Setting the Standard for Automation™

Dynamic Modeling and Control of an Integrated Solid Sorbent Based CO_2 Capture Process

Benjamin Omell, Debangsu Bhattacharyya*
Department of Chemical Engineering
West Virginia University, Morgantown, WV

David C. Miller,
National Energy Technology Laboratory
US DOE, Pittsburgh, PA

Jinliang Ma, Priyadarshi Mahapatra, Stephen E. Zitney
National Energy Technology Laboratory
US DOE, Morgantown, WV

58th Annual ISA Power Industry Division Symposium
7-11 June 2015, Kansas City, Missouri
Kansas City Marriott Hotel

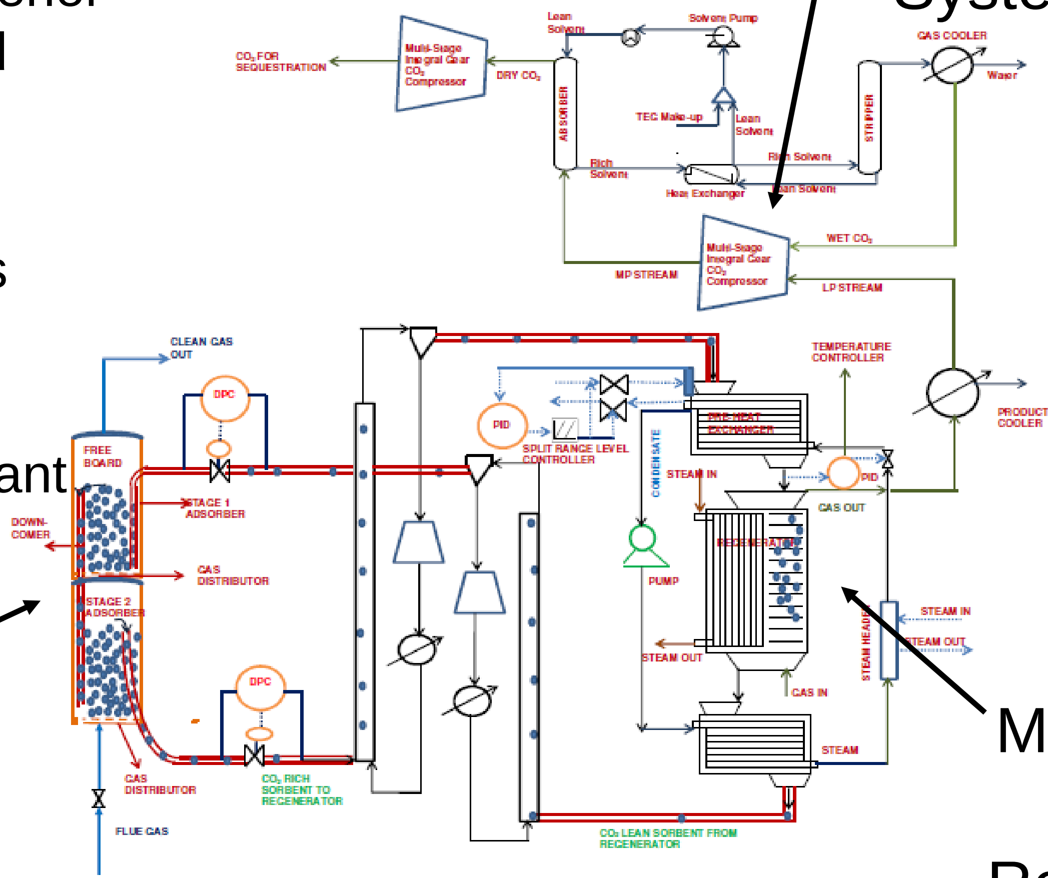
Short Biography of Benjamin Omell

- Post-Doctoral Fellow in the Department of Chemical Engineering at West Virginia University
- PhD from Illinois Institute of Technology, Chicago
- Research interest is in the area of steady-state and dynamic modeling and advanced process control of energy-generating and associated processes
- Member of AICHE
- Hobbies- Biking, hiking

CO_2 Capture & Compression Systems Coupled with the Steam Cycle

- Solid-sorbent systems are energetically superior to typical MEA-based solvent systems
- CCS system requires power and steam
- Dynamics are important during load-following

CO_2 Compression System



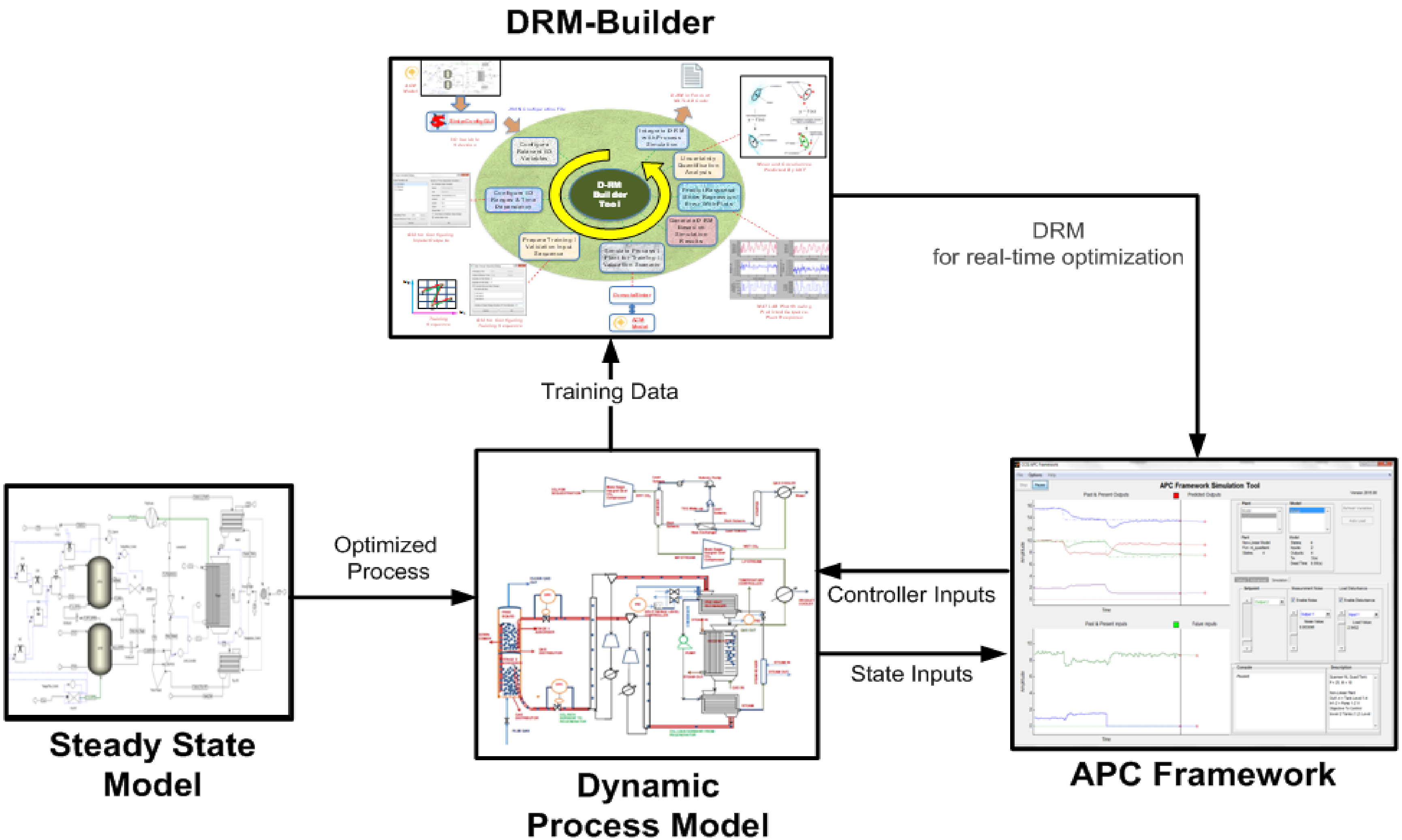
Bubbling Fluidized Bed (BFB) Adsorber

Moving Bed (MB) Regenerator

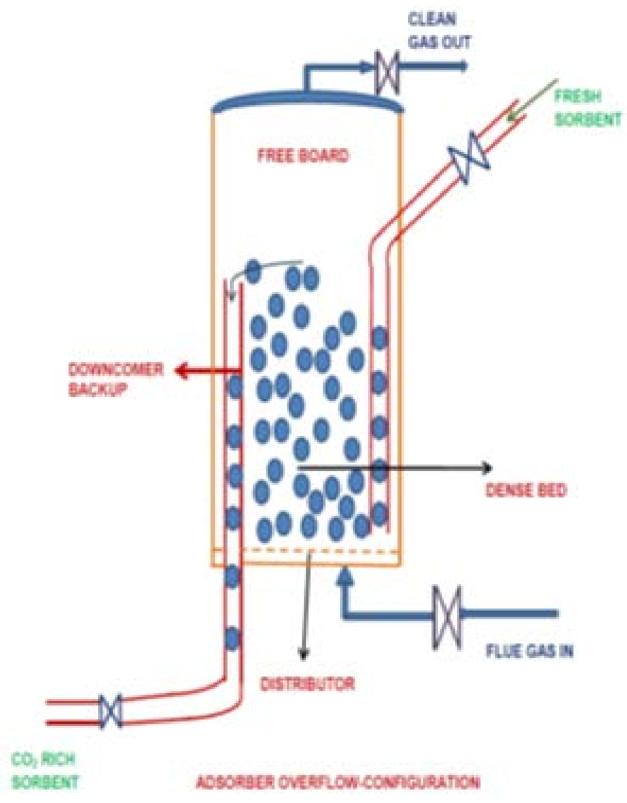
Goals and Objectives

- Develop accurate and flexible steady-state and dynamic solid sorbent models for CO_2 capture
  - BFB and MB adsorber/regenerator
  - Solids heat exchangers
  - CO_2 compression
  - Balance of the plant
- Create toolset to simplify implementation of advance control strategies that can perform efficiently in the presence of unmodeled disturbances, noisy measurements, and unmeasured variables
- Use these models and tools for optimization, transient studies, and control system design as part of DOE’s Carbon Capture Simulation Initiative (CCSI)

