CCSI²

Carbon Capture Simulation for Industry Impact

Development and Application of Advanced Process Control for UKy CO_2 Capture Pilot-Plant

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Overview

- **Background**
  - Motivation | Objectives
  - CCSI's APC Framework Toolset
  - UKy-CAER CO_2 Capture Pilot-Plant Facility
- **Project Plan / Status**
- **Past Accomplishments**
  - Identify "most-influential" I/O variables
  - Develop dynamic reduced models
  - Offline "simulation-based" control studies
- **Current Activity / Accomplishments**
  - Integration with pilot-plant DCS
  - Implement real-time APC
- **Results**
- **Summary**

Motivation / Contribution to CCSI^2

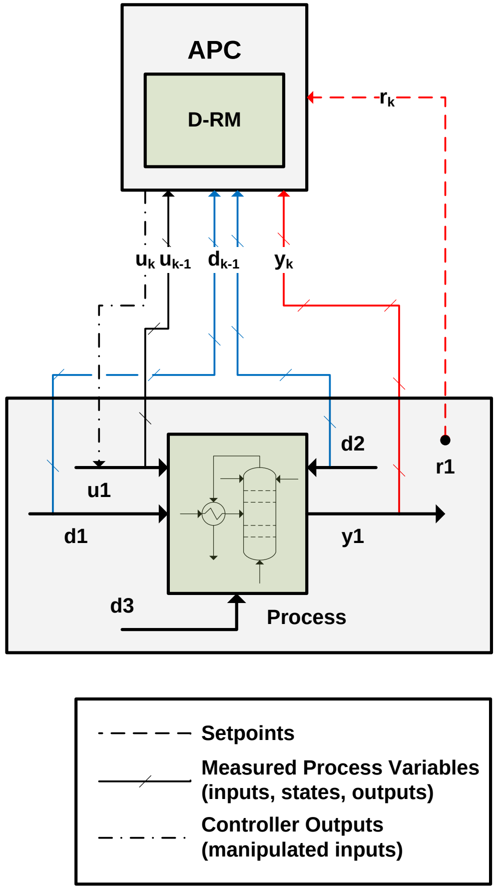
- **Industrial APC Ain't Easy**
  - Computational cost
  - Need for accurate and fast real-time prediction models
  - APC / NMPC module costs - $$$
  - Non-generic, embedded within DCS
- **New Contribution**
  - NMPC-based industrial control
    - Optimal dynamic operation
  - Exploit more-efficient third-party solvers (MATLAB – sparse matrix calculations, IPOPT, etc.)

Background

CCSI's Advanced Process Control Framework

Why Advanced Process Control (APC) Framework ?

- **Integrated framework for optimal control of CO_2 capture processes**
- **Efficient dynamic transition to desired set-point and mitigation of process uncertainties**
- **Enables to protection of intellectual data by serving as a "black-box" surrogate dynamic-model**
- **Leverage "fast" D-RMs from CCSI's D-RM Builder as predictive models to optimize control-moves towards cost-effective transient response in face of process constraints**



APC Framework Features

- **Constrained Nonlinear Model Predictive Control (NMPC) using DAB-Net D-RM model**
- **Constrained Multiple-Model Predictive Control (MMPC) based on multiple linear state-space "model-bank"**
- **Unscented Kalman Filter (UKF)-based state-estimation**

Background

- **University of Kentucky's CCS Project**
  - Center for Applied Energy Research (CAER)
    - Other Participants: LG&E/KU, Hitachi, EPRI, etc.
  - 2 MWth (0.7 MWe) slip stream test facility
  - At E. W. Brown Generating Station
    - Louisville Gas & Electric (LG&E) and Kentucky Utilities (KU)
    - In Harrodsburg, KY, 30 miles from UKy-CAER
  - Sponsors
    - DOE/NETL ($14.55 Million)
    - Kentucky Department of Energy Development and Independence
    - Carbon Management Research Group (Consortium)
  - Catch and release program
- **Opportunity: improve control responses time | residence time in solvent/desiccant loops**

CAER's CO_2 Capture Test Facility

LG&E/KU Brown Station

CO_2 Capture Facility

Existing Control System

- **Emerson's DeltaV system**
- **All standard PID Controllers (w/ 2-3 cascade loops)**
- **Currently uses 170 process variables**
  - Maximum 250 variables from the license
- **Over 20 manipulated input variables**
- **Solvent residence time: ~30 min through the loop; scope for improvement**

