The Ohio State University

ADVANCED CONTROL ARCHITECTURE AND SENSOR INFORMATION DEVELOPMENT

FOR PROCESS AUTOMATION, OPTIMIZATION, AND IMAGING OF CHEMICAL LOOPING SYSTEMS

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Crosscutting Research Review Meeting | April 20th, 2016

Project Team

Government Agencies

- DOE/NETL: Jessica Mullen
- Ohio Development Service Agency: Gregory Payne

Project Partners

- Ohio State University:
  Dr. Andrew Tong (PI, Dept. of Chemical & Biomolecular Engineering),
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- Tech4Imaging:
  Dr. Qussai Marashdeh, CEO and President of Tech4Imaging LLC

- Babcock & Wilcox
  Thomas Flynn, P.E.
  Timothy Fuller, P.E.
  Bijan Hosseininejad, P.E.

OSU Chemical Looping Platform Technology

Feedstock

- Coal
- Natural Gas
- Oil
- Petcoke
- Biomass
- Waste
- Syngas
- F-T light hydrocarbon

Driver

- Chemical Looping Combustion (CLC)
- Chemical Looping Gasification (CLG)
- Carbonation-Calcination Reaction (CCR)
- Calcium Looping Process (CLP)
- Direct Chemical Synthesis (with EcoCatalytic)

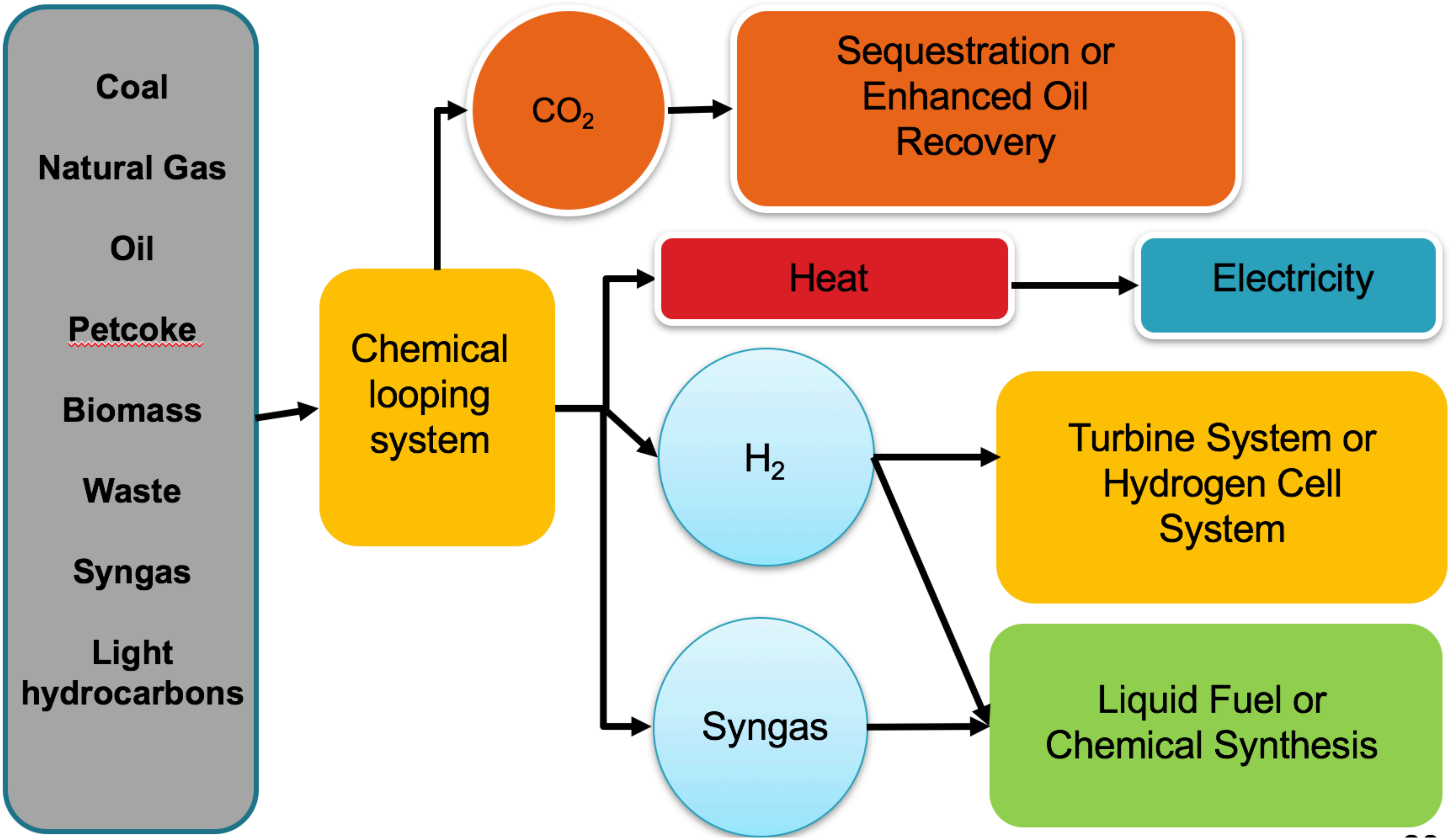
Applications and Products

- CO_2 Capture/Emission Control
- Electricity/heat
  - Retrofit to PC
  - New Plant
  - Combined Cycle
  - SOFC
- Hydrogen
- CLG Syngas
- Liquid fuel
  - F-T Synthesis
  - CO_2 Hydrogenation
  - Olefins to Liquid Fuel
- Chemicals
  - Olefins
  - Ammonia

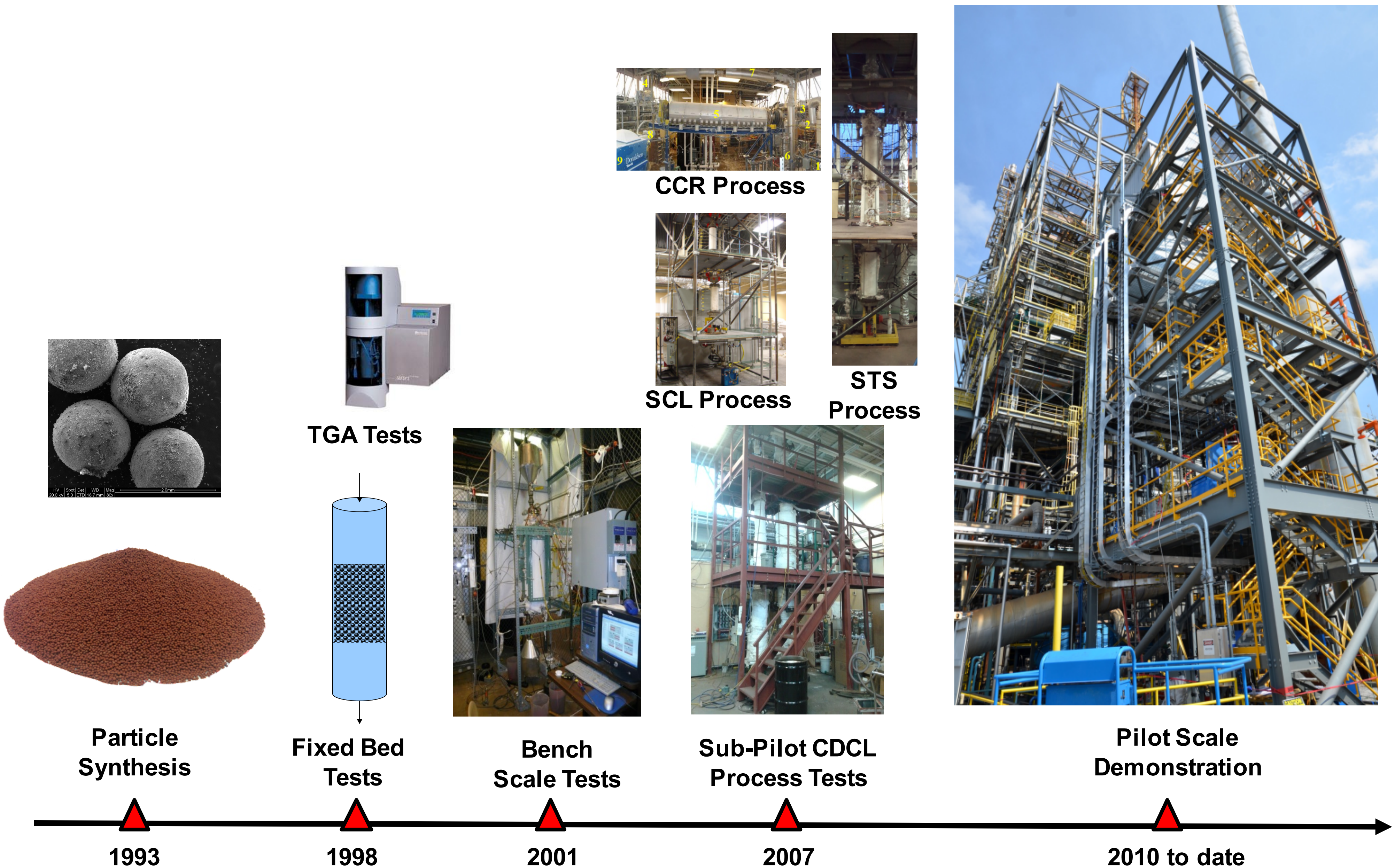
Metal Oxide Development

Thomas, T. J., Fan, L.-S., Gupta, P., Velazquez-Vargas, L.G. U.S. Patent 7,767,191.