CCSI Toolset Framework



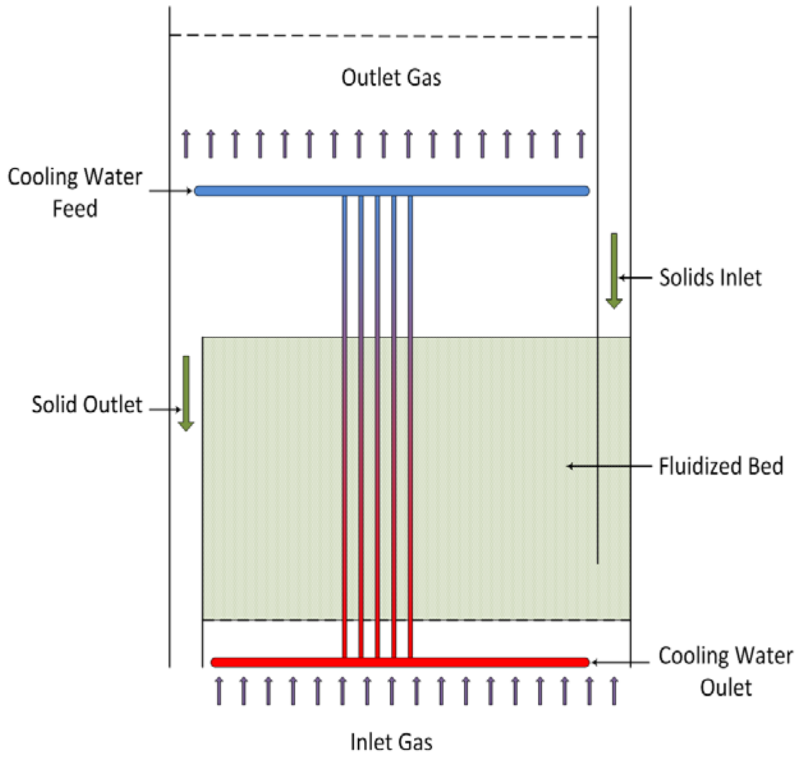
Challenge: Limitations in Previous Bubbling Fluidized Bed Models



- Typical simplifications to facilitate analytic solutions
  - Isothermal
  - Simplistic reaction kinetics and transport
  - Steady-state
  - Embedded heater/cooler neglected
- Limited support in commercial tools
- Minimal application to CO_2 capture in literature

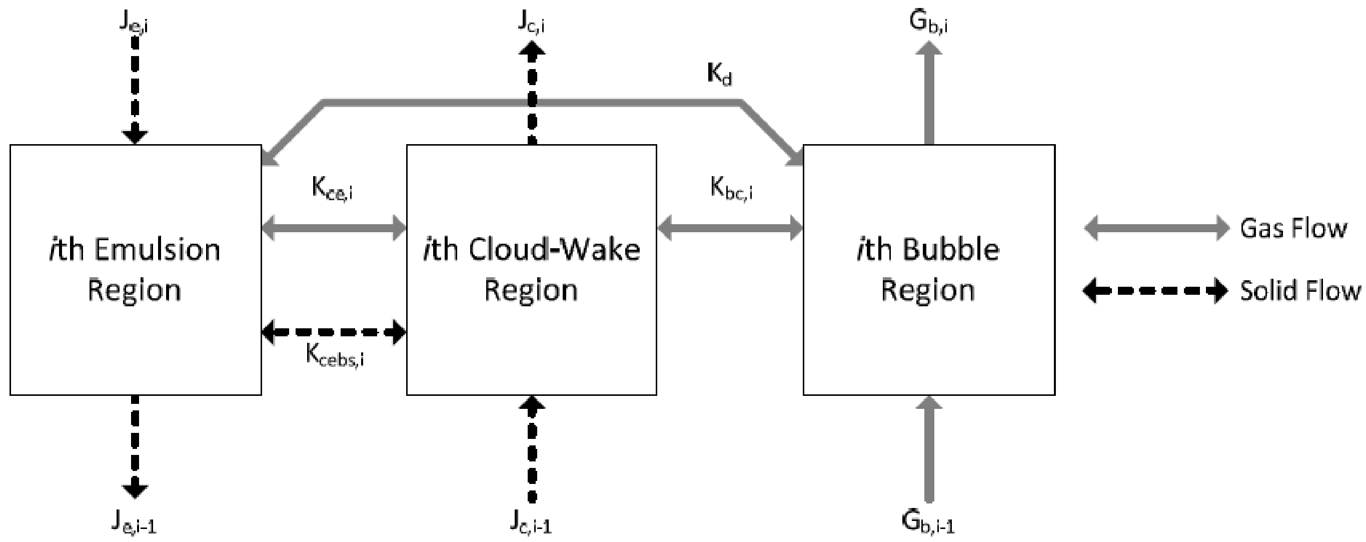
A Flexible BFB Model

1-D, two-phase, pressure-driven and non-isothermal models developed in both Aspen Custom Modeler (**ACM)** and **gPROMS**



- Flexible configurations
  - Dynamic or steady-state
  - Adsorber or regenerator
  - Under/overflow
  - Integrated heat exchanger for heating or cooling
- Supports complex reaction kinetics
- Compatible with CCSI uncertainty quantification (UQ) tools

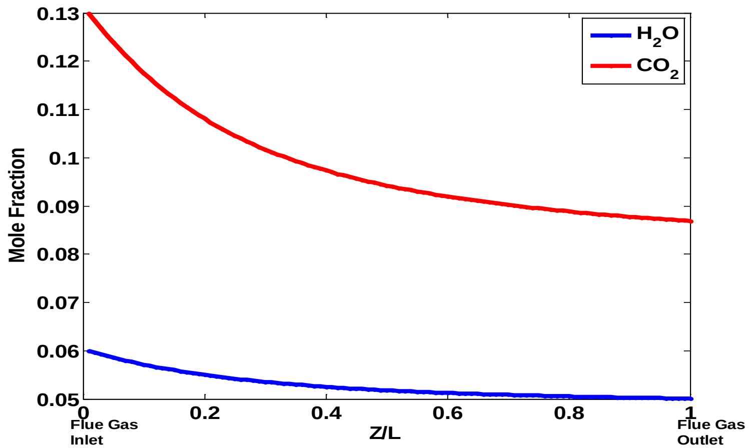
Model Development

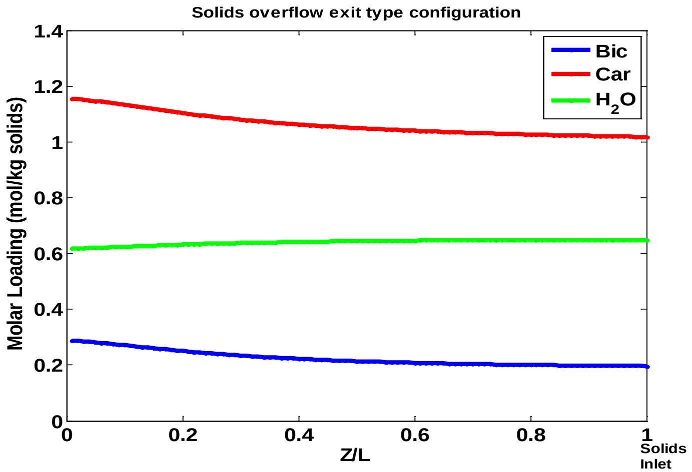


- Gaseous species : CO_2, N_2, H_2O
- Solid phase components: bicarbonate, carbamate, and physisorbed water.
- Transient species conservation and energy balance equations for both gas and solid phases in all three regions.

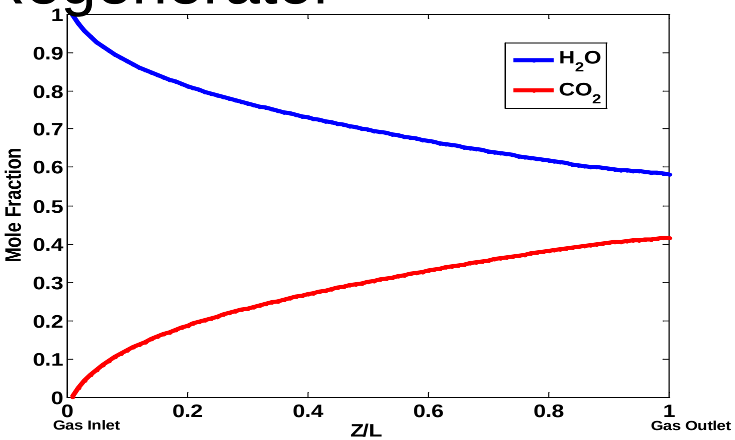
Single-Stage BFB Model: Steady-State Results

