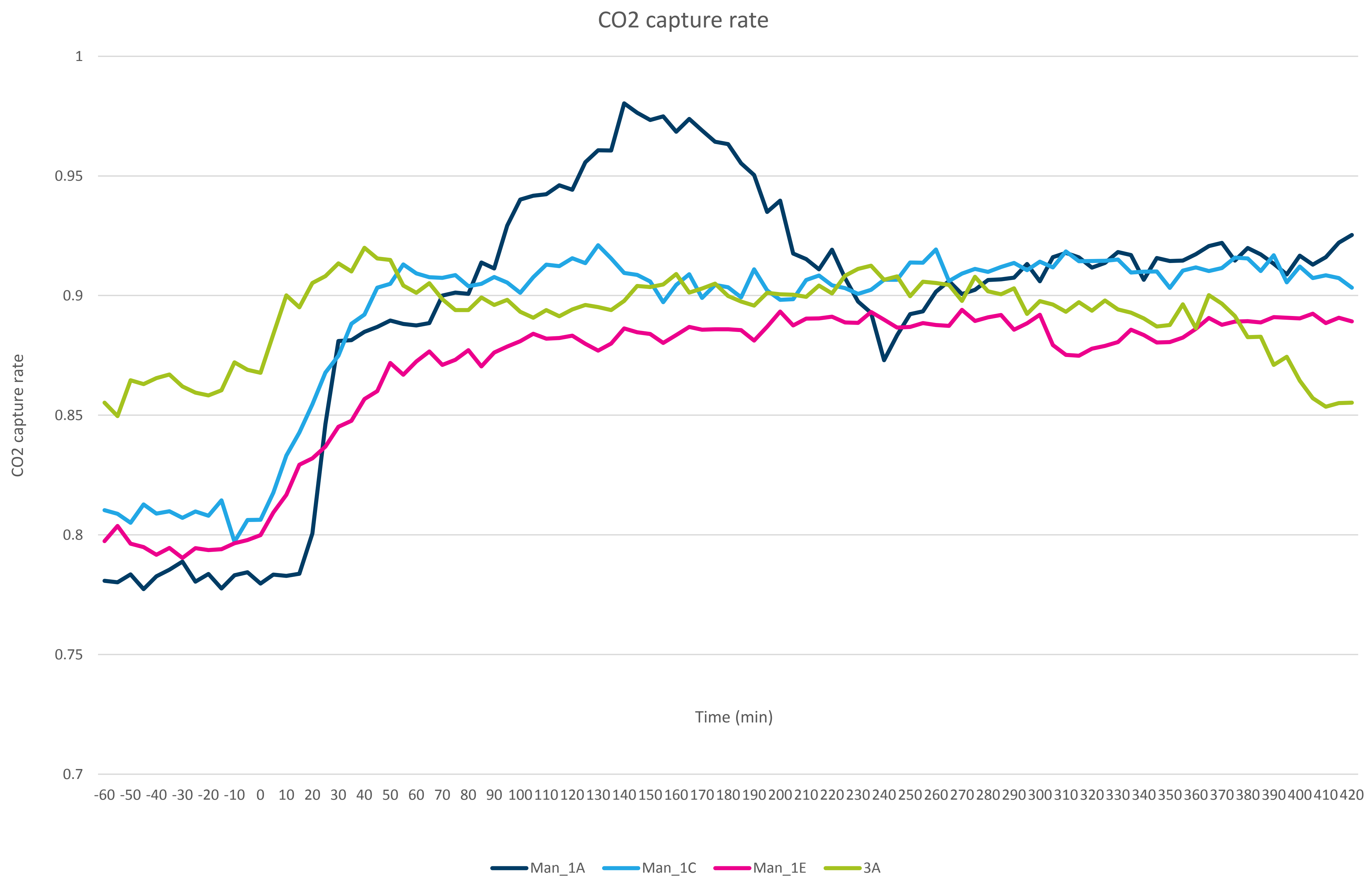
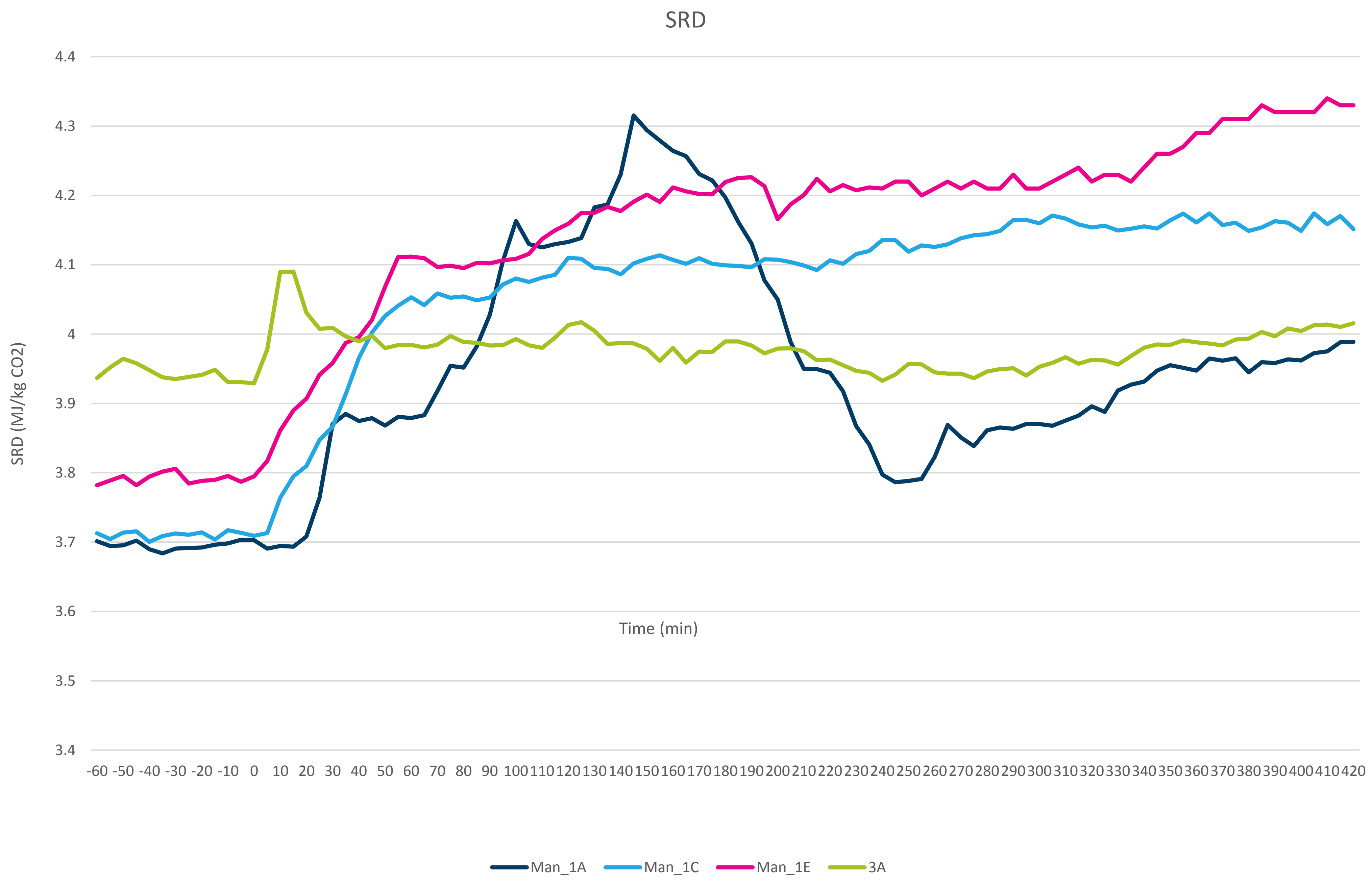
Results TCM: Comparing Manual and NMPC control