OSU Chemical Looping Platform Technology

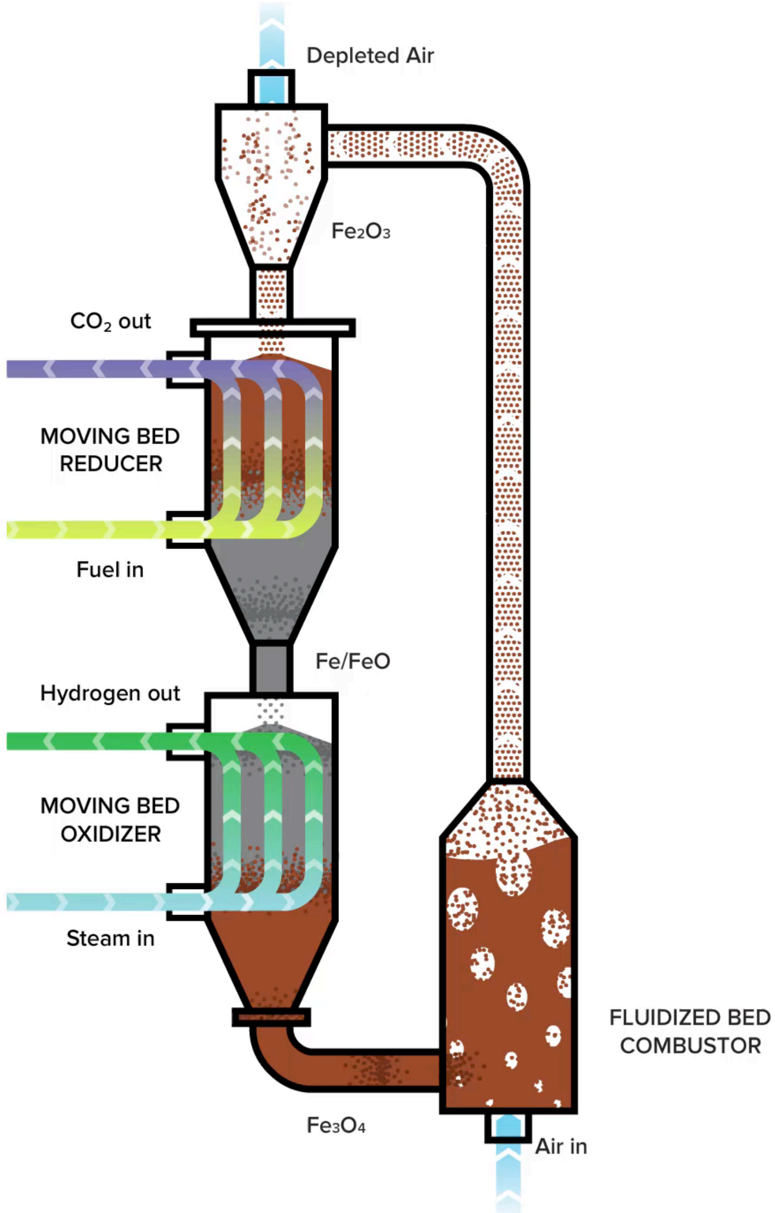


Evolution of OSU Chemical Looping Technology



Fan, L.-S., Zeng, L., Luo, S. *AIChE Journal*. 2015.

OSU Syngas Chemical Looping Process



Main reactions:

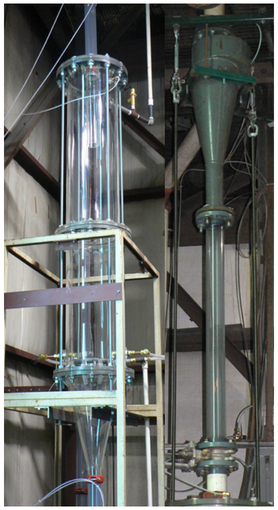
Reducer:	$C_xH_yO_z + Fe_2O_3 \rightarrow CO_2 + H_2O + Fe$
Oxidizer:	$Fe + H_2O \rightarrow Fe_3O_4 + H_2 + Q$
Combustor:	$Fe_3O_4 + O_2 \rightarrow Fe_2O_3 + Q$
Total:	$C_xH_yO_z + H_2O + O_2 \rightarrow CO_2 + H_2 + Q$

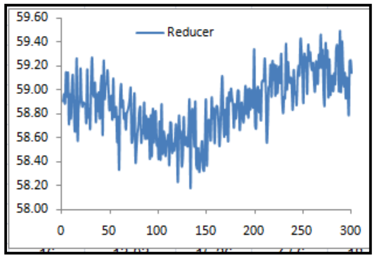
Unique Reactor Design:

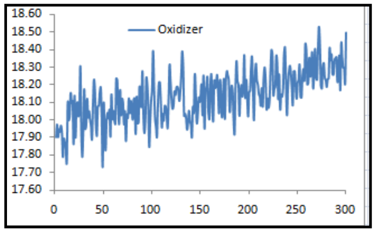
- High fuel conversion
- Near 100% in-situ CO_2 capture
- High purity H_2 generation
- High oxygen carrier conversion
- Low solid circulation rate

SCL Pilot Plant Development

1:1 Cold Flow Model Testing

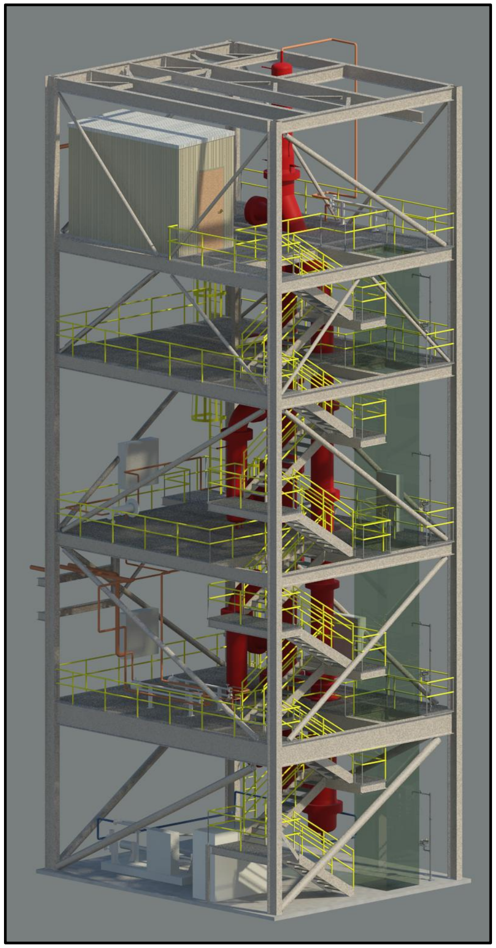






- Over 20 solids/gas flow operating conditions successfully tested
- System operation is robust
- >200 hrs continuous operation
- Non-mechanical system design successfully demonstrated
- Operational experience gained was used in developing the P&ID and operating procedures of SCL pilot scale unit at high temperature and pressure