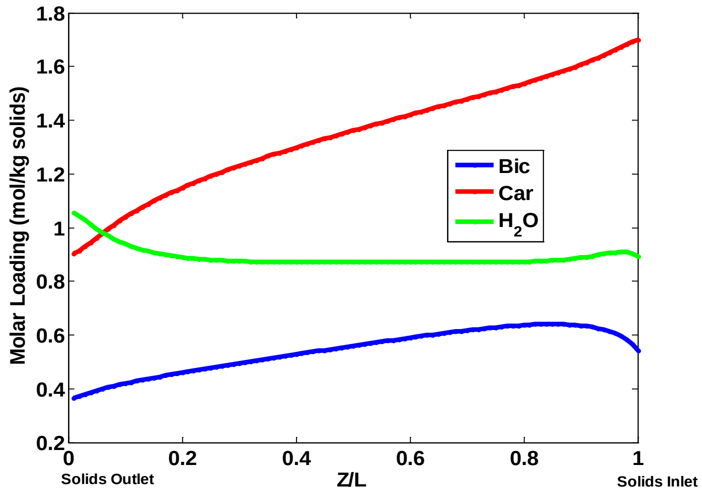
Adsorber





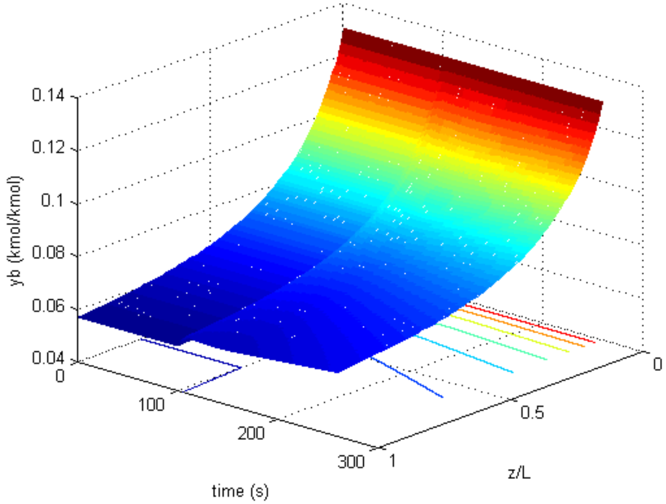
Regenerator



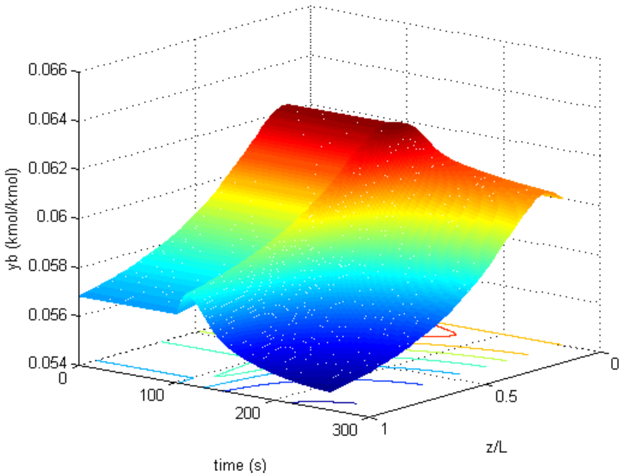


Dynamic Results – Increase Inlet Gas Flow by 20.6%

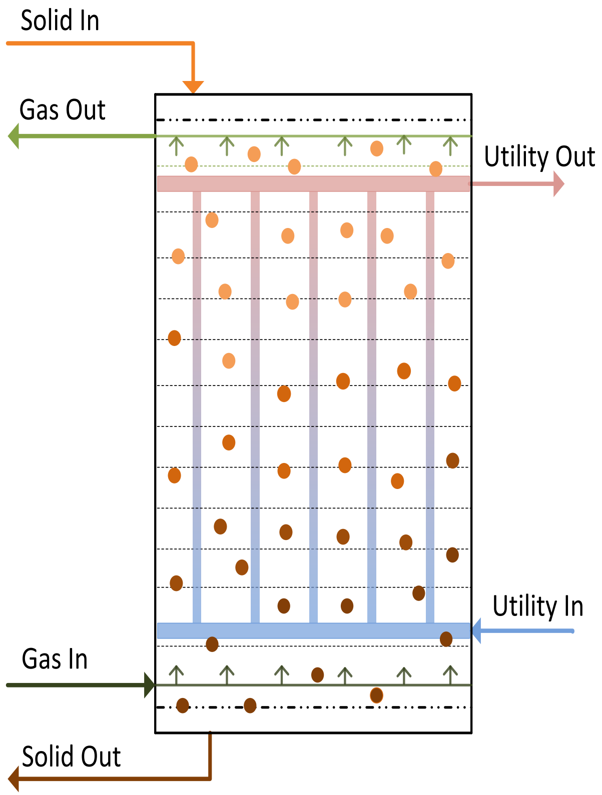
Gas CO_2 Concentration



Gas H_2O Concentration



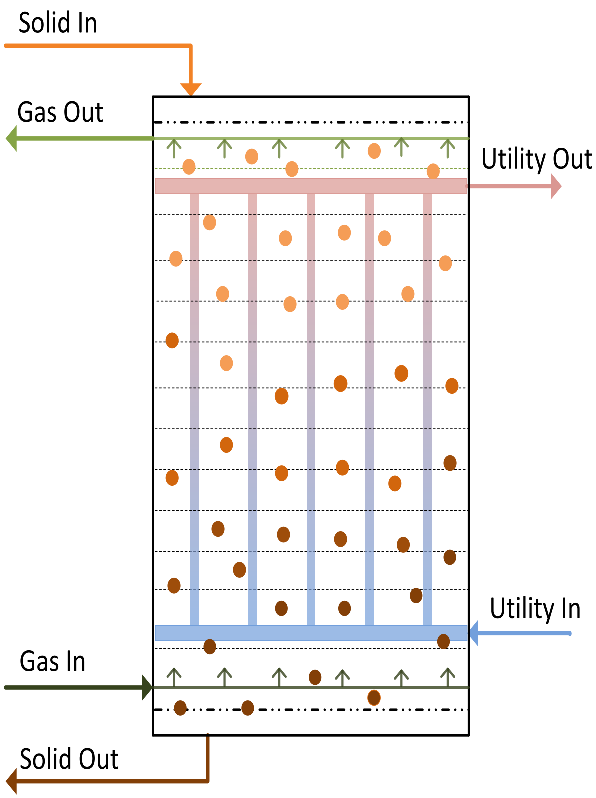
Challenge: Limitations of Existing Moving Bed Models



- Very few references in literature, little application to CO_2 capture
- Previous applications in literature include
  - MB furnaces for iron pellet reduction
  - Dryers
  - Non-catalytic gas-solid reactions
- Lack of mathematical model with large amount of heat transfer for solid sorbent regeneration
- Embedded heater/cooler not modeled
- Mainly steady-state model
- Hardly any model available in the commercial software

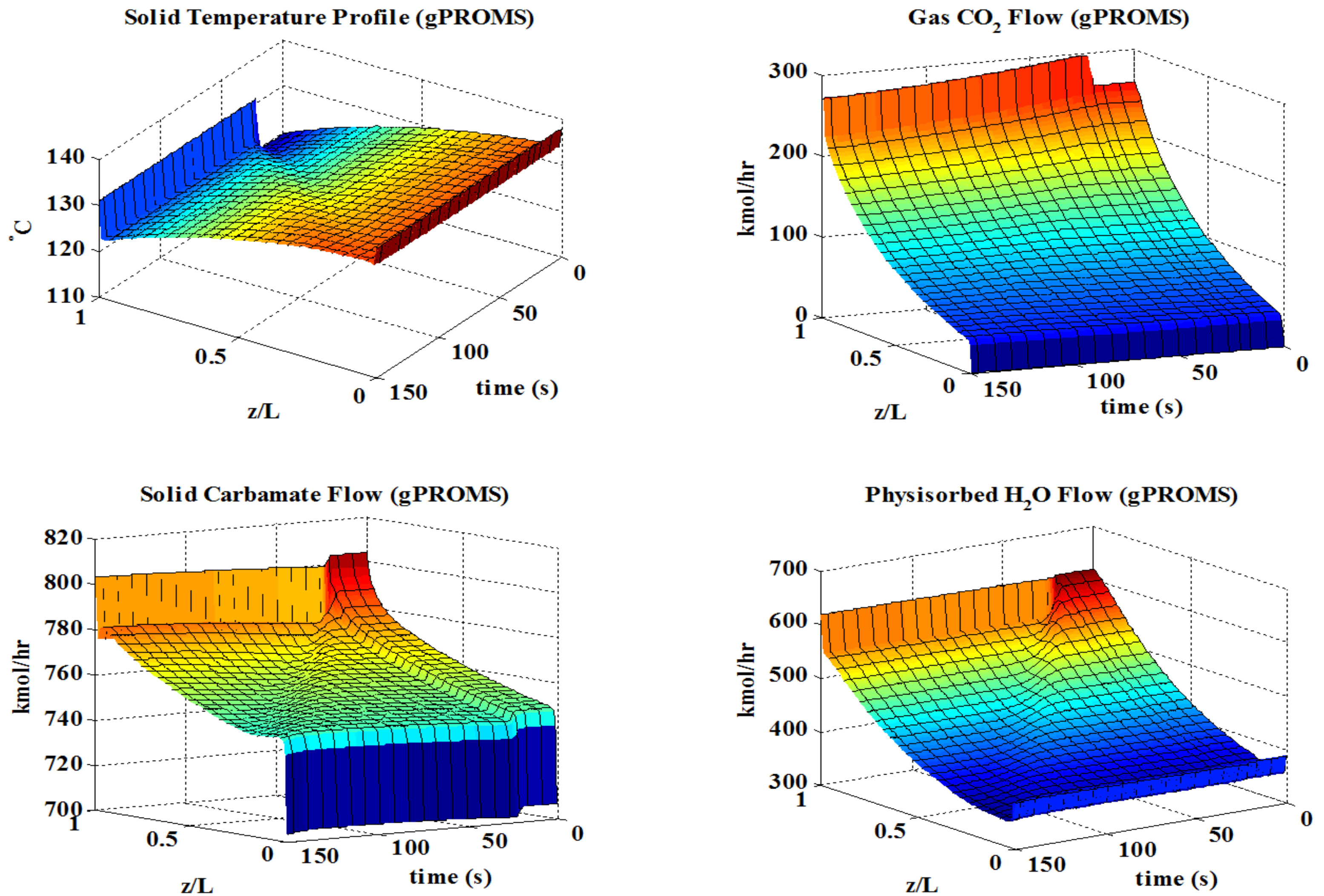
CCSI's Moving Bed Models

A1-D, two-phase, pressure-driven and non-isothermal regenerator model developed in both ACM and gPROMS

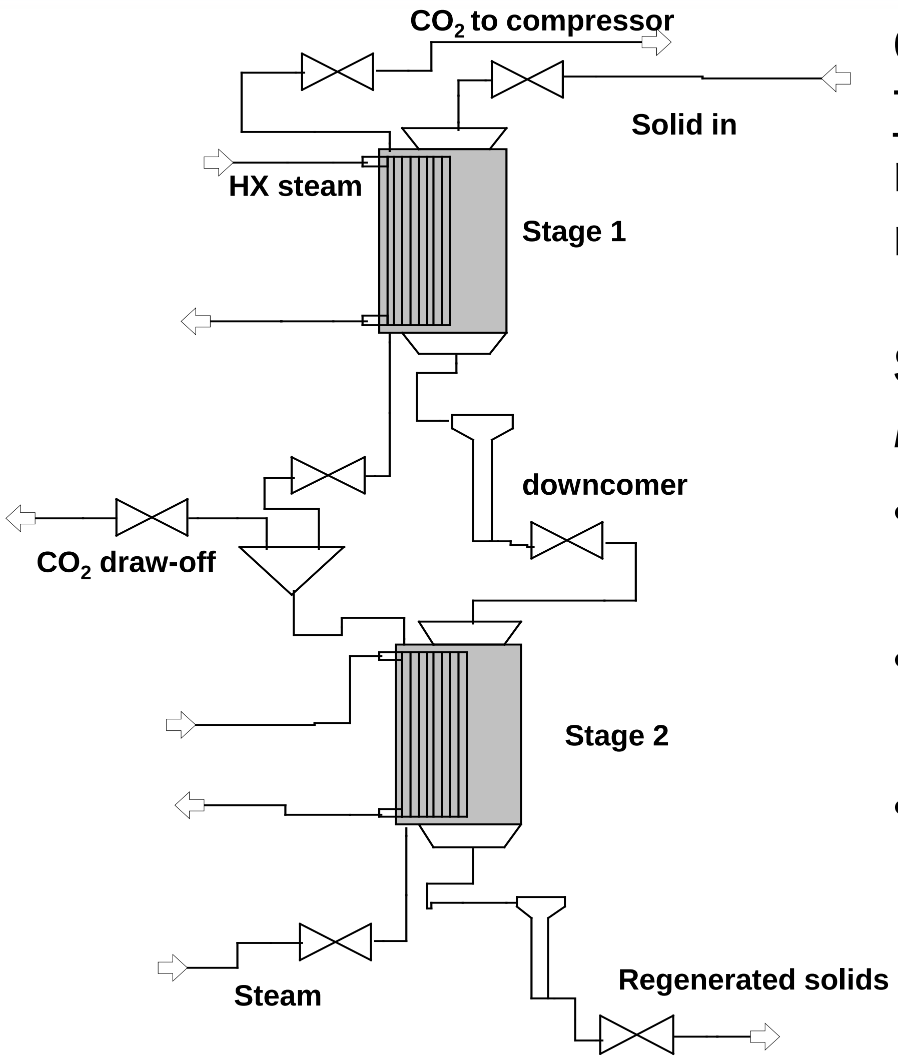


- Flexible dynamic and steady-state models
  - Integrated heat exchanger that can be used interchangeably for heating or cooling
  - Flexible enough for adsorber application