Project Status/Plan

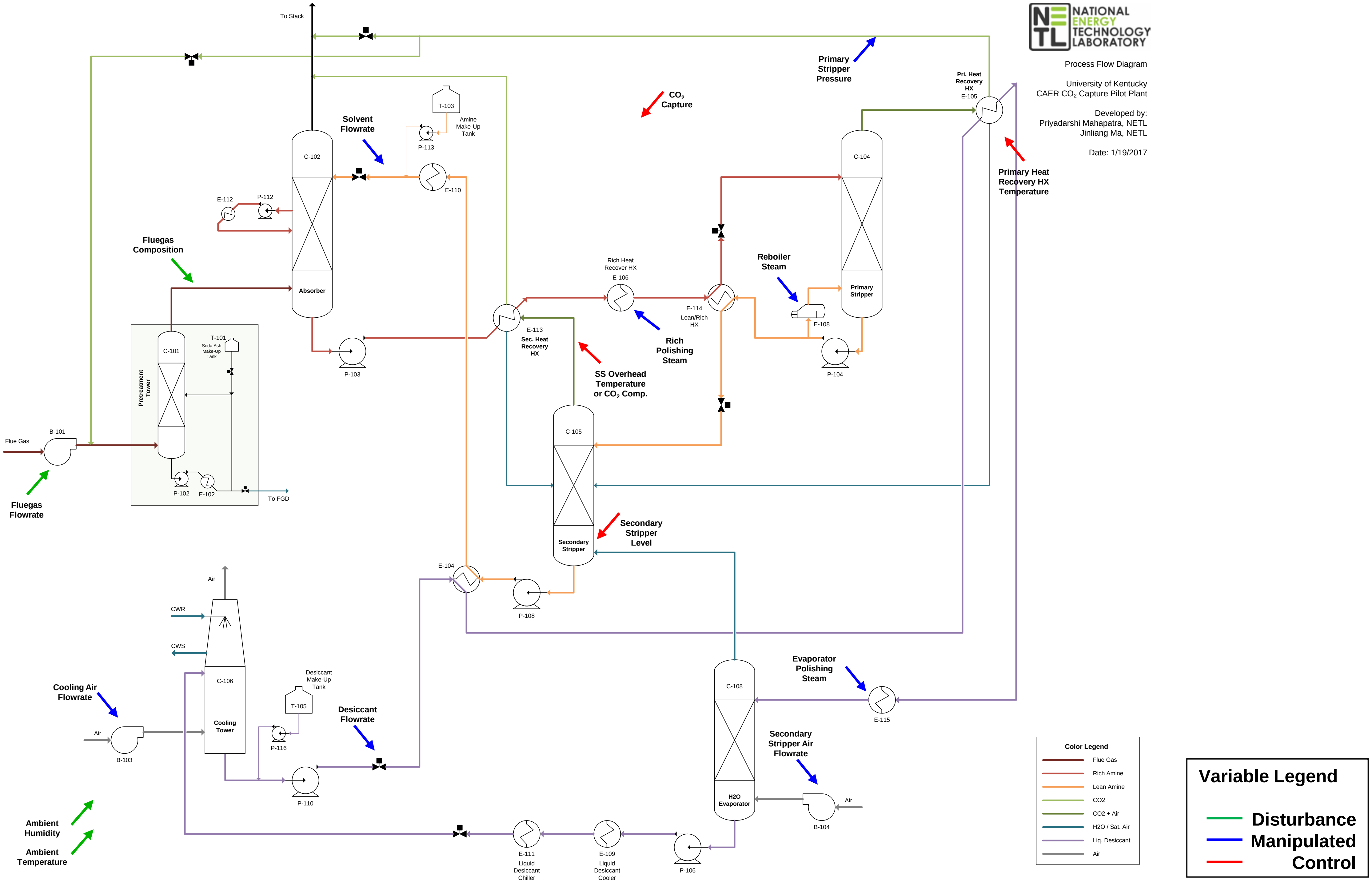
- **Assess control requirements**
- **Operability and controllability analysis**
  - Identify relevant I/O process variables
  - Design step-change sequence
  - Run step-tests
    - Keep low-level PID controllers unchanged
- **Build D-RM for the system**
  - Validate approach on secondary-stripping column sub-section
  - Develop D-RM for entire plant
    - Testing data | Validation data
- **Evaluate APC methodology for online real-time control**
  - Validate APC approach using offline “plant” based on D-RM – demonstrated benefits
  - Integrate CCSI’s APC Framework w/ pilot-plant’s DCS
  - Closed-loop identification based on historical data
- **Implement real-time nonlinear MPC**
  - Controller tuning and validation (preliminary)
  - Demonstrate operational improvement over existing methods

CAER's CO_2 Capture Process

- **Three loops**
  - Flue gas pretreatment loop
  - Amine solvent loop
  - Liquid desiccant loop
- **Solvent loop design**
  - Single absorber with intercooler
  - 2 strippers
    - Primary stripper
    - Secondary air stripper
- **Cooling tower/liquid desiccant loop design**
  - Removing moisture in humid air by liquid desiccant