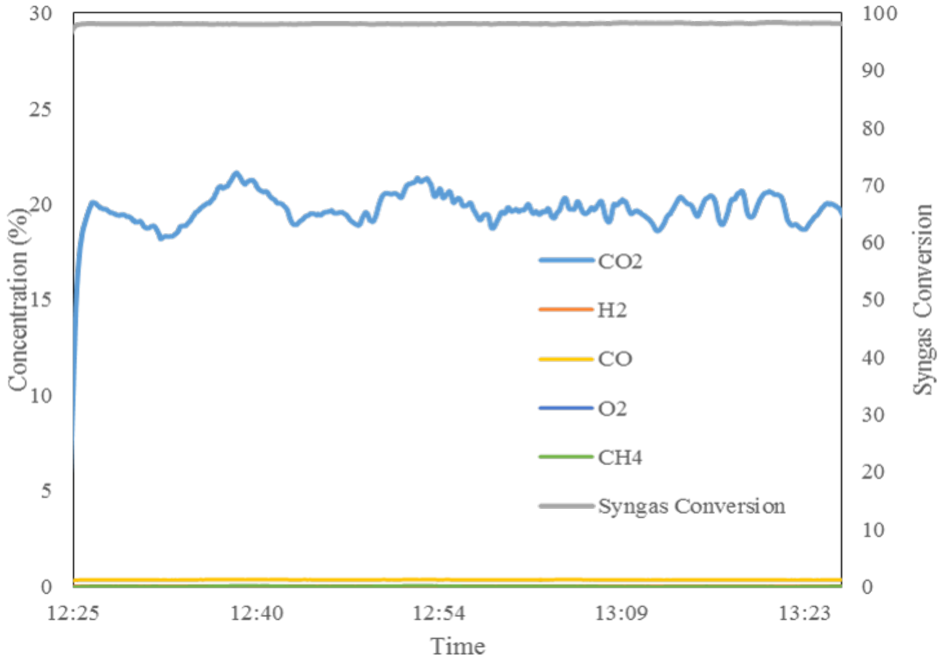
Pilot Plant Design

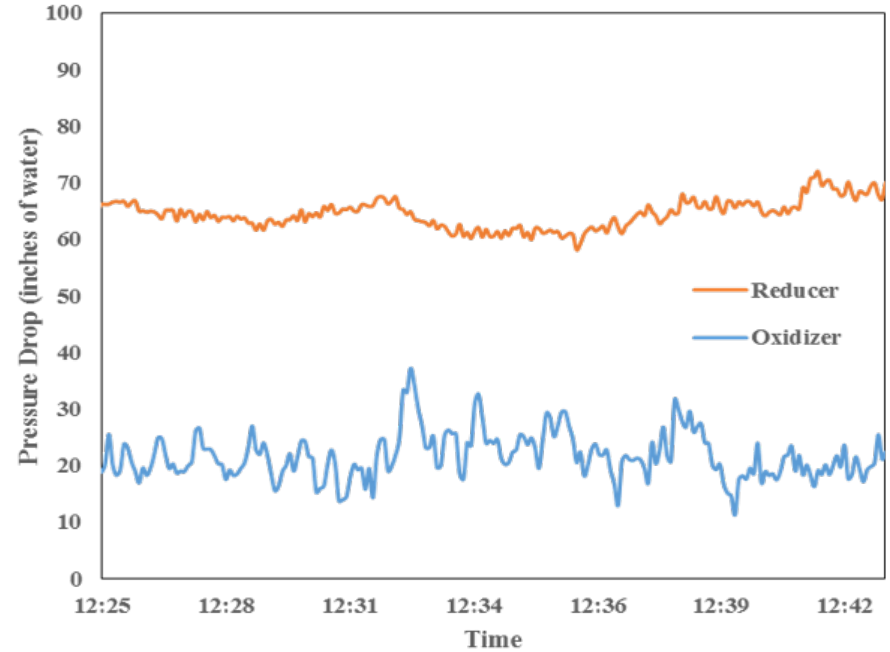


- 9 P&ID, mechanical and control specification documents
- Lab support studies
- Equipment and vessel fabrication drawings
- HAZOP Review