Step Test: Sorbent Temperature



Multi-Stage Moving Bed Design to Overcome Fluidization Concerns



Concern

Twenty-seven 9 m diameter MB regenerators in parallel required to maintain flow in moving bed regime*

Solution: *Multi-Stage Moving Bed Regenerator*

- Some CO_2 (gas) removed between stages
- Reduced gas flowrate at the top of the MB
- Requires an advanced control strategy

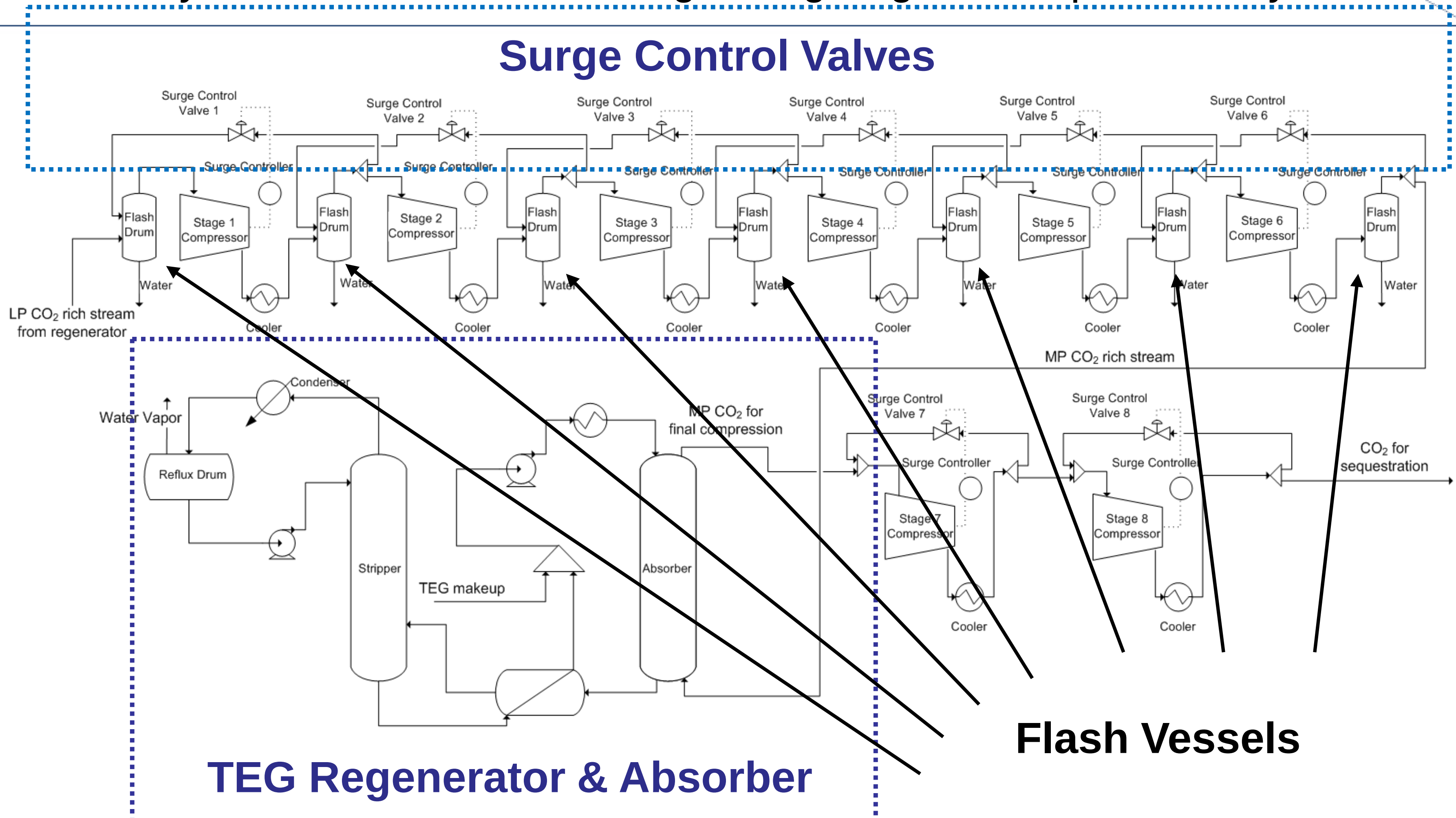
**Assumptions for preliminary analysis*: 12% CO_2 flue gas @ 2000 mol/s with 90% capture rate

Challenge: Limitations of Existing Compression Systems Models

- Has been mostly developed for non-CO_2 systems
- For CO_2 systems, developed mainly for sCO_2 cycles
  - Pressure ratio of 1 to 2.6 (about 150 for CCS)
  - Fixed inventory (variable for CCS)
  - Composition change, especially water content, is not a major concern for sCO_2 cycles
- Typically steady-state
  - Dynamics are essential for load-following in power systems
- Lack of performance curves for CO_2 systems
- Surge detection and control algorithms hardly studied for these systems

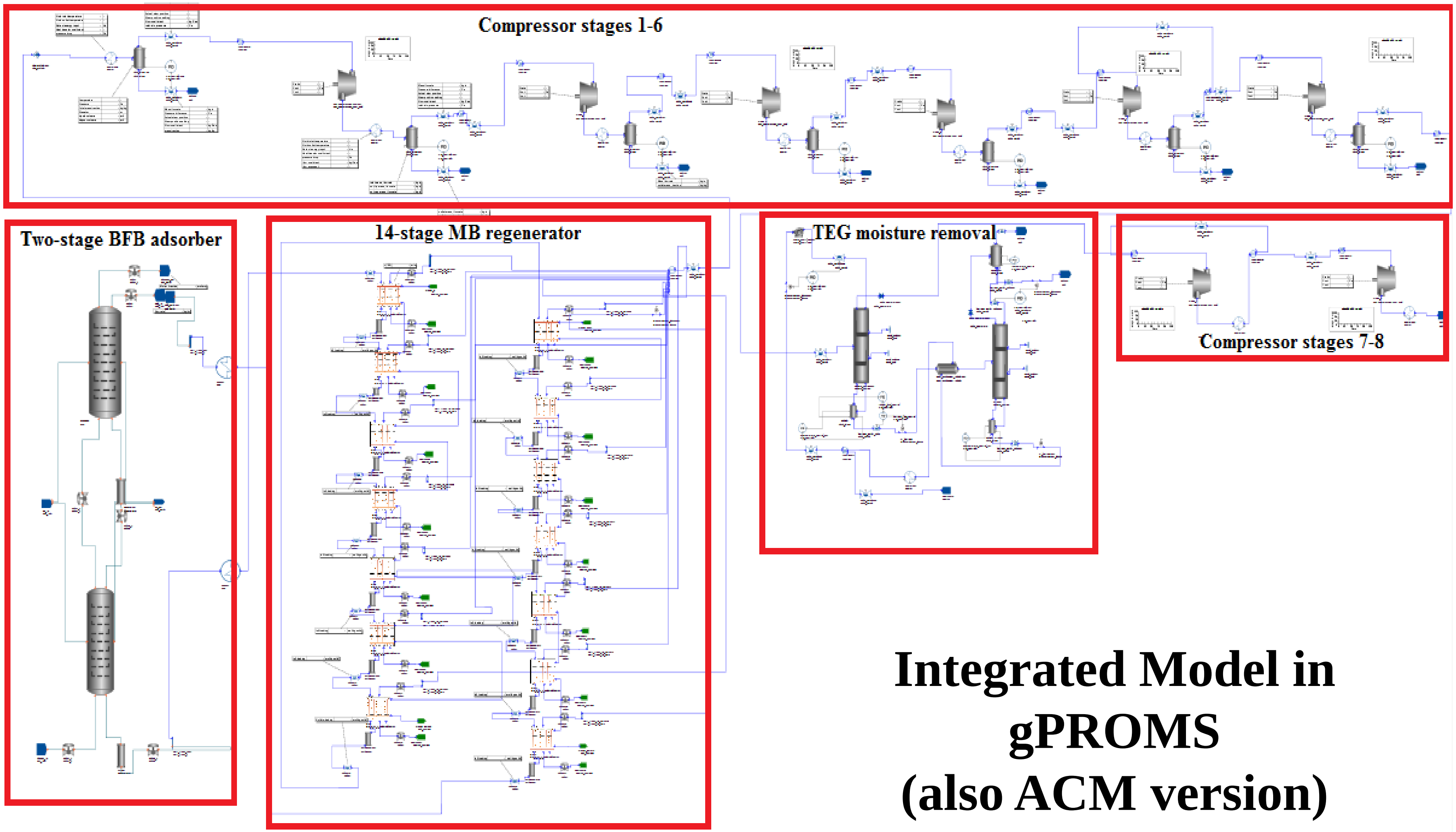
CCSI CO_2 Compression System Model

Dynamic model of multi-stage integral-gear compression system



Surge detection and control algorithm also developed

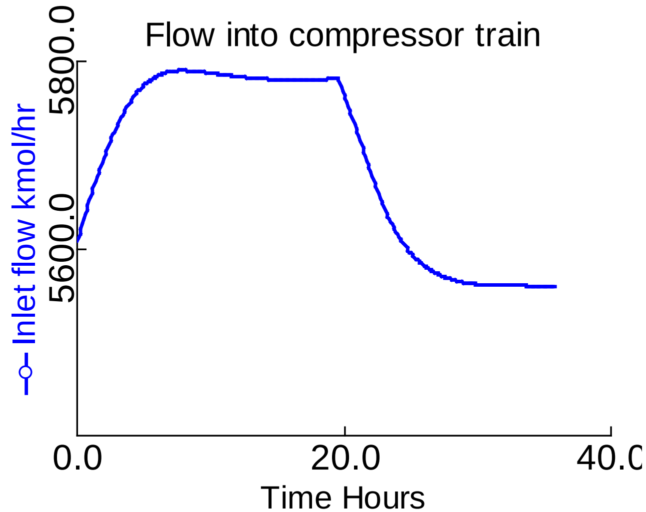
Integrated Model Enables Investigation of Entire Process Dynamics