Process Flow Diagram

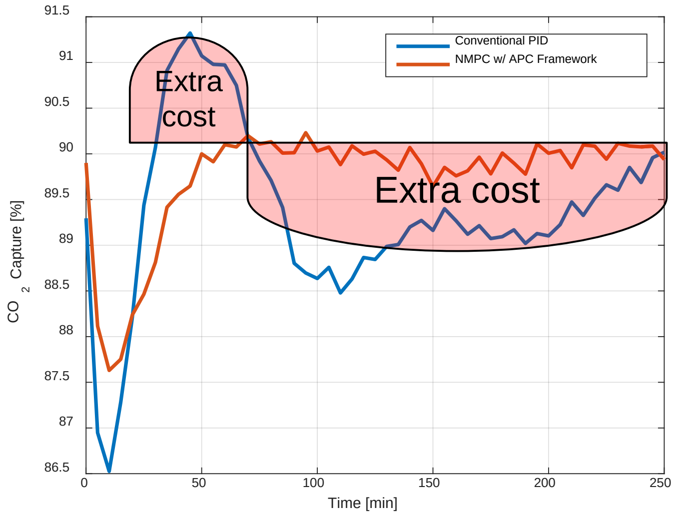
Material Streams + IO Variables

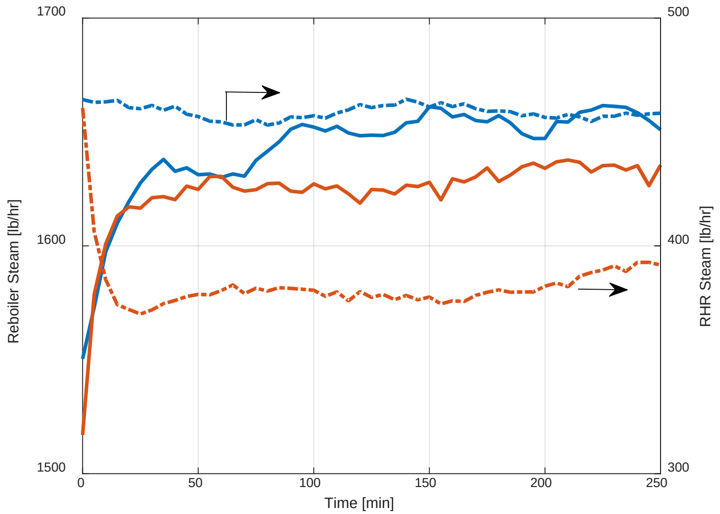


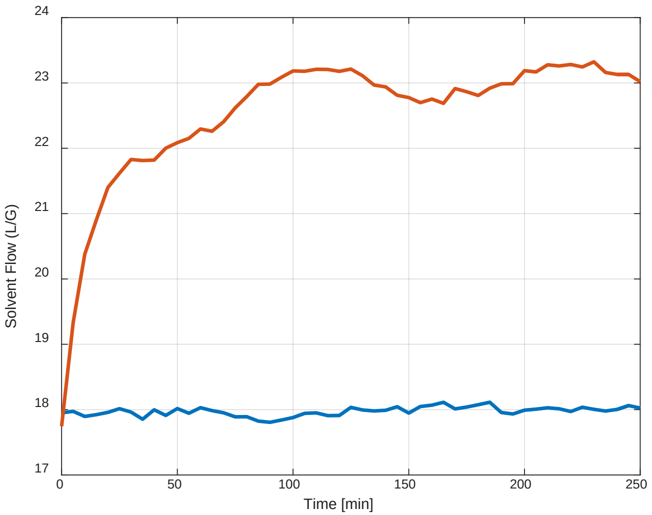
Relevant Process Variables

- **Manipulated Inputs (MV)**
  - Solvent flow rate
  - Primary stripper pressure
  - Reboiler steam flowrate
  - Flow rate of air to secondary stripper
  - Cooling air flowrate
  - Desiccant flowrate
  - Rich-solvent heater steam flowrate
  - CO_2 concentration of flue gas to absorber (disturbance)
- **Output / Controlled Variables (CV)**
  - Percentage of CO_2 captured
  - Temperatures of product streams of individual columns
  - Compositions of product streams

Previous "offline" Control Studies







CO_2 concentration disturbance in inlet flue gas (14% to 16%) at t = 0

NMPC Objective function

$$\min_{\Delta \mathbf{u}_1 \ldots \Delta \mathbf{u}_M} J = \sum_{p=1}^{P} \left(\mathrm{CO}_{2\ p}^{SP} - \mathrm{CO}_{2\,p} \right)^T \mathbf{w}_y \left(\mathrm{CO}_{2\ p}^{SP} - \mathrm{CO}_{2\,p} \right) + \left(\mathrm{Stm}_M^{Reb} + \mathrm{Stm}_M^{RHR} \right) + \sum_{m=1}^{M} \Delta \mathbf{u}_m^T \mathbf{w}_u \Delta \mathbf{u}_m$$

80% reduction in settling time

Less (~5%) steam duty

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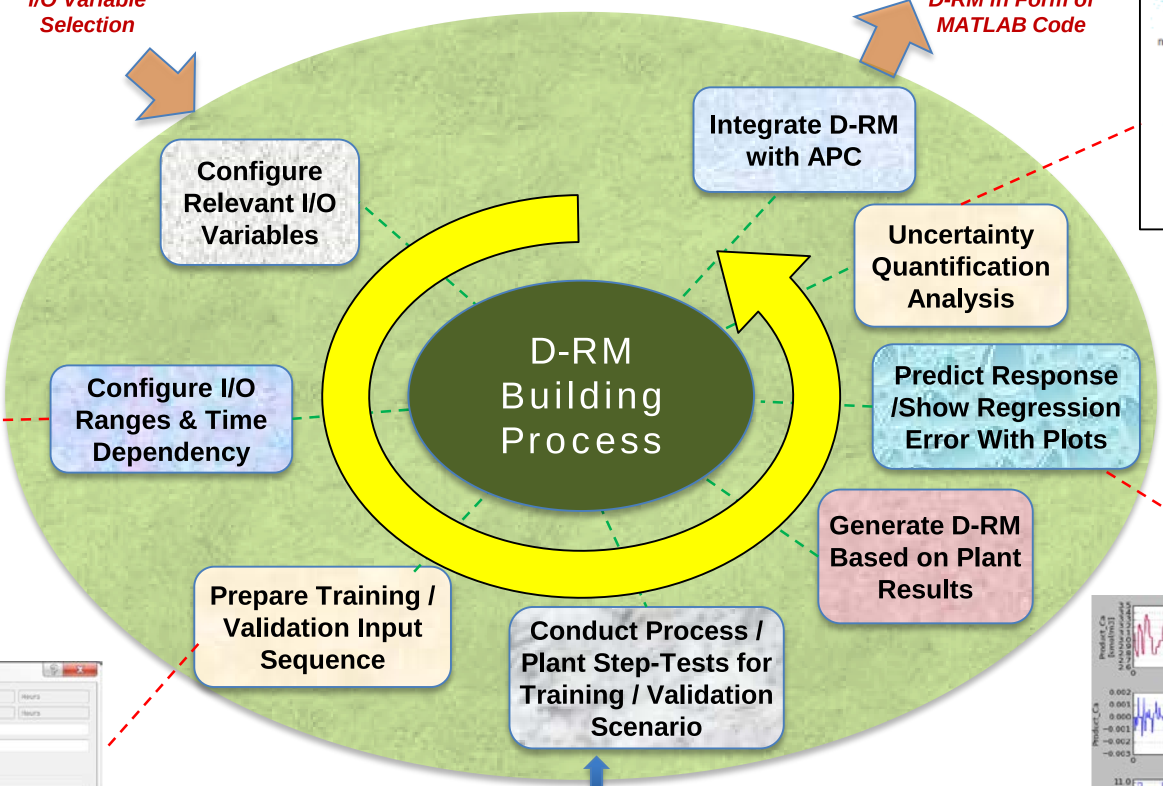
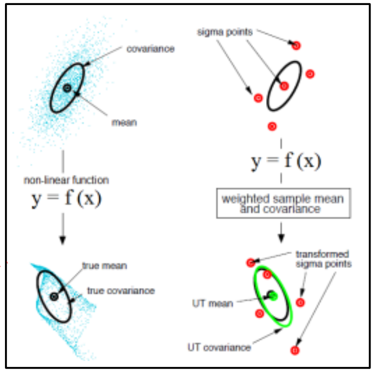
Industrial Implementation: D-RM development