- ❑ Case: Increase capture rate from 80 to 90%
- ❑ Manual operation (case Man_1A to Man_1E) and automatic operation with CENIT (case 3A)





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Conclusions: Increase capture rate from 80 to 90%

- ❑ In general tight control of CO_2 capture in both cases (manual and automatic), but CENIT controls both tighter and faster
- ❑ SRD keeps more constant when controlling with CENIT active
- ❑ SRD with CENIT could have been more optimal if the estimation of optimal solvent flow rate was improved/corrected
- ❑ It is very challenging to optimize two individual variables manually, thus only one variable is manipulated in the manual cases (steam flow)
- ❑ It is therefore very challenging to achieve optimal SRD manually

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Conclusions from tests both sites: Benefits (1)

- With CENIT active , the energy input and amine circulation flow is manipulated simultaneously, in order to both
  - ✓ Keep the specified CO2 capture rate
  - ✓ Minimize the required energy (SRD)
- NMPC allows to specify CO_2 capture ratio, and the operator can change the setpoint from knowledge of time-varying energy prices
- A new steady-state value is reached within 20-30 minutes
- The specified setpoint is kept, regardless changes in feed flow and feed composition

Conclusions from tests both sites: Benefits (2)

- We have verified that an NMPC system can automate the operation of a post combustion capture plant
  - ✓ (Nearly) optimal control of the plant can be performed without intensive operator intervention
  - ✓ The NMPC system performs multivariable control, by manipulating energy and solvent rate simultaneously
  - ✓ In manual control, the operators prefer to only manipulate the energy input (unless a change in solvent circulation is required from other reasons)

Conclusions from tests both sites: Challenges (1)

- ❑ It is not proven that the NMPC in general gives faster and more precise responses compared to manual control
  - ✓ For setpoint changes in CO_2 capture ratio, the operator learns from each sequence, and the result is comparable with the NMPC solution after some “training”
  - ✓ For planned changes in feed flow and compositions, the operator knows ahead the final value of the disturbance. The NMPC only “knows” the current values read by the flow transmitters / analyzers, and assume the values will be fixed during the prediction horizon. This may “delay” the controller action if the disturbance is changing gradually.
    - ➢ We should think of improvements in the NMPC disturbance handling

Conclusions from tests both sites: Challenges (2)

- Finding the minimum SRD is a challenge, because of the steep left-hand side of the U-curve
  - ✓ The NMPC tends to calculate a too low circulation flow (TCM)
    - ➢ From a starting point of e.g. 68000 kg/h, the optimal decrease in flow should be 29.5 % (found by tests), while the NMPC decreases the flow by 34.5%
  - ✓ The results are dependent on a very precise controller model, combined with reasonable methods for online model corrections
- However,
  - ✓ Iterative tuning of the online model lead to improved SRD optimization throughout the test period
  - ✓ By initiating the NMPC control with a high circulation flow, the controller reduces the flow to a value close to the minimum (TCM plant)
  - ✓ By initiating the NMPC control with a random circulation flow, the controller reduces SRD by about 4% (Tiller plant)
  - ✓ Through time-varying feed properties and CO_2 capture rate setpoints, the NMPC continuously seeks the minimum SRD.

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FURTHER WORK WITHIN DOCPCC AND FURTHER PLANS

- ❑ Two cases were not completed:
  - ✓ Two level optimization: Keep 90% accumulative capture rate while minimising costs over 24 hours, without and with (Tiller only) intermediate solvent storage tanks
  - ✓ The optimization was as expected for the first 3 hours, then the controller output tend to deteriorate and test was stopped (at Tiller)
  - ✓ Tuning of the optimization criterion is not trivial and the problem may be non-convex.
- ❑ No further tests in the project, but the two remaining tests will be simulated
- ❑ Plan to write a journal publication
- ❑ Future projects:
  - ✓ The dynamic model is based on 30 wt% MEA, will be made more generic
  - ✓ Improvement in model based on the experiences
  - ✓ Will test CESAR 1 solvent within the ALIGN-CCUS project

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Thank you for the attention!

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