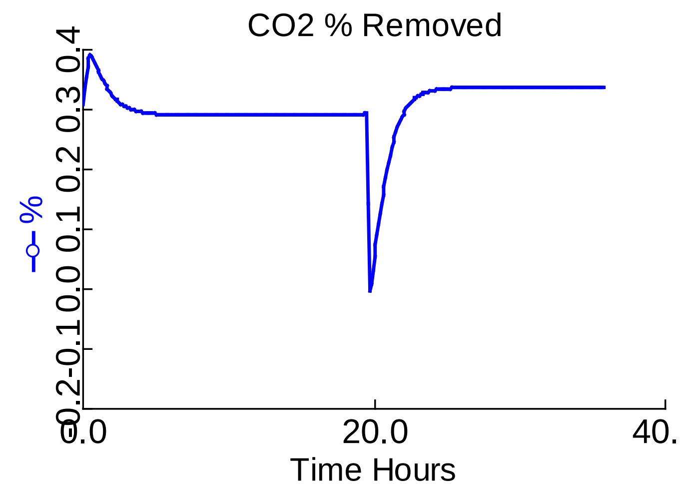


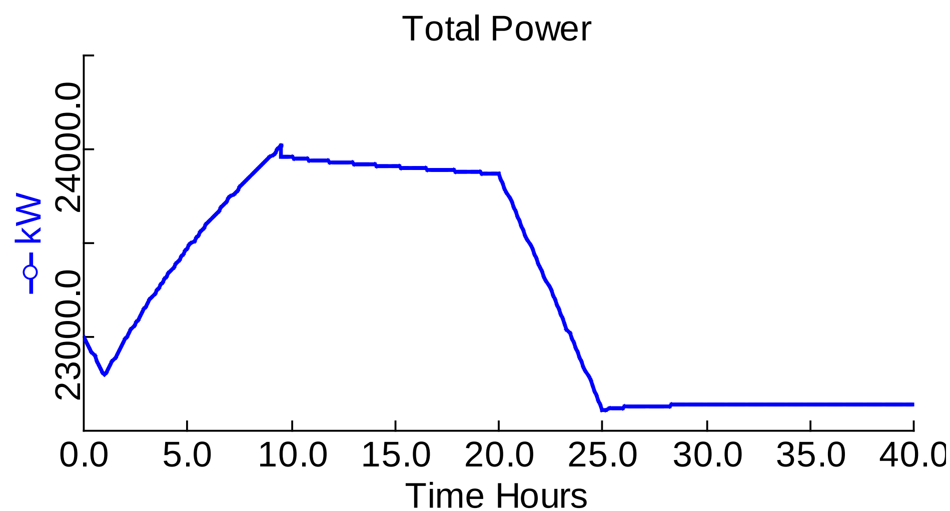
Integrated Model in gPROMS (also ACM version)

Ramp In Flue Gas

<u>Ramp in flue gas</u>
Time=0 : 15.8% increase
Time=20: 28.8% decrease

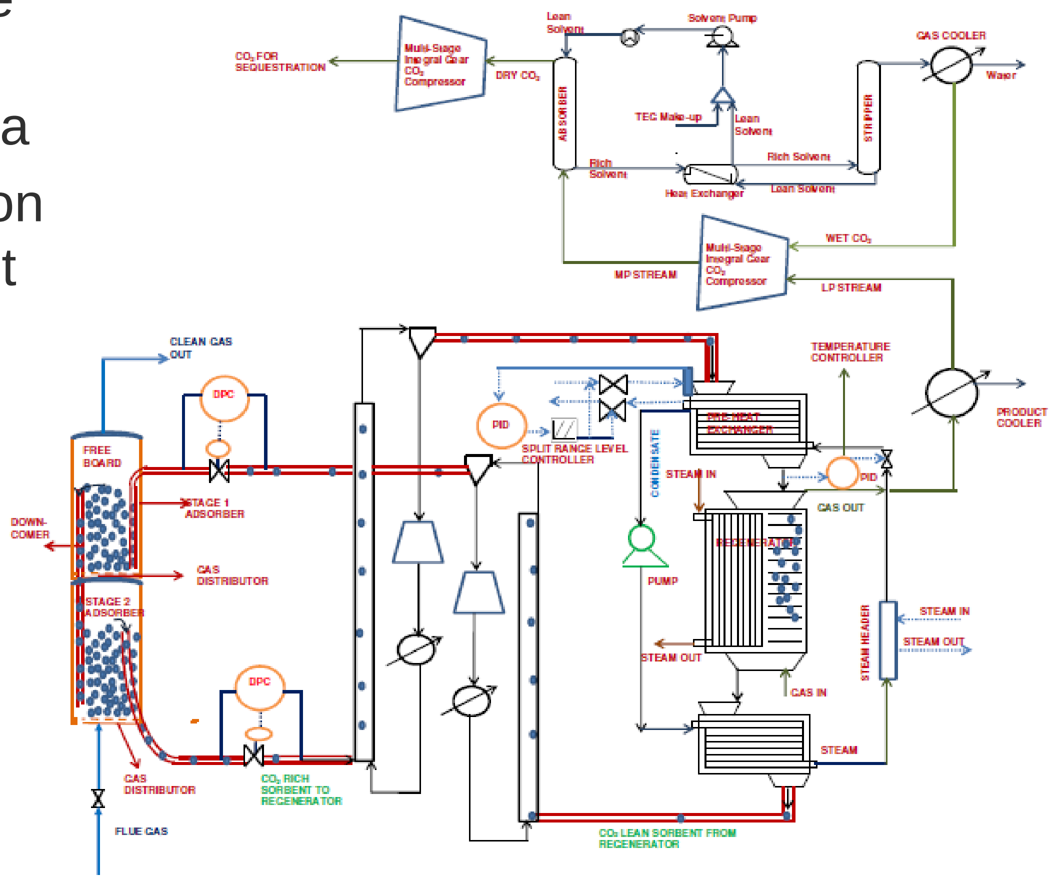




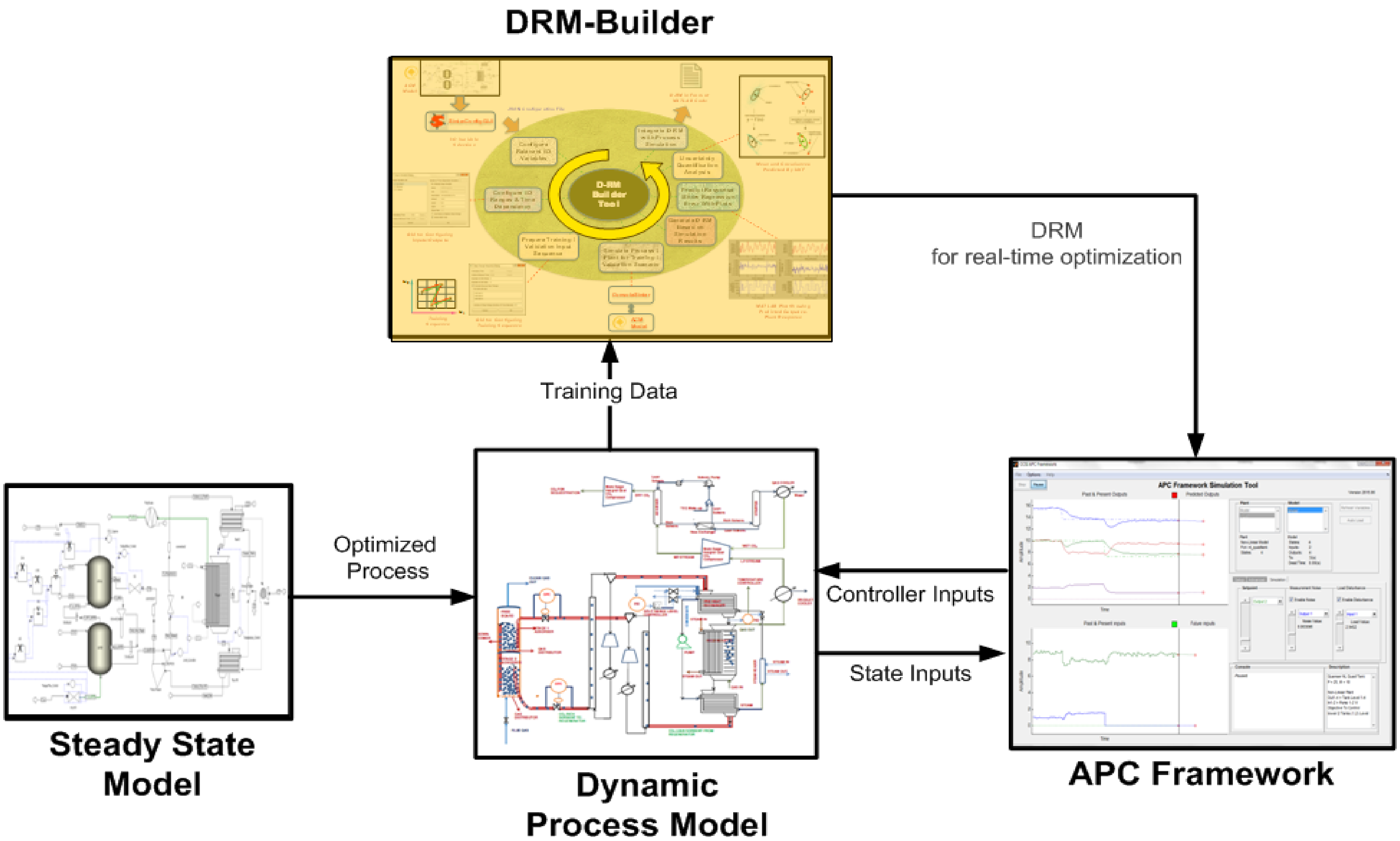


Dynamics of Integrated Process

- Transient effect of the capture and compression process on the power plant and vice versa
- Can result in temporal variation in CO_2 capture target-different time constants depending on the type of the bed
- CCSI tools DRM-builder and APC toolset can improve system dynamics



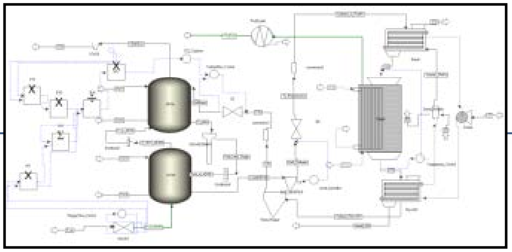
CCSI Toolset Framework



Motivation

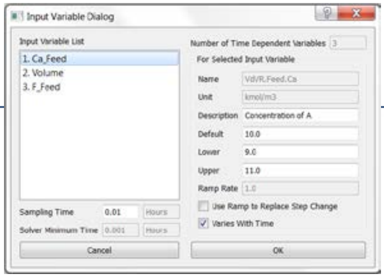
- High-fidelity dynamic models (e.g. ACM dynamic models) are computationally expensive
  - Need to solve many Differential Algebraic Equations (DAEs)
  - May require small time steps due to stiffness of DAEs
  - Not fast enough to catch up with real time
- Dynamic reduced models (D-RMs)
  - Speed up the dynamic simulations
  - Capture dynamic systems with reasonable accuracy
  - Can be used for Advanced Process Control (APC) and Real Time Optimization (RTO)