- Reboiler Steam Flowrate
- RHR Steam Flowrate
- Desiccant Flowrate
- Cooling Tower Air Flowrate
- L/G
- CO_2 Capture
- Primary HX Overhead Temp

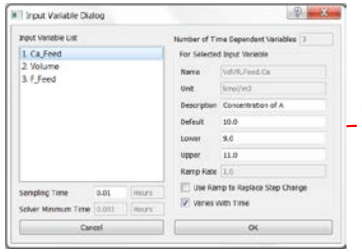
I/O Variable Selection

D-RM in Form of MATLAB Code

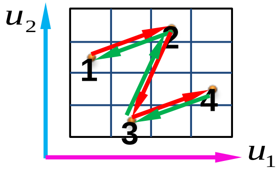




Mean and Covariances Predicted By UKF

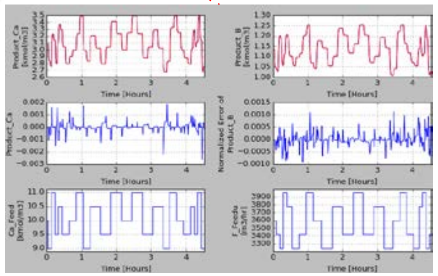


Configuring Inputs/Outputs



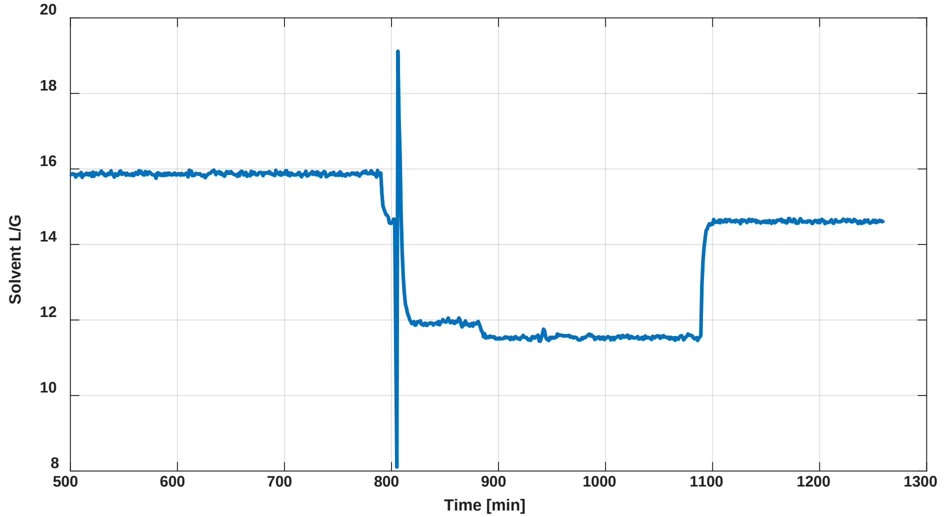
Training Sequence

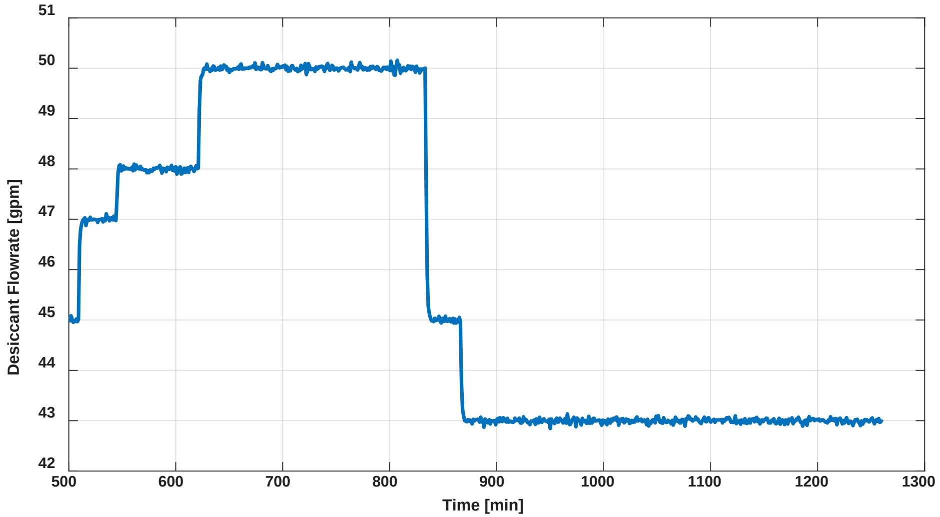
Configuring Training Sequence



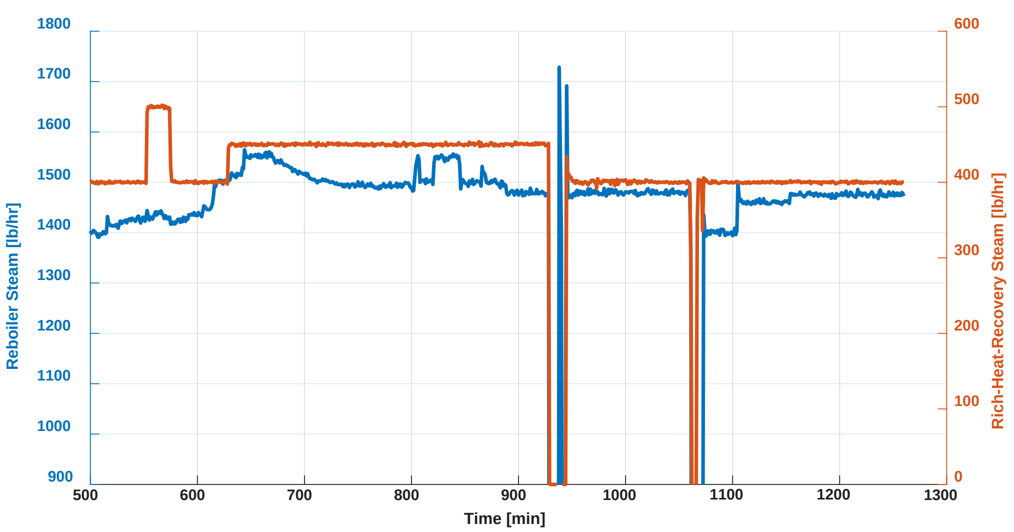
MATLAB Plot Showing Predicted Output vs. Plant Response