Construction

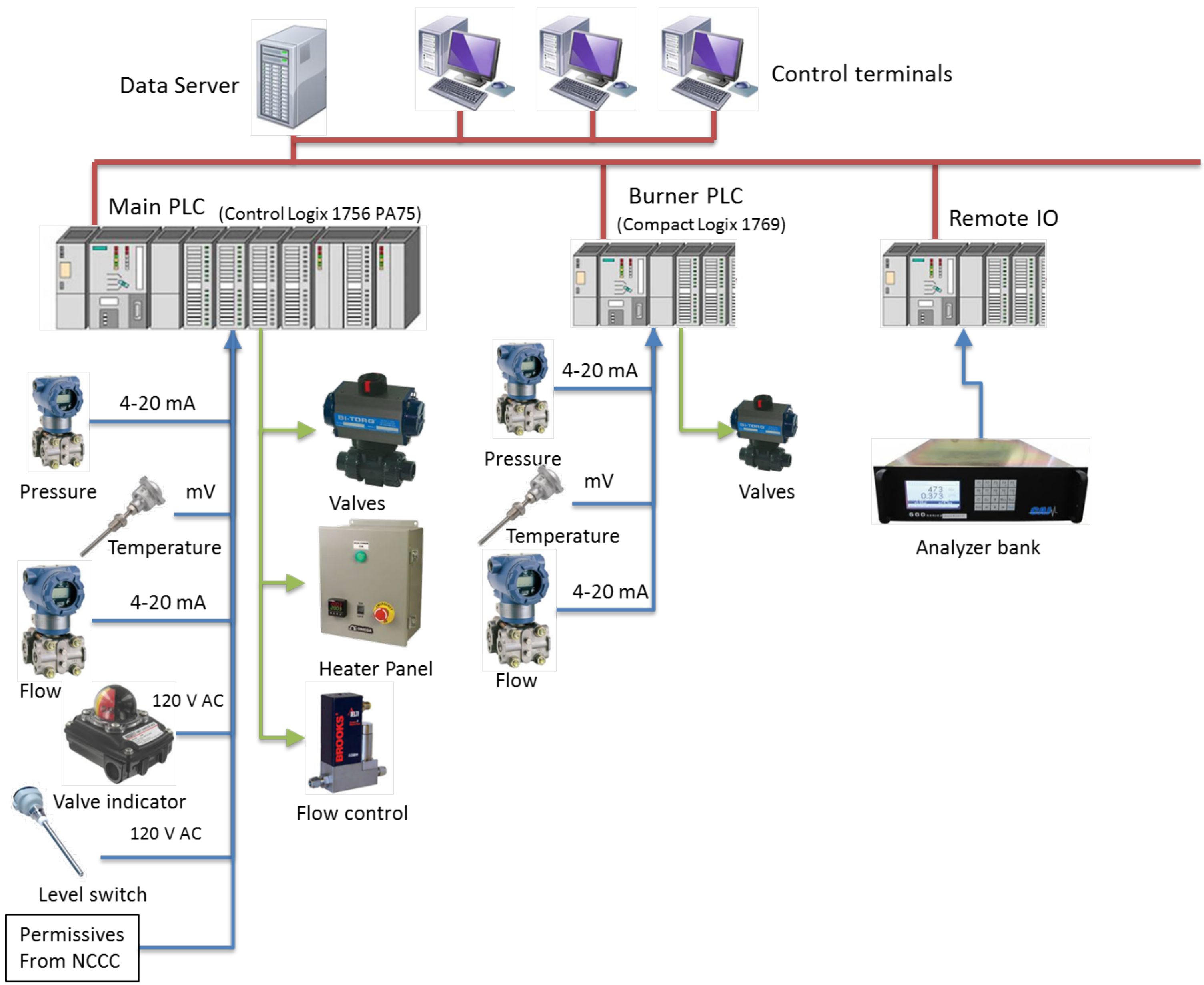
April Operations: Syngas Injection



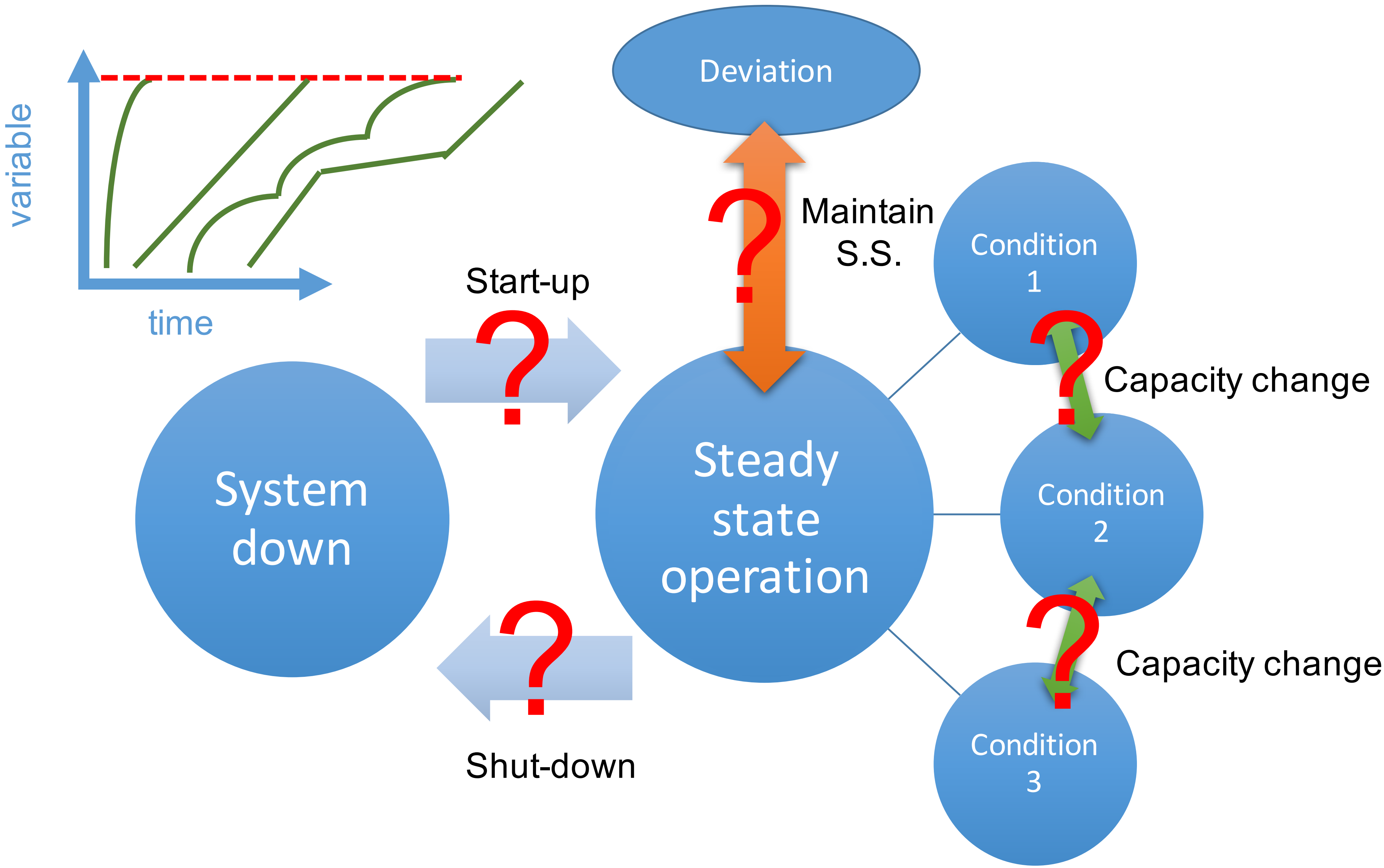


- Syngas operation initiated
  - 350 lb/hr syngas processed
- Achieved >98% syngas conversion
- Pressure balance and gas sealing maintained
- Elevated combustor temperatures confirm redox reactions
- Achieved first large-scale demonstration of high pressure, high temperature chemical looping process

SCL Controls and Integration with DCS



Transition between stages



Start-up: What to watch?

Pressurization

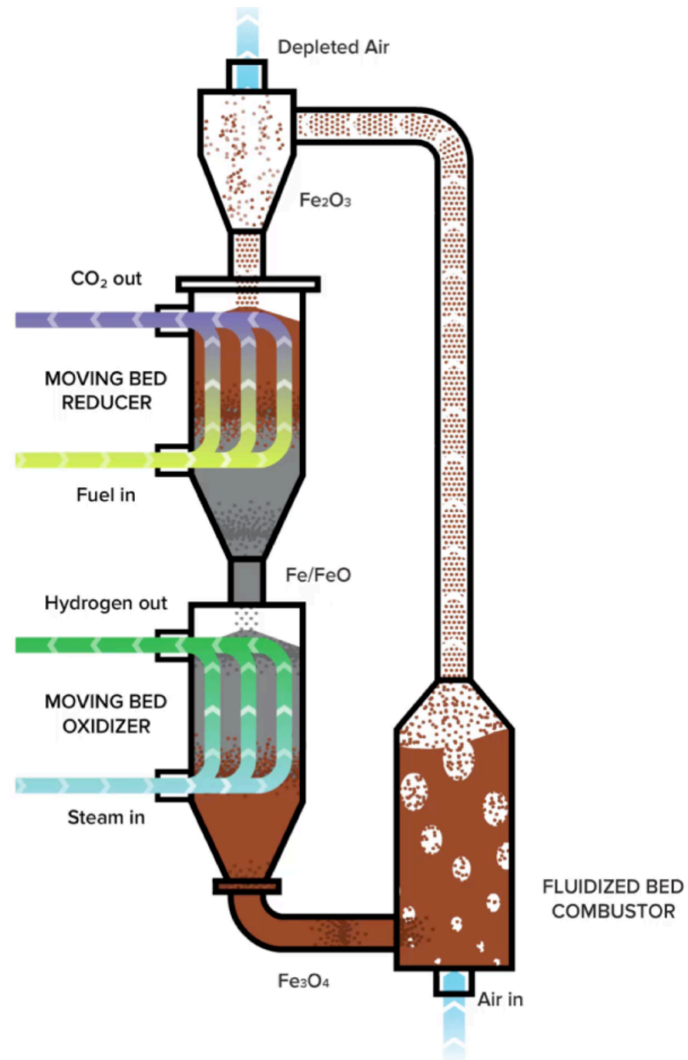
- Open combustor gas inlet/outlet to gradually pressurize, avoid local high pressure difference
- Achieve fluidization velocity in the combustor

Initiate solid flow into the combustor

- Turn on aeration gas
- Observe pressure drop across the bed, watch for value increase and fluctuation
- Further open combustor gas inlet/outlet to achieve entrainment velocity while maintaining system pressure steady

Confirm solid circulation established

- Watch for pressure drop spikes across riser
- Maintain fluctuation & positive value of pressure drop across the non-mechanical valve

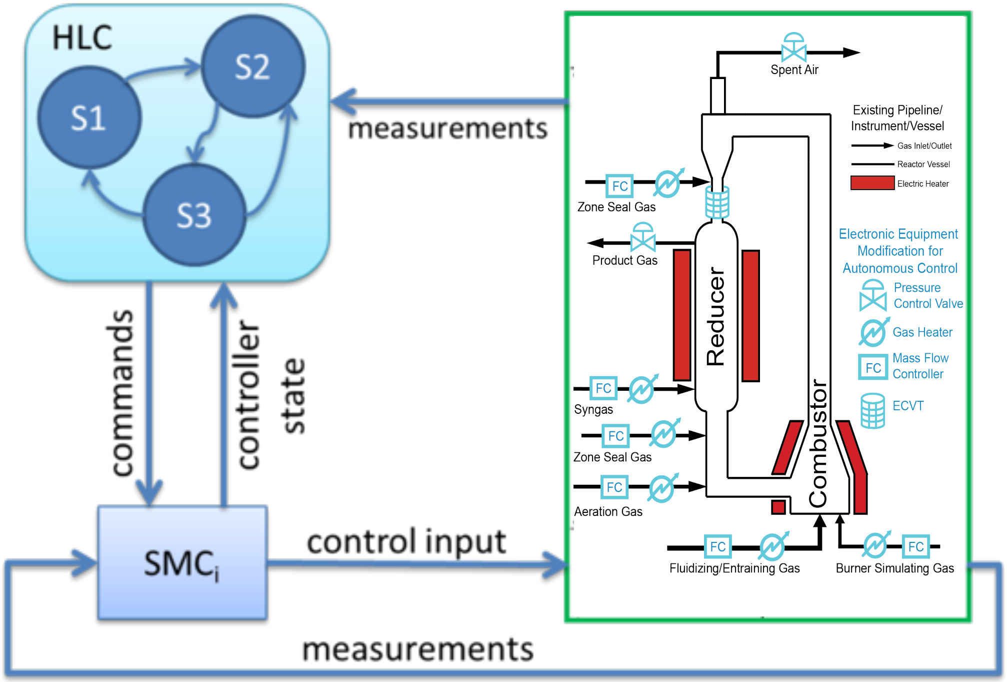


Motivation

- Currently an open-loop system
- Highly sequential operation
- Experience- and knowledge-intensive
- Require operators' constant attention to watch for deviations
- Traditional controllers are not very effective
  - Tuned to specific operating condition
  - Not appropriate for multiple-in-multiple-out (MIMO) system
  - Lack robustness