D-RM Builder Workflow

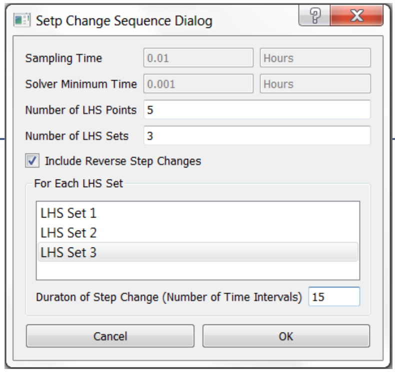


SinterConfigGUI

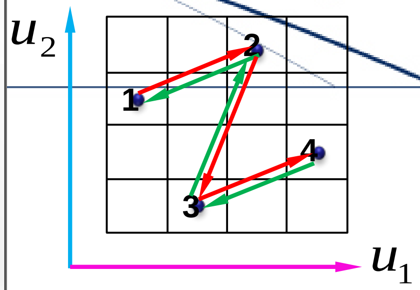
I/O Variable Selection



GUI for Configuring Inputs/Outputs

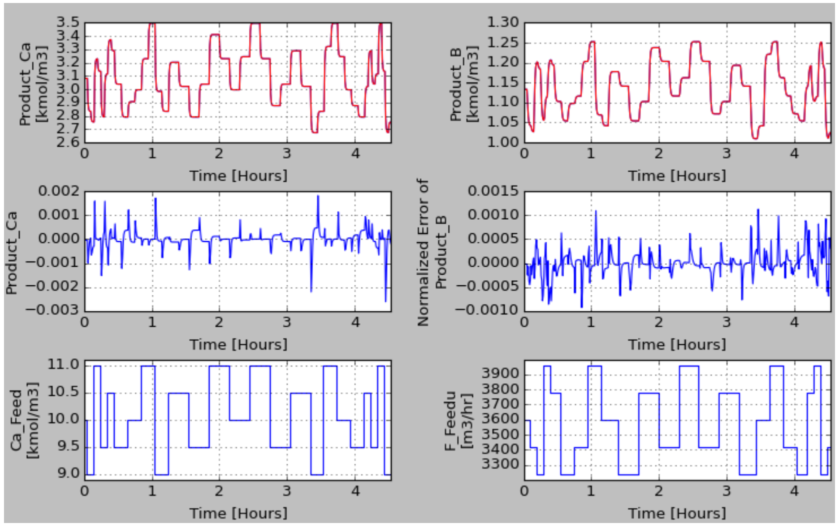


GUI for Configuring Training Sequence



Run Training Sequence

Generate D-RM Based on Simulation Results



Analyze Reduced **Model using UQ Tools, Validation Sets, Plots**

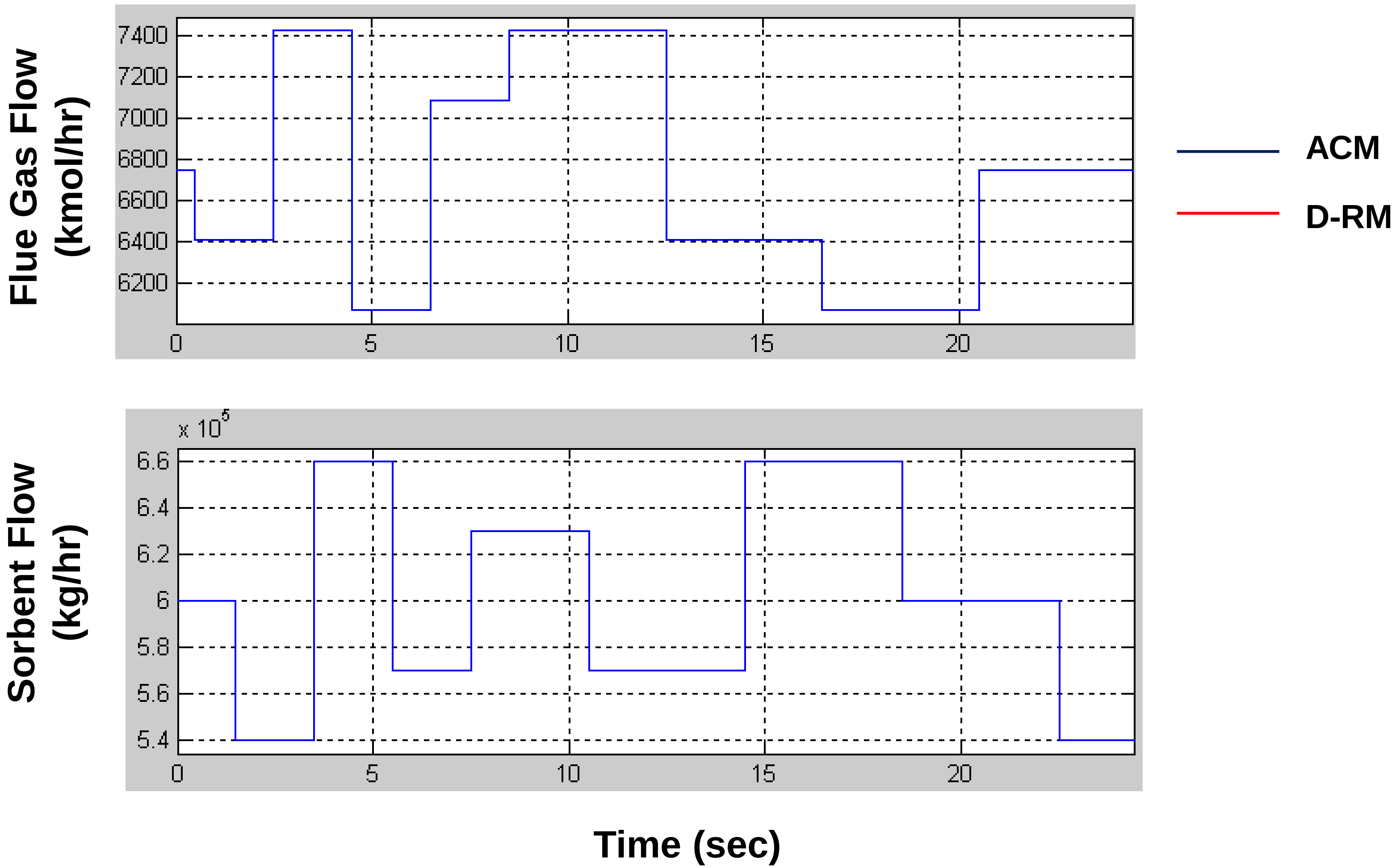
D-RM in Form of MATLAB Code

D-RM for the BFB Adsorber

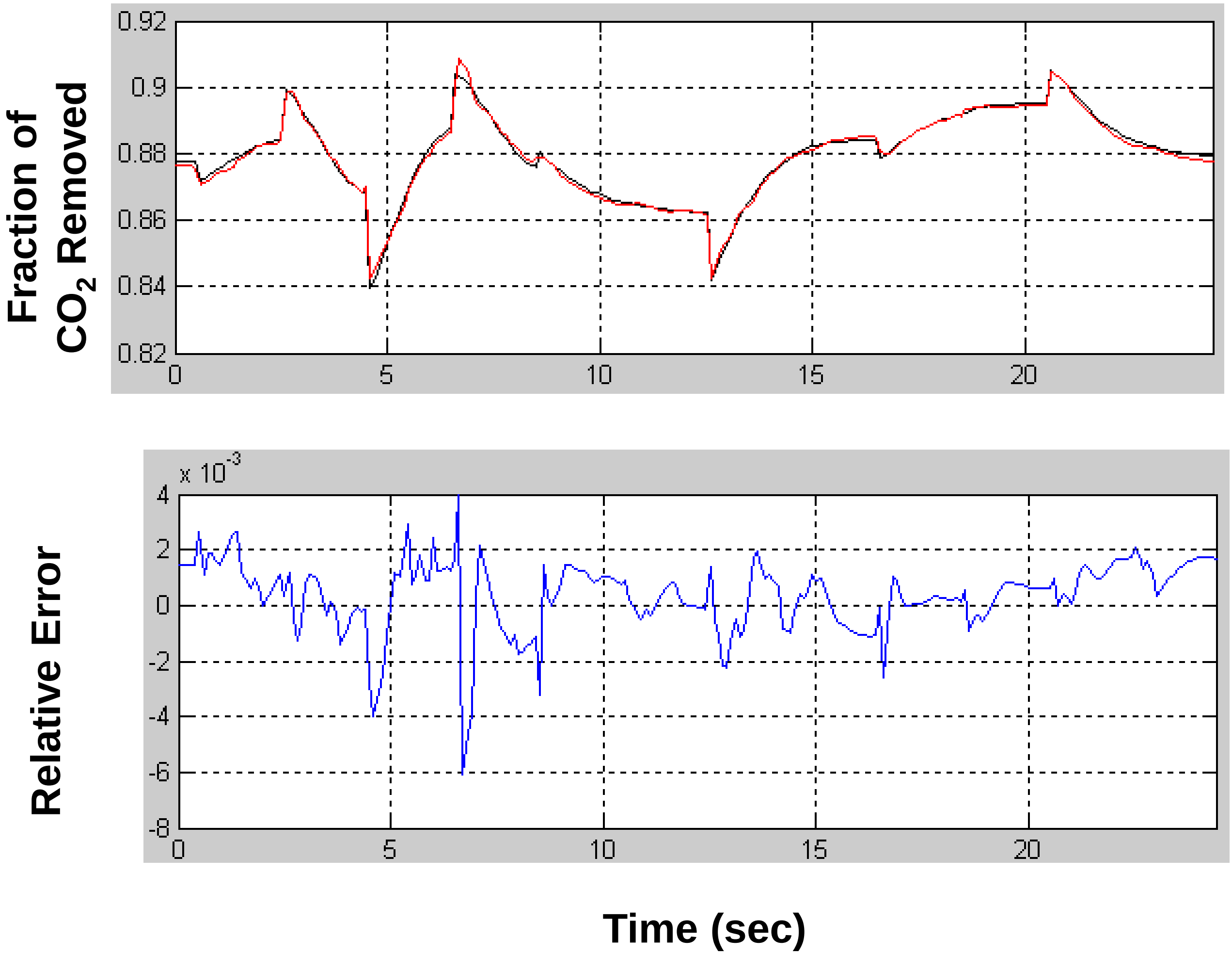
- D-RM generated based on open-loop ACM model
- Inputs:
  - Flue gas flow rate: 6,075 to 7,425 kmol/hr
  - Sorbent flow rate: 540,000 to 660,000 kg/hr
- Output:
  - CO_2 removal (Fraction of CO_2 in flue gas removed)
- DABNet* model with pole values optimized
- CPU time required for ACM simulations
  - Approximately 50 minutes for 2500 sampling steps (Sampling time interval at 0.1 second)

*Sentoni, G.B., L.T. Biegler, J.B. Guiver and H. Zhao, "State-Space Nonlinear Process Modeling: Identification and Universality," AIChE Journal, 44(10), 2229-2239, 1998.