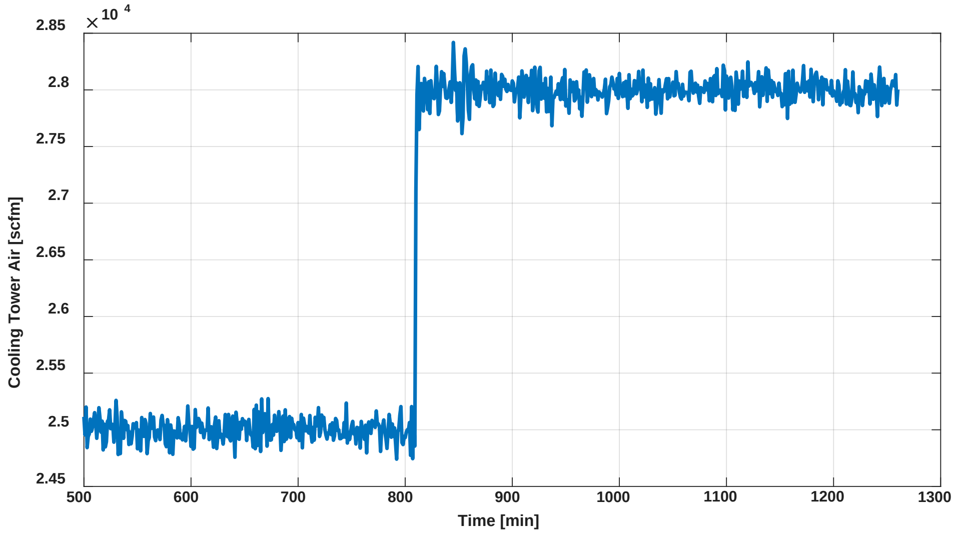
Results – System Identification / D-RM Building