Summary of DE-FE0026334

Autonomous Process Control Concept



Sub-Pilot Unit

Pilot Unit

- Objective: develop an advanced process automation control architecture and imaging and optimization sensor information for the OSU chemical looping process
  - Develop HLC-SMC control scheme for process automation (**OSU ECE**)
  - Establish sensor algorithm for high temperature ECVT (**Tech4Imaging/OSU CBE**)
  - Integrate process performance parameters with FocalPoint Optimization System (**B&W/OSU CBE**)
  - Prepare and test process control and optimization concepts in 25 kW_{th} sub-pilot test unit (**OSU CBE**)

- OSU chemical looping technology: advanced solid and gaseous fuel conversion process for H_2 and electricity co-generation with in-situ CO_2 capture
- Phase I: test control concept in an integrated sub-pilot test unit at high temperature, reactive conditions
- Phase II: demonstrate control concept at commercially applicable pilot scale test unit at high temperature, high pressure, reactive conditions

Project Team

TECH 4 IMAGING

B&W power generation group

AEP

Phase I Project Objectives

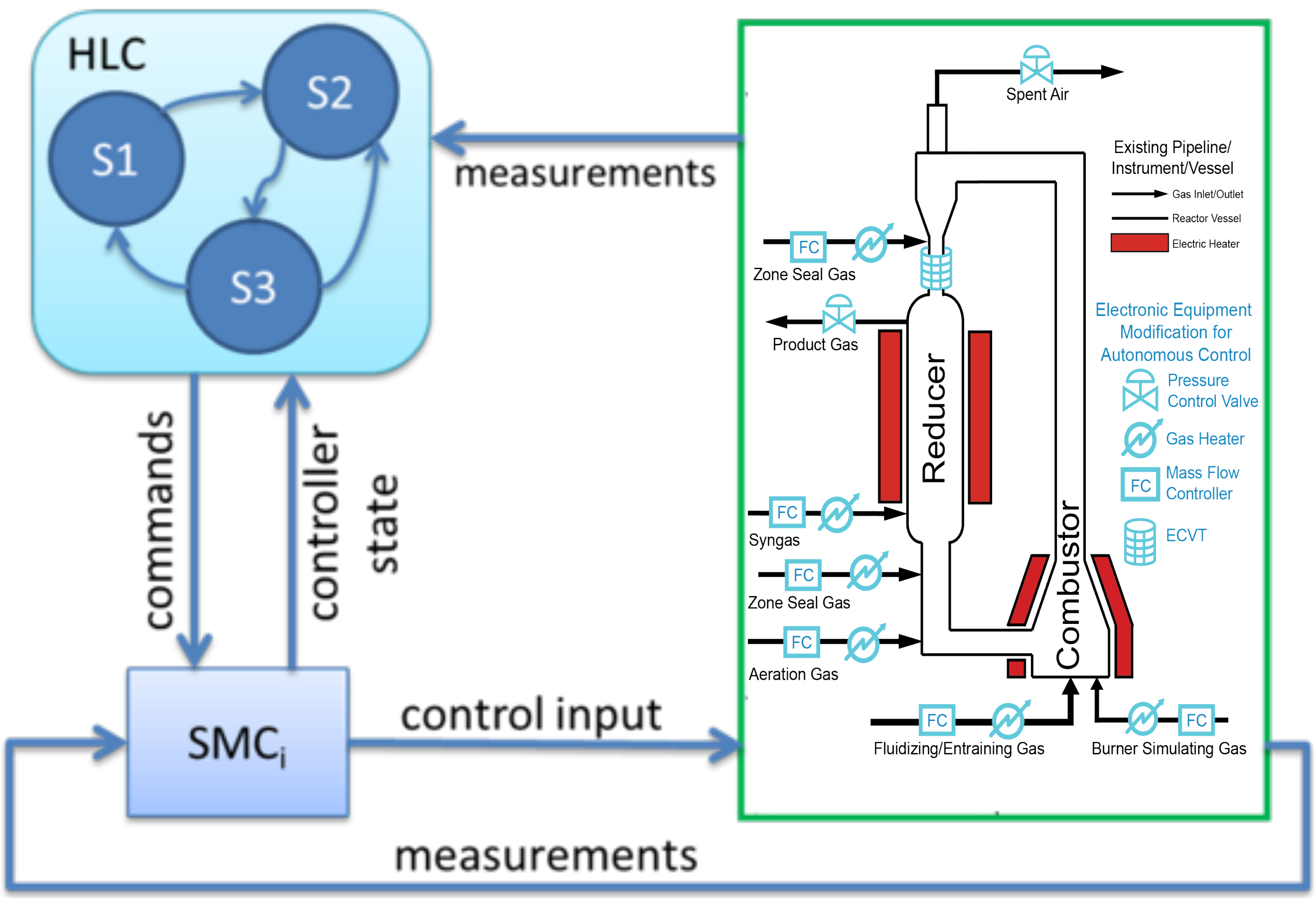
- Develop advanced controller, HLC-SMC, for autonomous control of chemical looping system
  - Also applicable to conventional CFB systems
- Develop high-temperature ECVT sensor and software for real-time solid flow rate measurement
- Apply FocalPoint for system performance optimization
  - Software developed by Babcock and Wilcox
  - Focus on optimizing (a) fuel/solid ratio and (b) sealing gas usage
- Demonstrate continuous operation on existing SCL sub-pilot and pilot units

Technical Approach – Tasks and Schedule

	Task	Start Date	End Date	Budget Period 1												Budget Period 2					
				10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
1.0	**Project Management and Planning**	**10/1/15**	**3/31/17**																		
2.0	**Control Scheme Development for Process Automation**	**10/1/15**	**9/30/16**																		
2.1	Dynamic Process Model Development	10/1/15	3/31/16																		
2.2	HLC-SMC Control Algorithm Design and Realization	1/1/16	9/30/16																		
	Milestone 1 - Complete HLC-SMC Algorithm Development		*9/30/16*												◆						
3.0	**Visualization Software Development for High Temperature ECVT**	**10/1/15**	**12/31/16**																		
3.1	Software Development	10/1/15	9/30/16																		
3.2	Incorporate ECVT Sensor into Sub-Pilot Test Unit	4/1/16	12/31/16																		
	Milestone 2 - Confirm Accurate Measurement of Solid Flow Rate at High Temperatures		*12/31/16*															◆			
4.0	**Implementation of Process Optimization Software**	**10/1/15**	**9/30/16**																		
4.1	Performance Parameter Assessment and Programming	10/1/15	6/30/16																		
4.2	Software Interface Programming	7/1/16	9/30/16																		
	Milestone 3 - FocalPoint Programming Completed		*6/30/16*									◆									
5.0	**Chemical Looping Testing Unit Preparation and Testing**	**10/1/15**	**3/31/17**																		
5.1	Design, Procure, and Install Controller-Compatible Mechanical Components	10/1/15	6/30/16																		
5.2	Design, Construction, Programming of the Distributed Control System	1/1/16	9/30/16																		
5.3	Integration of HLC-SMC to the DCS	7/1/16	12/31/16																		
5.4	Comissioning and Tesing of the Sub-Pilot Test Unit	10/1/16	3/31/17																		
	Milestone 4 - Mechanical Components Selected and Procurement Initiated		*12/31/15*			◆															
	Milestone 5 - DCS Design Complete and Construction Commenced		*3/31/16*						◆												
	Milestone 6 - Demonstrate Complete Automated Chemical Looping Operation		*3/31/17*																		◆

Technical Approach – Task 2

Develop advanced hybrid controller, HLC-SMC, for autonomous control of chemical looping system



TWO SIDES OF THE CONTROL AND AUTOMATION WORK

State regulation

- Continuous states are to be controlled:
  - Temperature
  - Pressure
- Not only around setpoints
- Transitions are to be regulated
- Model uncertainties are expected
- Sliding Mode Control is chosen