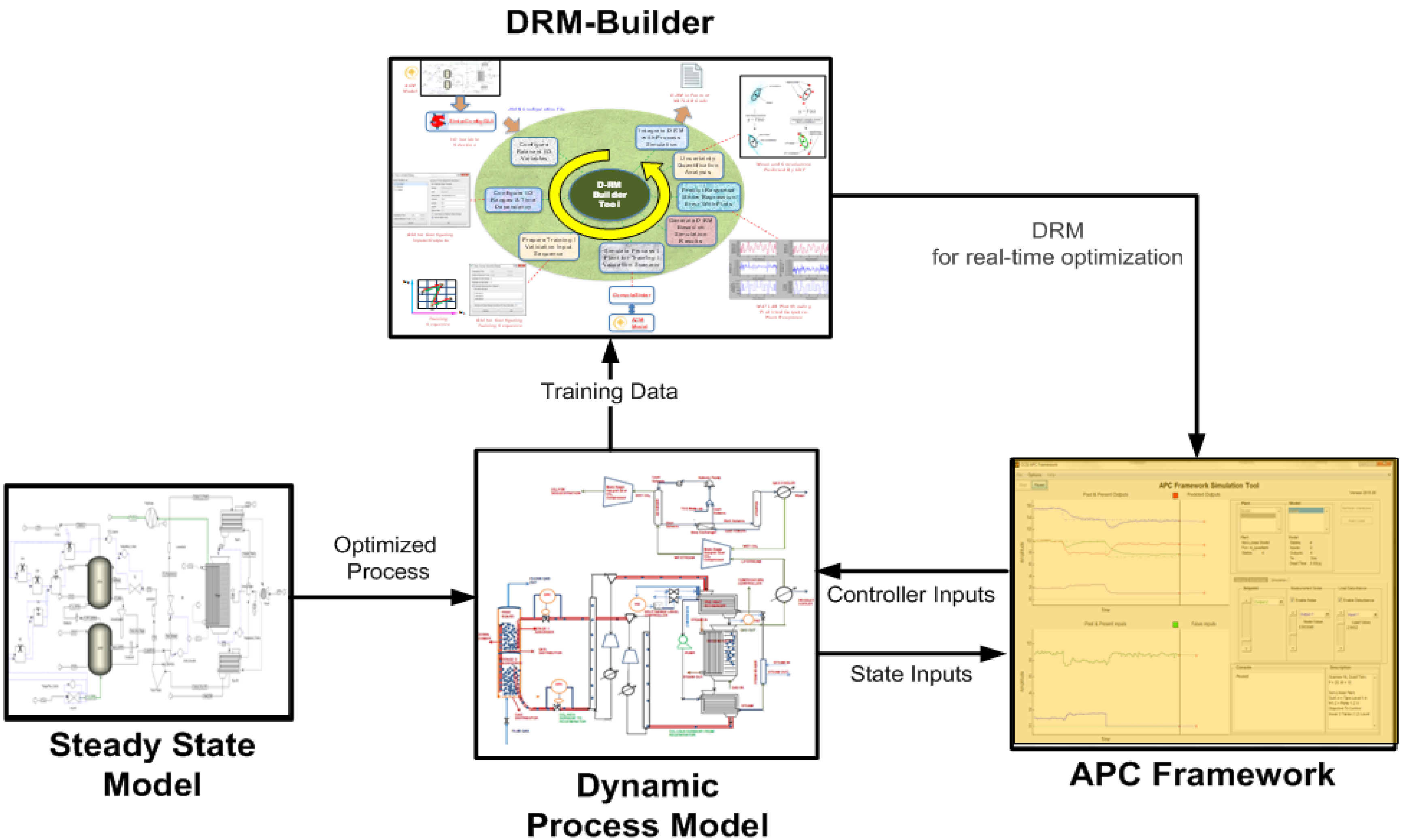
Validation Input Data



Validation Output Data

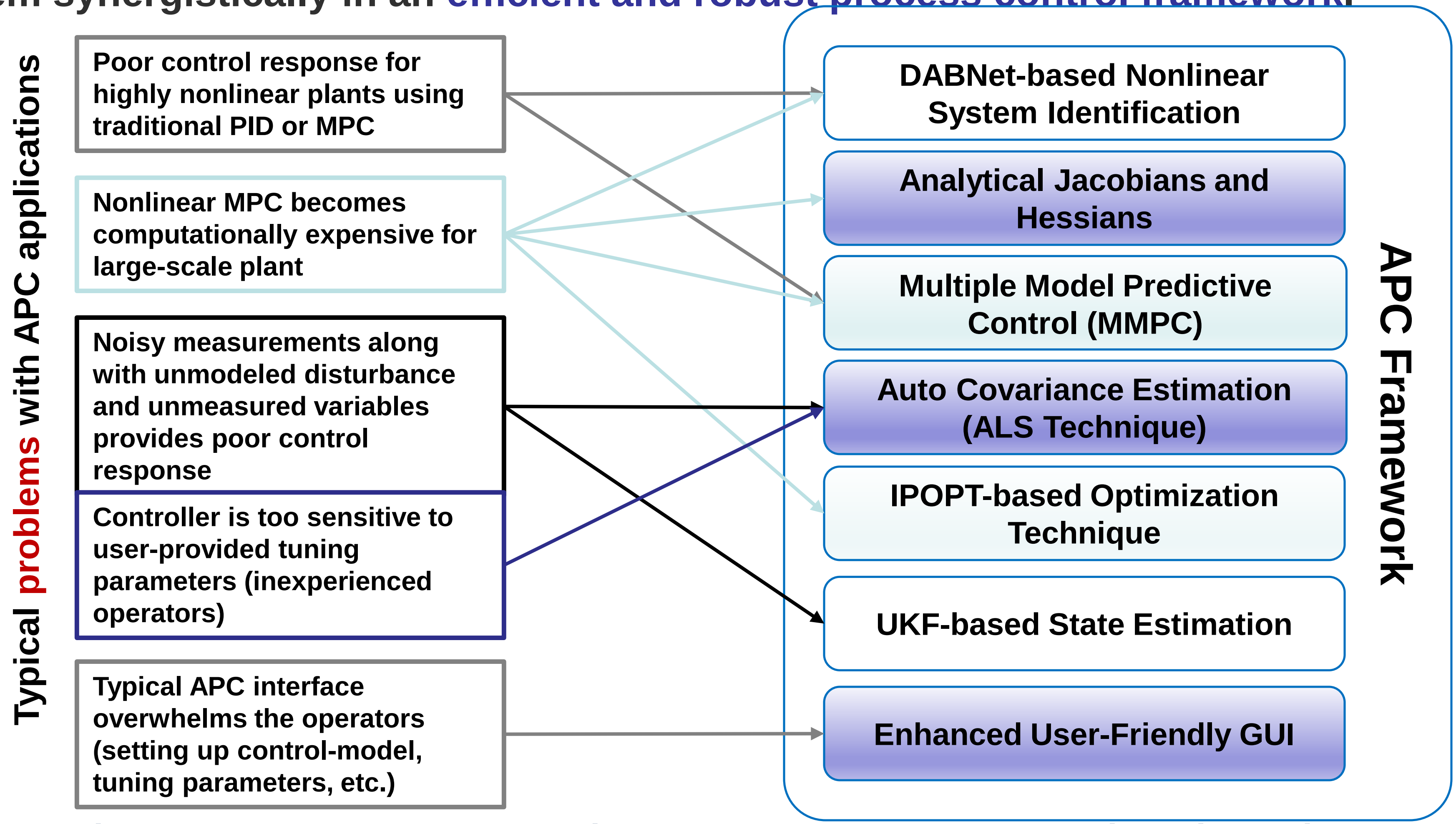


CCSI Toolset Framework

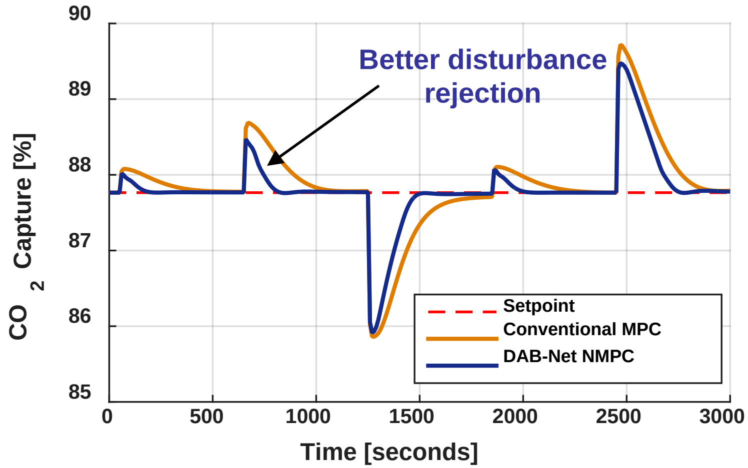


APC Framework's Capabilities

Utilize **proven techniques** from control relevant studies in literature and combine them synergistically in an **efficient and robust process control framework**.