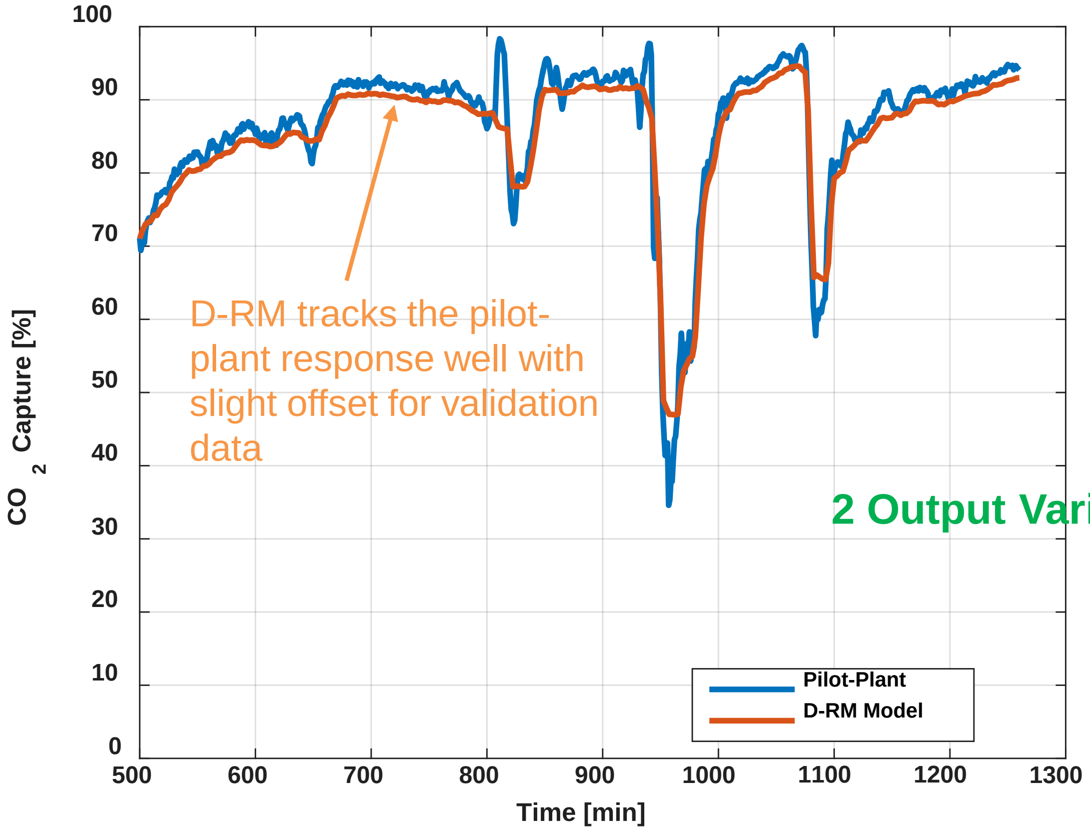


5 Input Variables

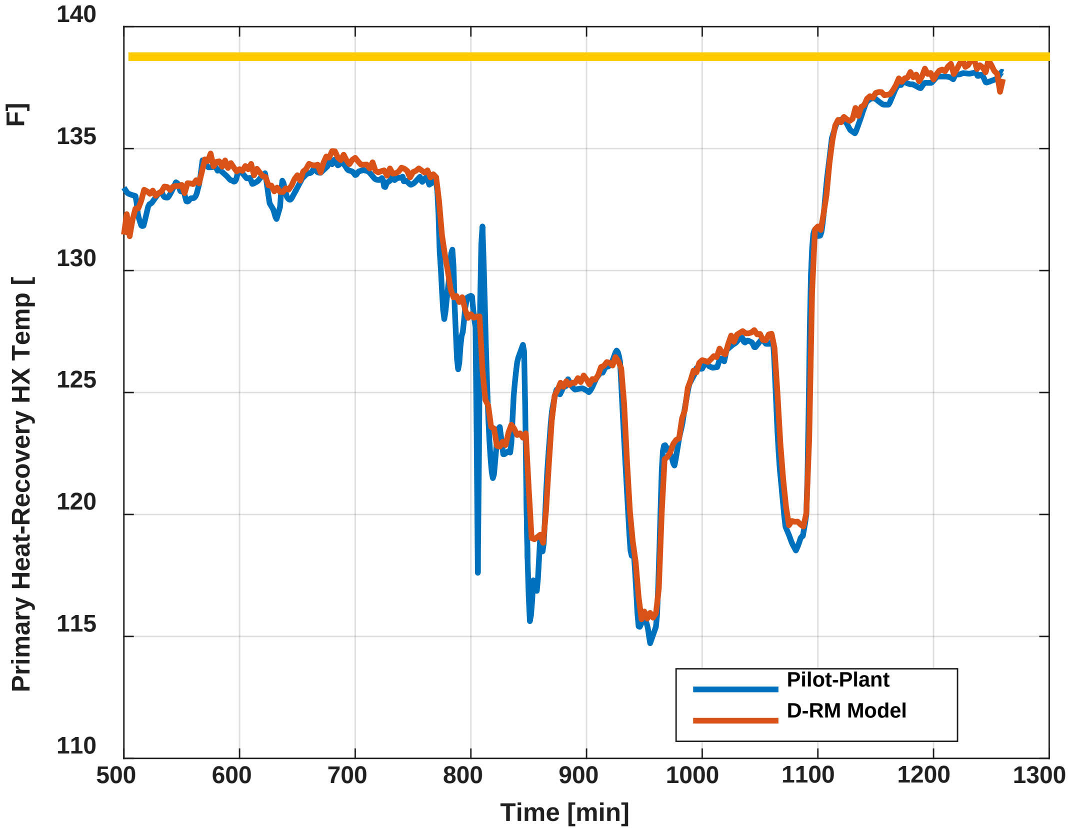




Results – System Identification / D-RM Building



2 Output Variables



Primary Control Variable – Minimize settling times

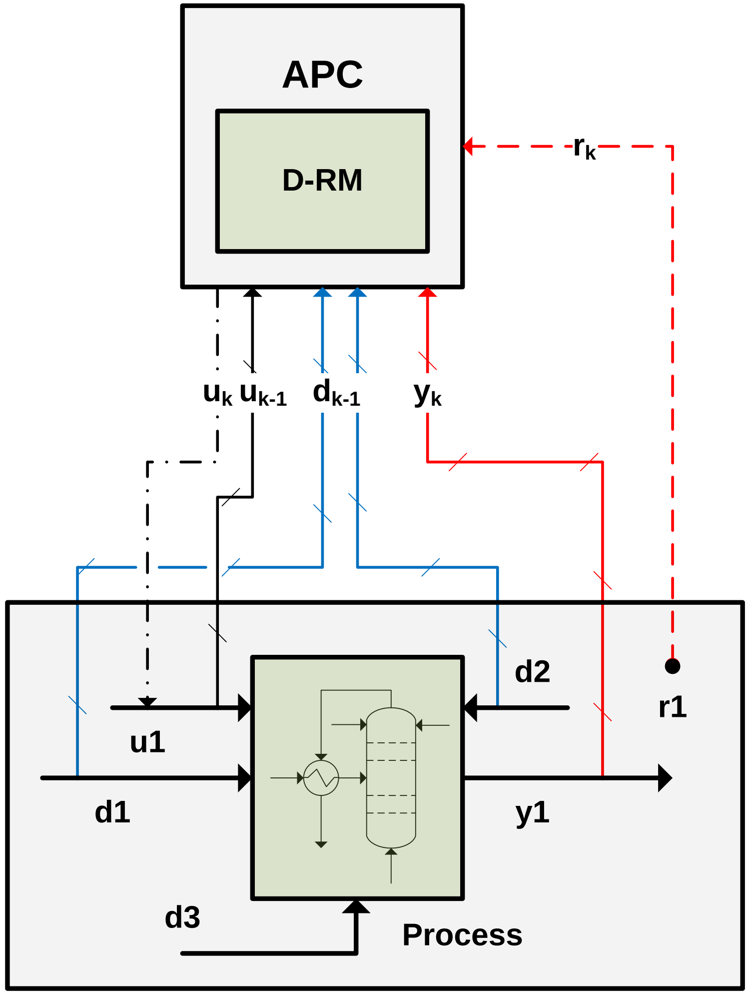
Critical Constraint Variable – Values above 139F leads to solvent leakage from stack (closely monitored)