Operational Automation

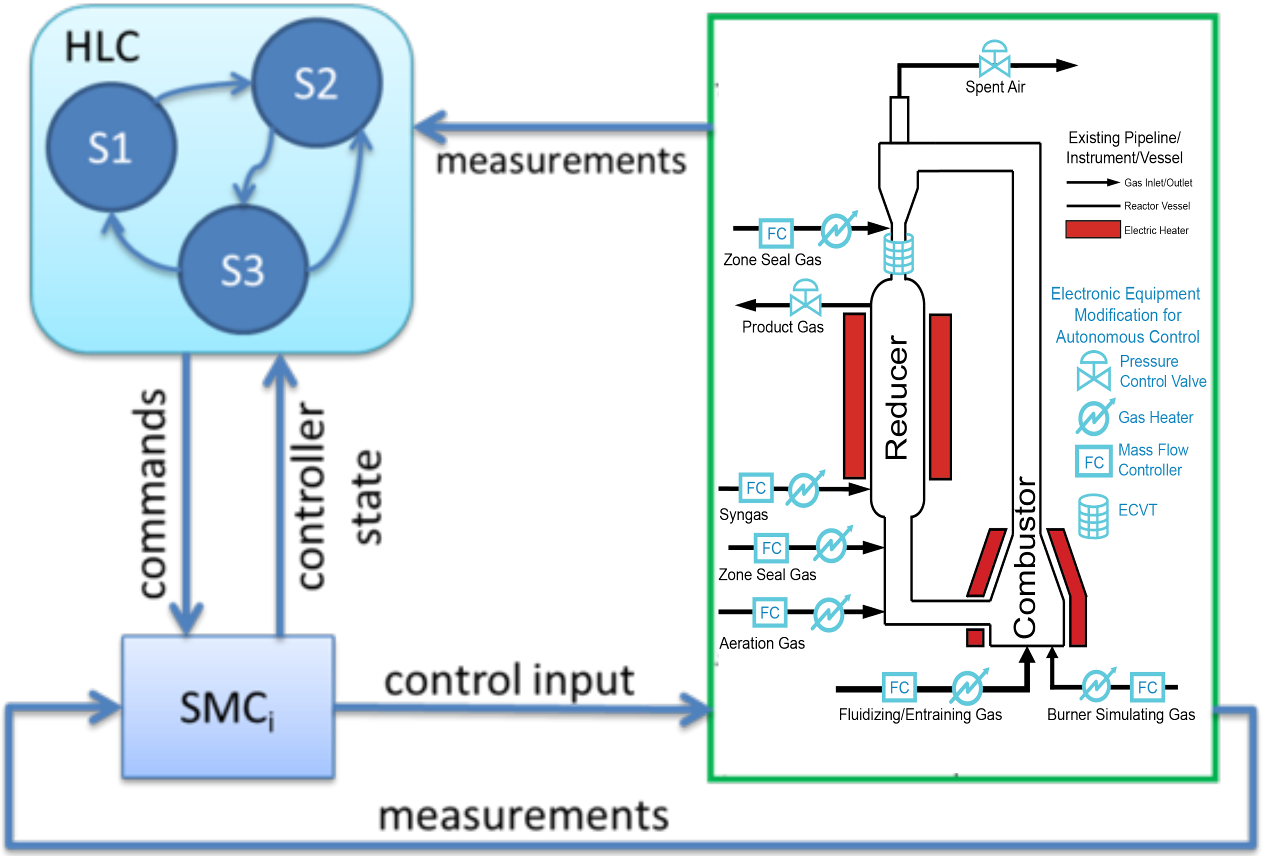
- Current plant operation is manually controlled
- Operator skill is a major factor
- Discrete events will be defined:
  - Transition from one step to the next in the operational sequence
  - React to continuous-state changes based on thresholds
- The combined continuous/discrete setup will form a Hybrid State System

MOTIVATION BEHIND CHOOSING SLIDING MODE CONTROL

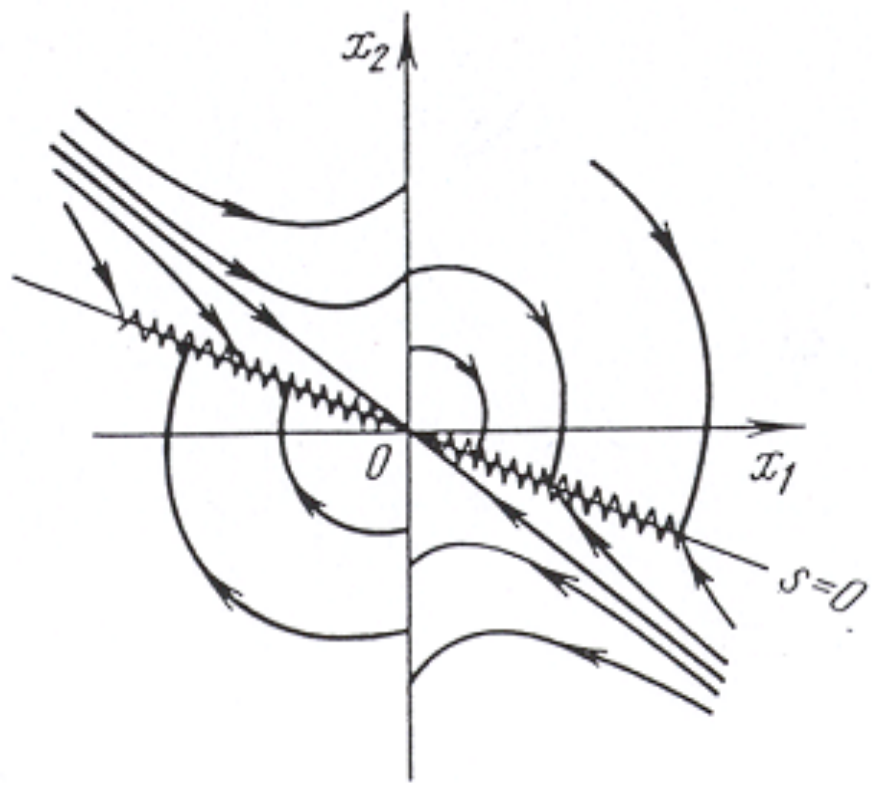
- Conventional Controllers:
  - PID
  - Smith Predictors
  - Lead-Lag Controllers
- Not robust/versatile enough
- Highly affected by modeling uncertainties
- Designed to control the system around a sequence of waypoints
  - No explicitly designed transient behavior
- Alternative:
  - Sliding Mode Control

IN A HYBRID-STATE SYSTEM

- High-level controller (HLC) observes the system and switches SMCs (controllers/surfaces) as desired setpoints are reached.

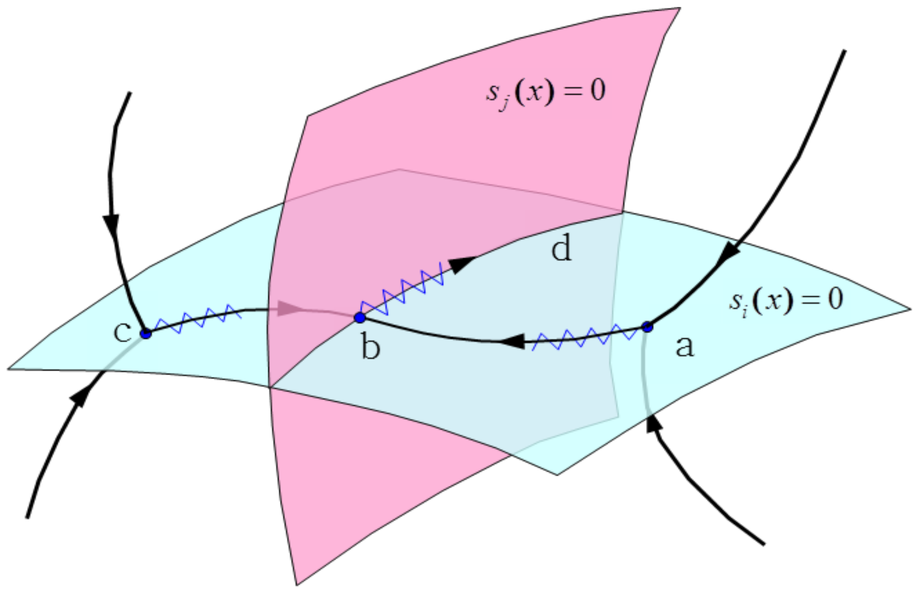


- Control where the system states will converge, and restrict the trajectory to get there
- Find/define a surface that the states can slide to its desired value
- Derived from Variable Structure Control [Utkin1977]
- Controller changes behavior as the state trajectory crosses the surface
- Two stages:
  - Reaching mode: to get to the sliding surface
  - Sliding mode: reduced order motion on the surface
  - The discontinuity of the controller is responsible for reaching



Utkin, V., "Variable structure systems with sliding modes," *Automatic Control, IEEE Transactions on* , vol.22, no.2, pp.212,222, Apr 1977

MULTI-DIMENSIONAL SMC



- Use multiple surfaces in multiple dimensions
- Along a series of setpoints
- Surfaces/controllers switch once certain points are reached
- Transient between setpoints governed by the sliding surfaces

- Two possible SMC extensions are being considered right now:
  - Second order SMC
  - Extremum-seeking SMC
- Depending on the simulation results with the models that are being built, we might consider other specific SMC implementations or go back to the traditional first order SMC if that gives adequate control performance