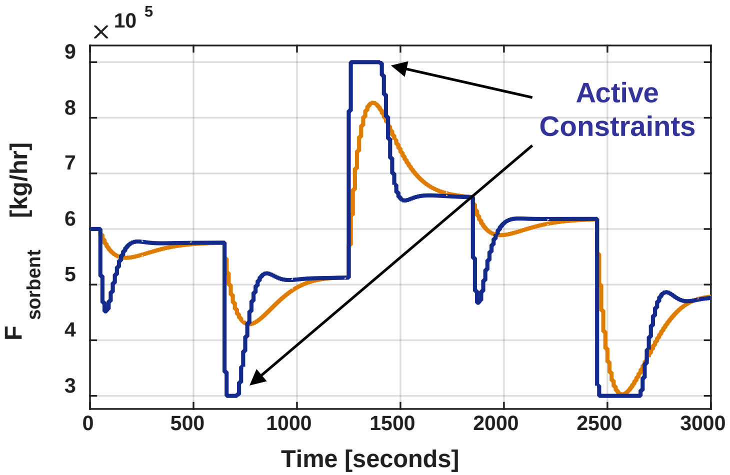
Performance Comparison on 2-Stage BFB Adsorber (ACM)

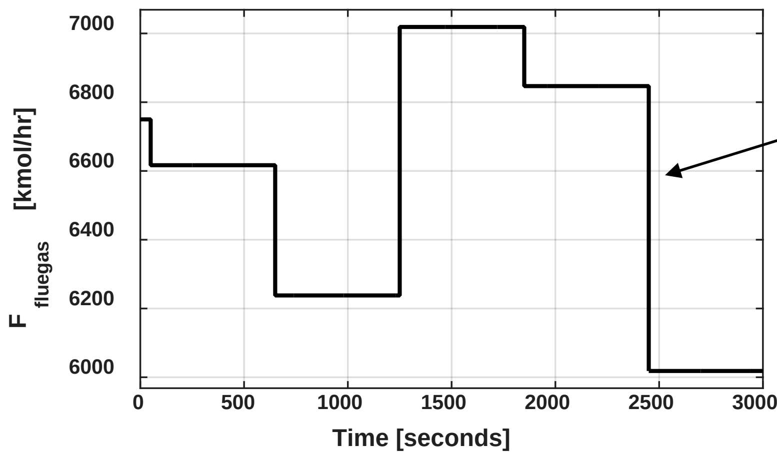


Controller responses to drastic plant-load changes – Comparison with standard MPC controller

Algorithm	Cumulative Residual	Computational Cost		
		Cumulative Control Calculation Time (sec)	Max Control Calculation Time (sec)	Total Simulation Time (min)
Conventional MPC	0.019	9.54	0.33	18.39
DAB-Net NMPC	0.007	19.97	3.43	18.92

Note: Max. Control Calculation Time << Sample Time (T_s = 20 sec), Real-Time Operation with APC

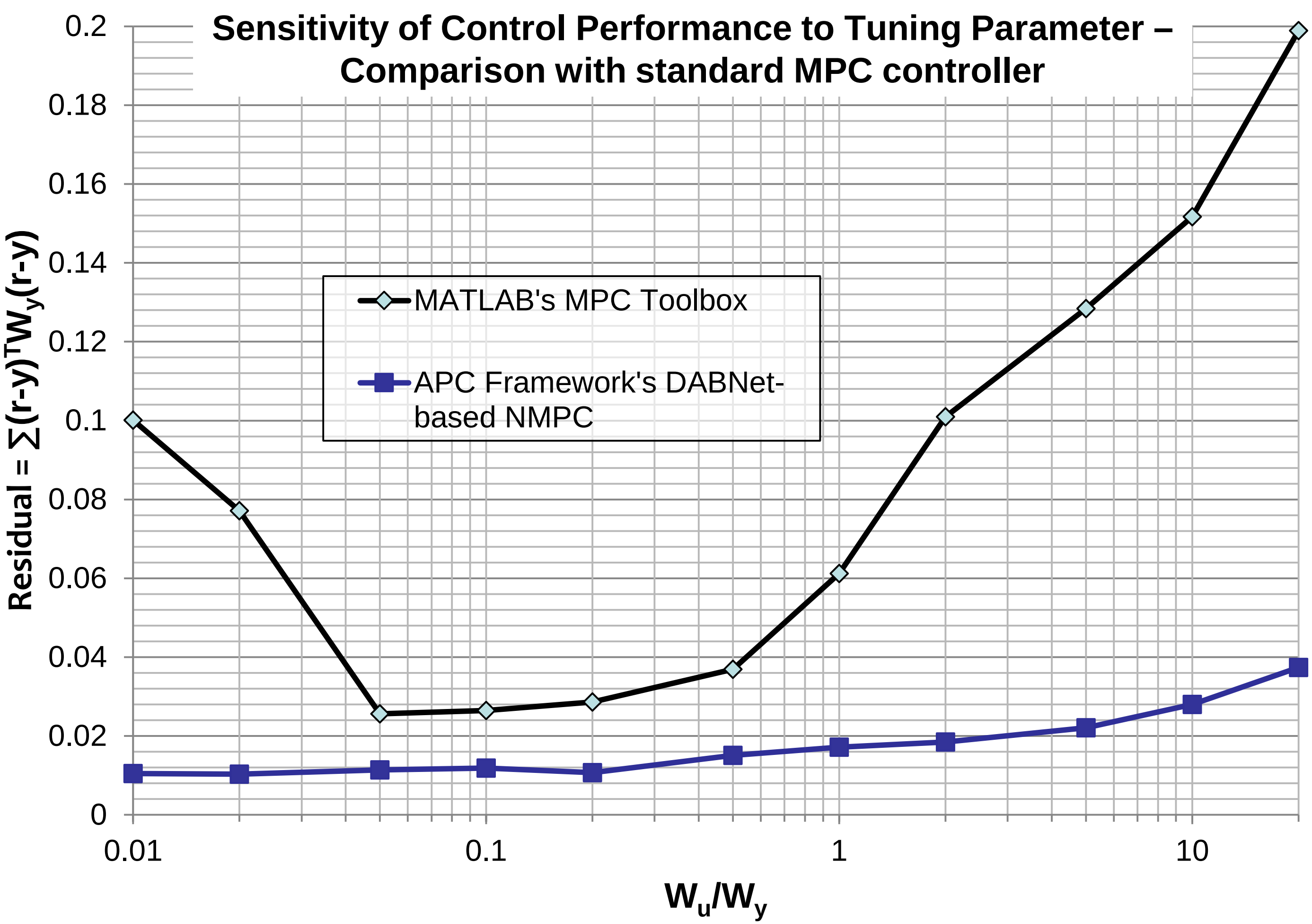




Controller Parameters

Prediction Horizon = 50
Control Horizon = 10
Wu/Wy = 0.2

Performance Comparison on 2-Stage BFB Adsorber (ACM)



Benefits of APC Framework

1. **Low residuals – tracks setpoint better over time**
2. **Low sensitivity for user-provided tuning parameters (W_u/W_y in this case)**

Summary

- Developed high-fidelity steady-state and dynamic solid sorbent models for CO_2 capture
- Utilization of DRM-builder tool to generate reduced ordered models
  - Use reduced order model to generate control strategy with APC framework to handle moving boundary problem of multi-stage moving bed regenerator
- APC performance is relatively insensitive to tuning parameters and results in efficient disturbance rejection and load-following characteristics

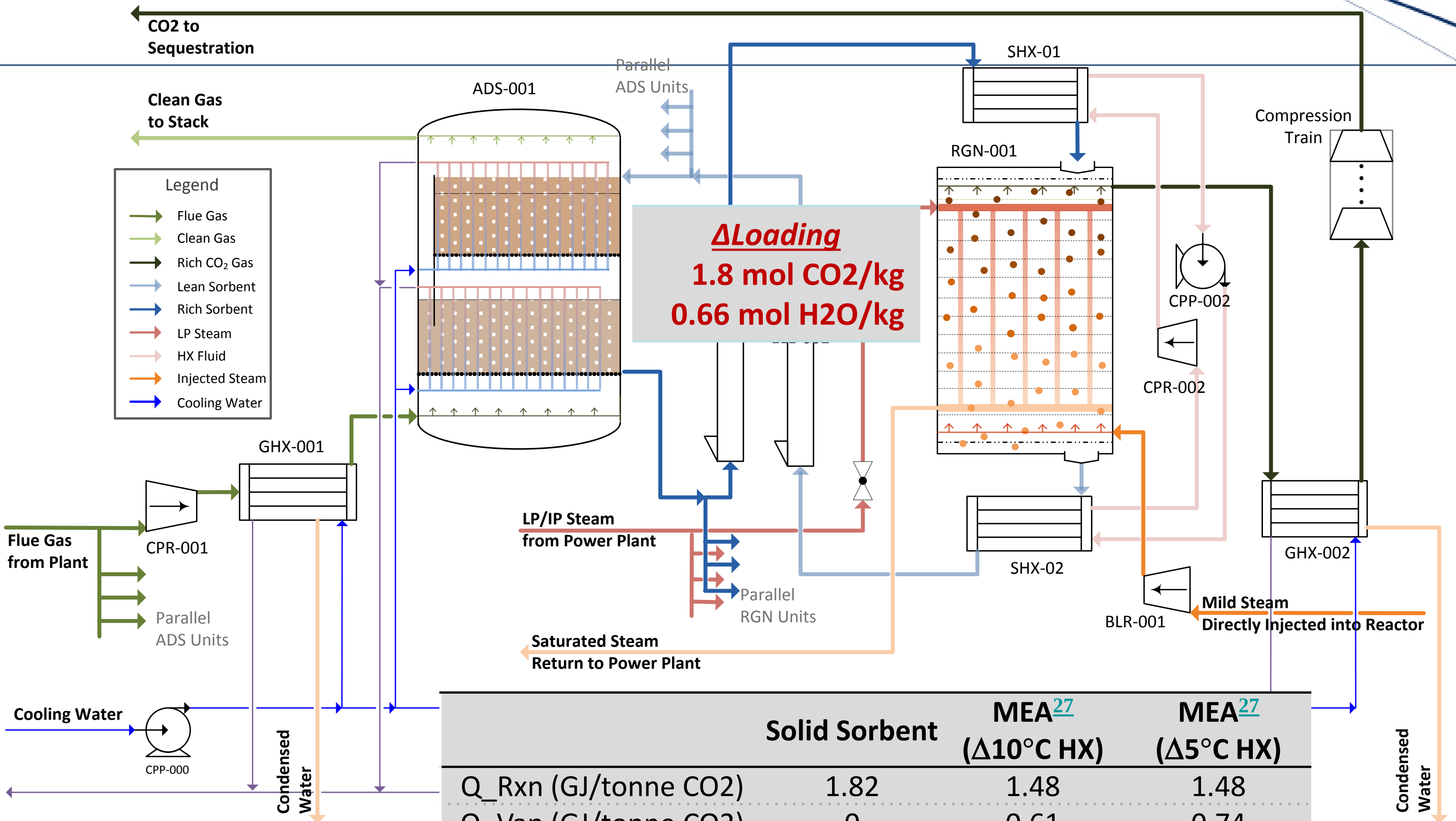
Acknowledgement

DOE's Carbon Capture Simulation Initiative for funding. Part of this technical effort was performed under the RES contract DE-FE0004000 through National Energy Technology Laboratory's Regional University Alliance (NETL-RUA.

Disclaimer

Thank You

Optimized Process Developed using CCSI Toolset



	Solid Sorbent	MEA[27] (Δ10°C HX)	MEA[27] (Δ5°C HX)
Q_Rxn (GJ/tonne CO2)	1.82	1.48	1.48
Q_Vap (GJ/tonne CO2)	0	0.61	0.74
Q_Sen (GJ/tonne CO2)	0.97	1.35	0.68
Total Q	2.79	3.44	2.90