Industrial APC Implementation

MATLAB

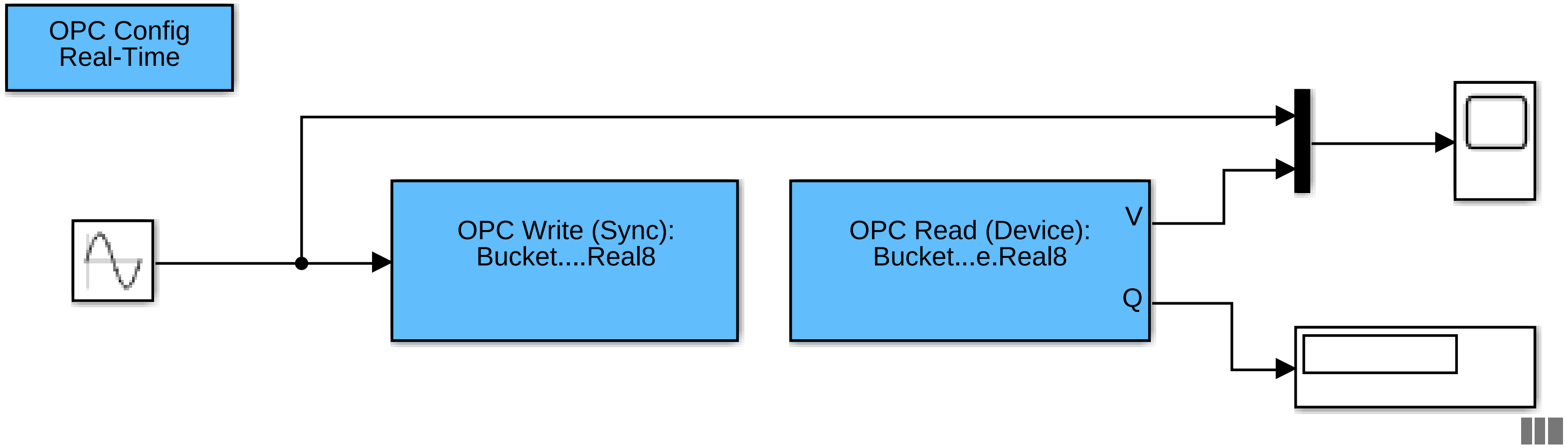
Real-time exchange of values, events, R/W state

Emerson DeltaV DCS



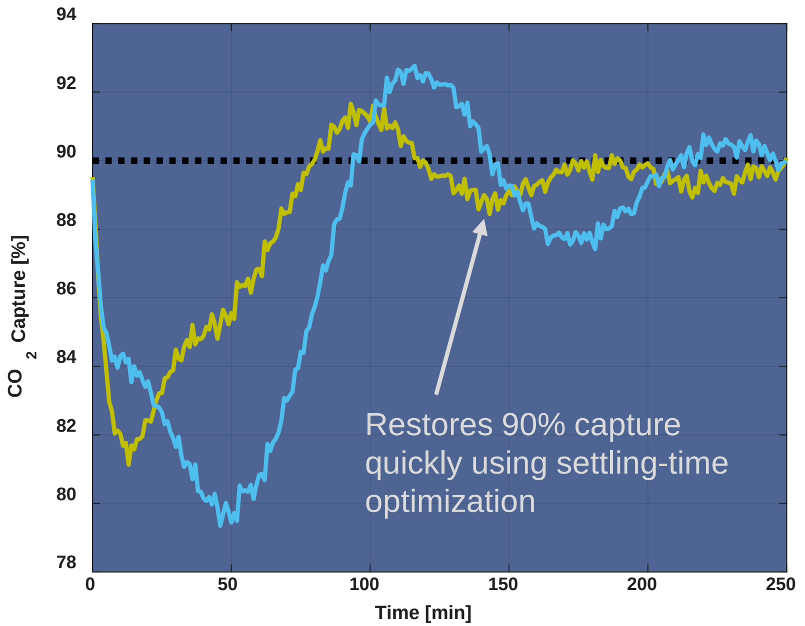
Integration with pilot-plant DCS

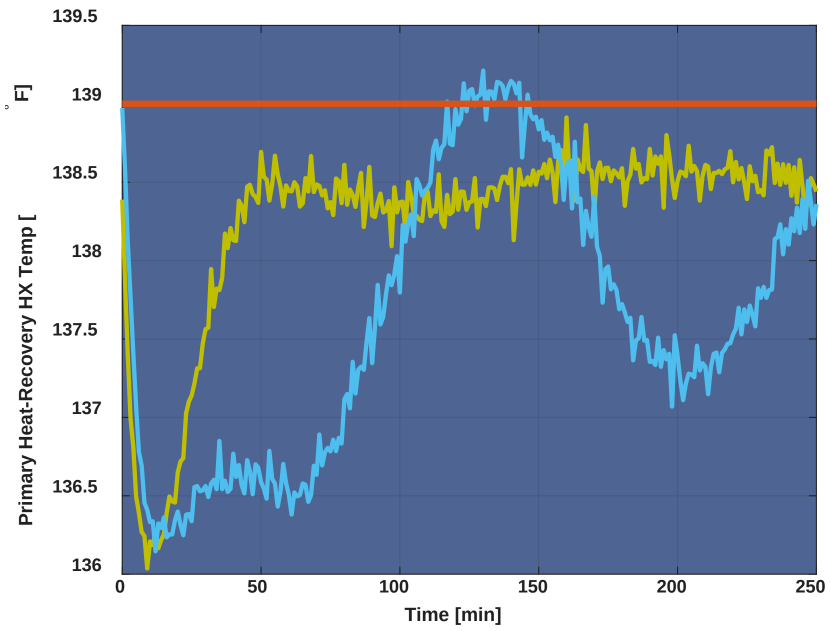
- **OPC (OLE for Process Control) Protocol**
  - Identify existing Emerson Delta-V OPC server on pilot-plant DCS
  - Create OPC client within CCSI APC Framework
  - Establish connection from client to server
  - Identify process variables tags (r/w permissions) available on server – PLC/charm names
  - Create read-only PV tags and writable remote setpoint (SP) tags on client
  - Conduct step-tests on relevant remote SP and validate PV with DCS historian
- **Develop event callbacks routines for solving real-time control optimization problem**
- **Establish real-time communication at each sampling "clock" time**