- The system is given $\dot{x}_2 = f(t, x_1, x_2) + g(t, x_1, x_2)u$
- The control is defined $u = u(x_1, x_2)$ with a bounded disturbance $f(x_1, x_2, t)$
- Proposed SOSMC is

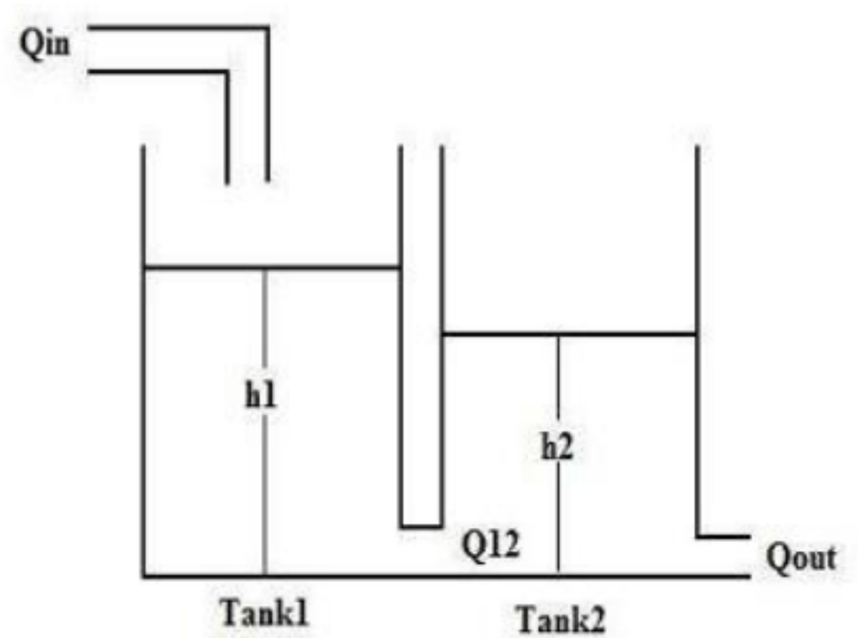
$$u = -\rho_1 \left|\sqrt{\sigma}\right| sign(\sigma) - \rho_2 \left|\sqrt{-2\lambda x_1 + \sigma}\right| sign(-2\lambda x_1 + \sigma)$$

- In SMC, the aim is to force the state or error to move on the switching surface $\sigma(t)$, so $\sigma = \lambda e(t) + \dot{e}(t)$,where

$e = x_1 - x_{desired}, \lambda > 0$

Parvat, B. J., & Ratnaparkhi, S. D. (2015) A Second Order Sliding Mode Controller Applications in Industrial Process. in International Journal of Engineering Trends and Technology (IJETT). Volume 19 Number 4. Jan 2015.

Level Control of Two-Tank System

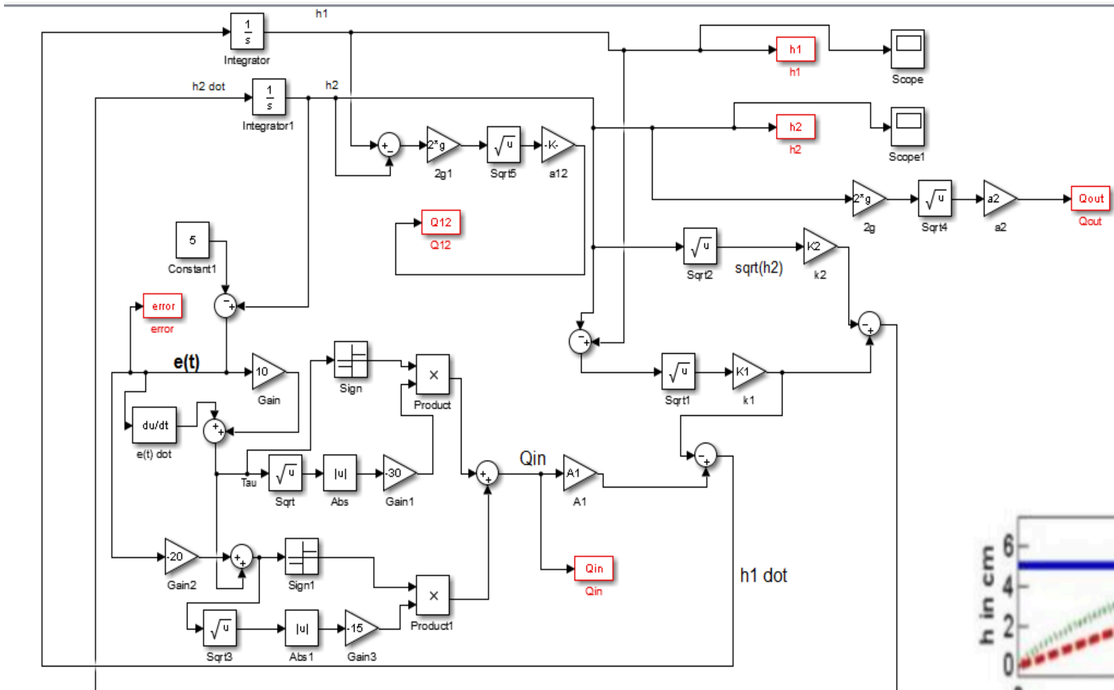


$$\frac{dh_1}{dt} = \frac{Q_{in}}{A} - k_1\sqrt{h_1 - h_2}$$

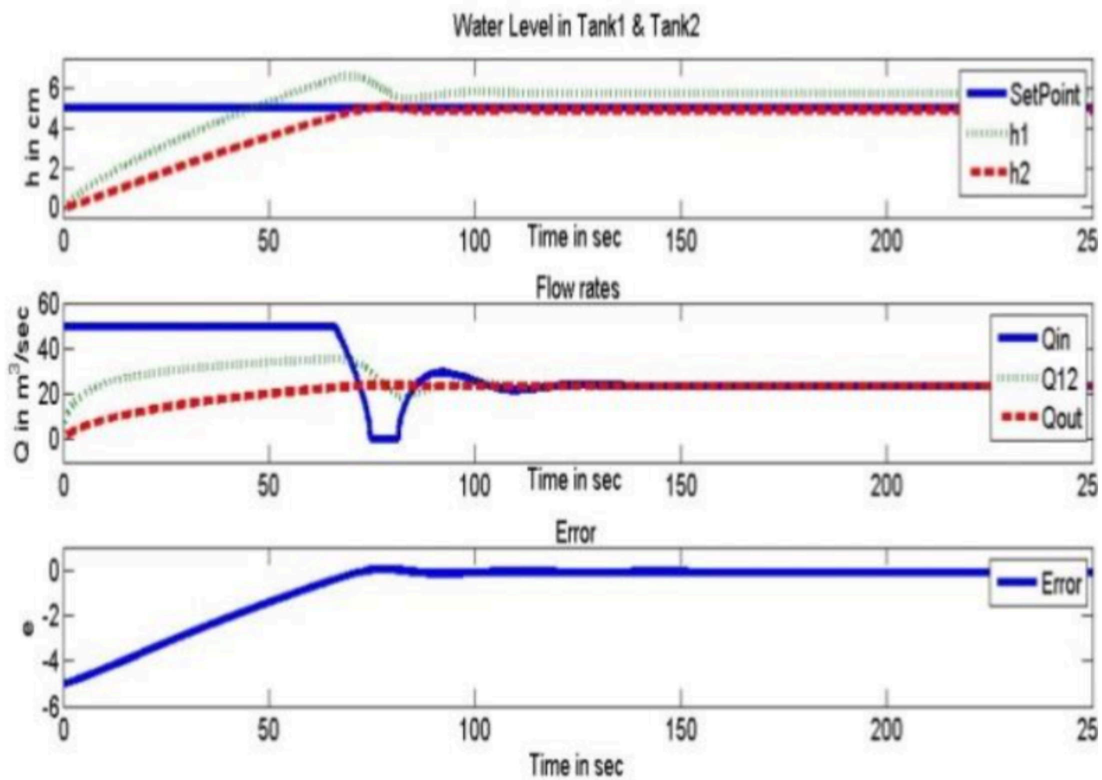
$$\frac{dh_2}{dt} = k_1\sqrt{h_1 - h_2} - k_2\sqrt{h_2}$$

$$u = -30\left|\sqrt{\sigma}\right| sign(\sigma) - 15\left|-2\lambda e + \sigma\right| sign(-2\lambda e + \sigma) \qquad \sigma = \lambda e(t) + \dot{e}(t) \qquad \lambda = 10$$

Proposed SOSMC is applied to, Qin=u, e(t)=h2(t)-h2_desired=h2-5



Simulink model



Simulation results

- Extremum Seeking Control (ESC) deals with the problem of tracking an optimum operating point for a system with unknown performance function.
- Extremum Seeking control via sliding mode (ESC-SM) approach introduced in the context of static optimization by Korovin and Utkin and generalized, analyzed and applied by Ozguner and his co-authors.
- Applications: ABS (Automotive), PID tuning, Photovoltaic systems,…etc.
- In chemical systems, it was introduced, in the context of **Bioreactor** optimization in [Wang99]. Further development was introduced later with the application to general **batch reactor** [Titica2003] ,**continues stirred tank reactors** [Guay2004], **and tubular reactors** [Cougnon2006] and with consideration of **multivalued cost function** [Bastin2009].