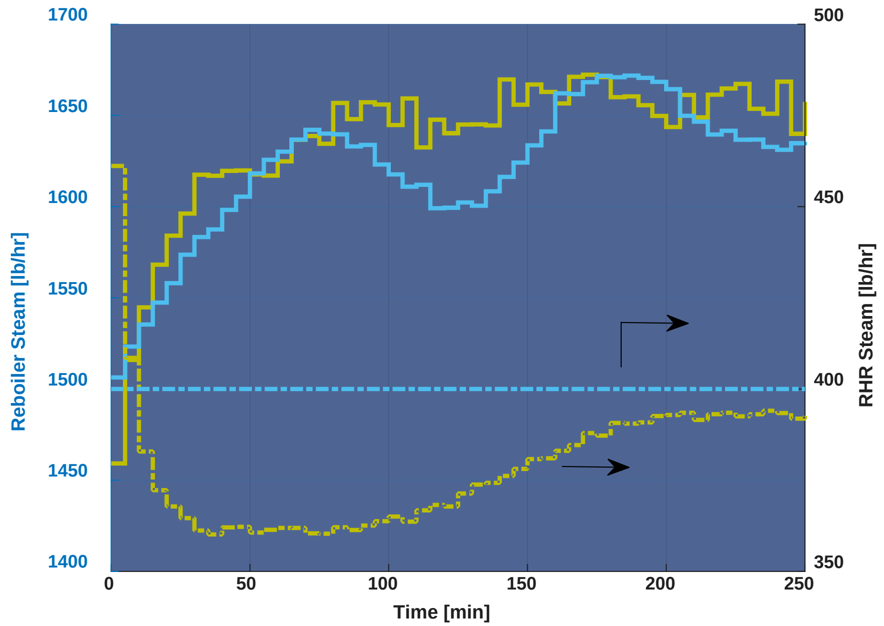
Results – Real-time APC (preliminary study)

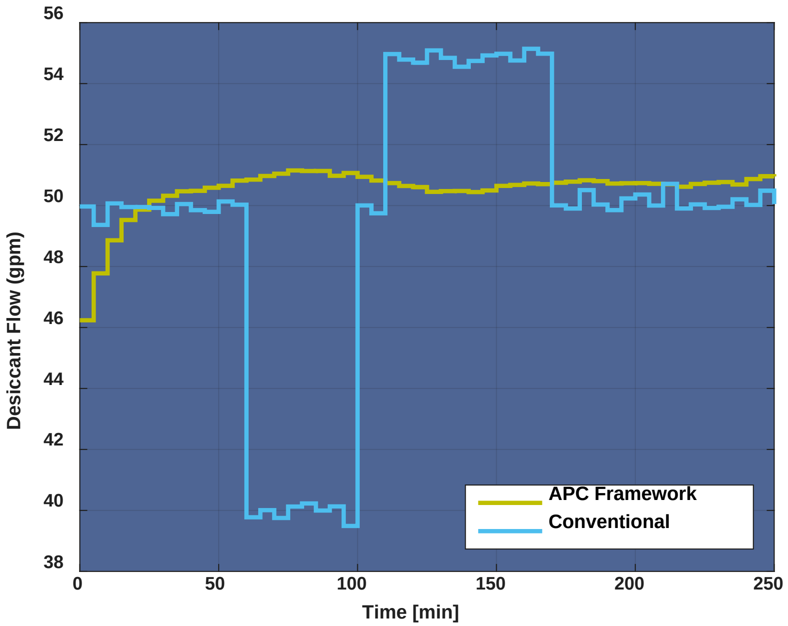
Control Variables





Manipulated Inputs





Study Details

- 3 input – 2 output
- CO_2 concentration disturbance in inlet flue gas (14% to 16%) at t = 600 min
- Control objective

$$\min_{\Delta \mathbf{u}_1 \ldots \Delta \mathbf{u}_M} J = \sum_{p=1}^{P} \left(CO_{2\,p}^{SP} - CO_{2\,p} \right)^T \mathbf{w}_y \left(CO_{2\,p}^{SP} - CO_{2\,p} \right) + \sum_{m=1}^{M} \Delta \mathbf{u}_m^T \mathbf{w}_u \Delta \mathbf{u}_m$$

- Sampling-time = 1 min
- Prediction Horizon = 2 hr
- Control Horizon = 10 steps

Summary

Performance Improvement

UKy/CAER existing control	APC Framework
No automated control of CO_2 capture	Optimal setpoint tracking of CO_2 possible using NMPC
Rely on overhead T high-alarm visual feeds to rectify solvent loss to stack.	Overhead T monitored and predicted via model. Take necessary steps before violating constraints
Square I/O system required for multiple single-input-single-out controllers – e.g. CO_2 capture may only be paired with reboiler-steam flow	One output may optimally be controlled by two or more sensitive inputs – e.g. both reboiler and RHR steam contribute to controlling CO_2 capture
Fixed control parameters leading to sub-optimal performance when operating far from “tuned” regime	NMPC with Kalman Filter updates the model based on extent of plant-model mismatch

Summary

Demonstrated CCSI's APC Tools applicability and benefits in CO_2 capture plant

- Identified most-influential pilot plat's PV
- Developed dynamic reduced-order model (D-RM)
- Demonstrated ability to interface with existing pilot-plant DCS using industry-standard OPC
- Implement real-time APC for CO_2 capture SP tracking with temperature constraint

Future Work

- Refine existing D-RM through closed-loop identification using historical data
- Implement plant-wide APC with economic optimization and demonstrate benefits over existing control methods

Acknowledgement

- **University of Kentucky's CAER Team**
  - Kunlei Liu, Jonathan Pelgen, Heather Nikolic, Zhen Fan
  - Control Room Operators: Len, Marshall, Otto
- **OPC Foundation**
  - Provide educational material for efficient OPC implementation
- **Matrikon OPC Team**
  - Provide test-bench for OPC communication offline
- **MATLAB OPC Toolbox**
  - Provide OPC client interface for APC-DeltaV communication

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For more information

https://www.acceleratecarboncapture.org/

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