ESC-SM SIMULATION EXAMPLES

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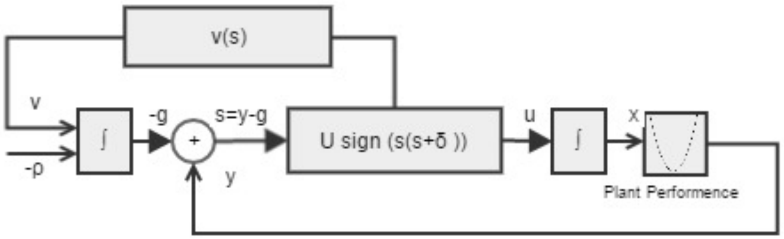
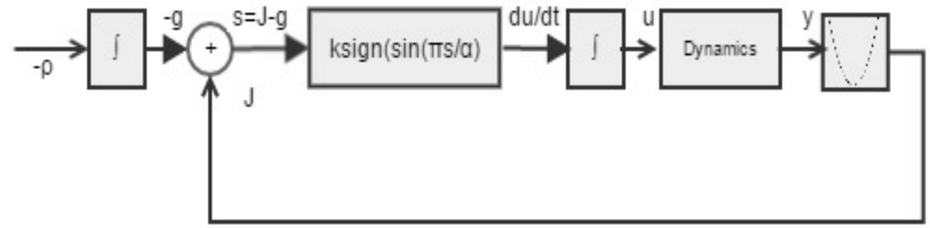


Figure.1 Block Diagram [1]



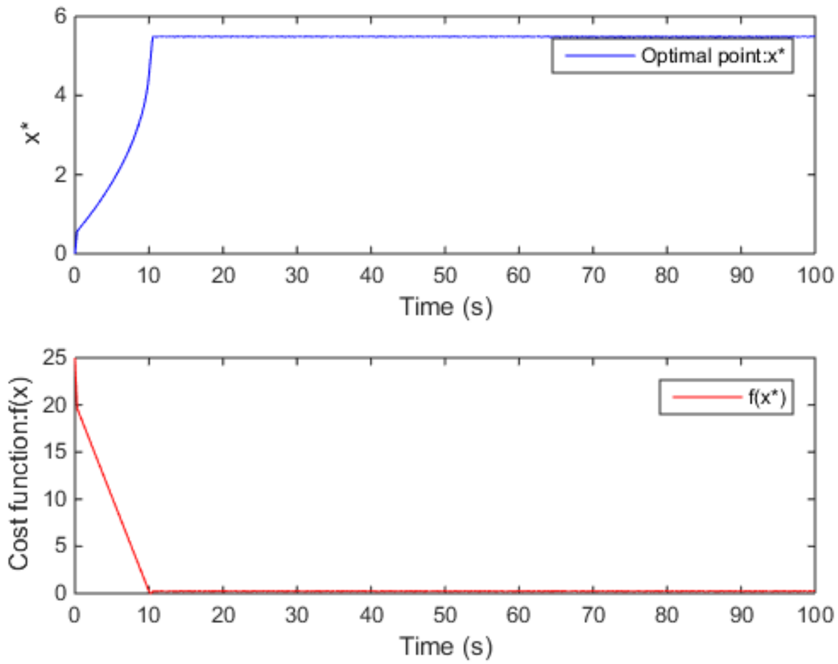


Figure.2 Simulation Results

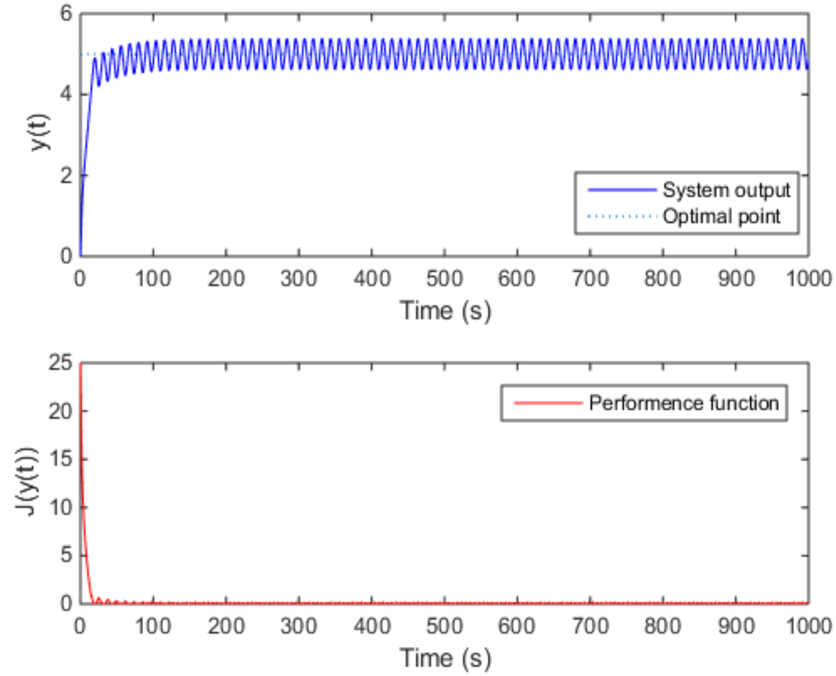


Figure.2 Simulation Results

Control and Intelligent Transportation
Research Lab

SAMPLE REFERENCES

- Utkin, V., "Variable structure systems with sliding modes," *Automatic Control, IEEE Transactions on* , vol.22, no.2, pp.212,222, Apr 1977.
- Sira-Ramirez, Hebertt, and Orestes Llanes-Santiago. "Dynamical discontinuous feedback strategies in the regulation of nonlinear chemical processes." *Control Systems Technology, IEEE Transactions on* 2.1 (1994): 11-21.
- Camacho, Oscar, and Carlos A. Smith. "Sliding mode control: an approach to regulate nonlinear chemical processes." *ISA transactions* 39.2 (2000): 205-218.
- Wang, Gow-Bin, Sheng-Shiou Peng, and Hsiao-Ping Huang. "A sliding observer for nonlinear process control." *Chemical Engineering Science* 52.5 (1997): 787-805.
- Shahraz, Azar, and R. Bozorgmehry Boozarjomehry. "A fuzzy sliding mode control approach for nonlinear chemical processes." *Control Engineering Practice* 17.5 (2009): 541-550.
- Young, K. David, Vadim I. Utkin, and Umit Ozguner. "A control engineer's guide to sliding mode control." *IEEE transactions on control systems technology* 7.3 (1999): 328-342.
- Su, Wu-Chung, Sergey V. Drakunov, and Umit Ozguner. "An O (T 2) boundary layer in sliding mode for sampled-data systems." *Automatic Control, IEEE Transactions on* 45.3 (2000): 482-485.
- David Young, K., and Ümit Özgüner. "Frequency shaping compensator design for sliding mode." *International Journal of Control* 57.5 (1993): 1005-1019.

REFERENCES - 2

THE OHIO STATE UNIVERSITY
CENTER FOR AUTOMOTIVE RESEARCH

- Korovin, S.K., Utkin, V.I.: Using sliding modes in static optimization and nonlinear programming. Automatica **10, 525–532 (1974).**
- Drakunov, S.V., Özgüner, Ü.: Optimization of nonlinear system output via sliding mode approach. In: Proceedings of the IEEE International Workshop on Variable Structure and Lyapunov Control of Uncertain Dynamical Systems, Sheffield, UK, pp. 61–62 (1992)
- Drakunov, S.V., Özgüner, Ü, Dix, P., Ashrafi, B.: ABS control using optimum search via sliding modes. IEEE Transactions on Control Systems Technology (3), 79–85 (1995)
- Yu, H., Özgüner, Ü.: Extremum-seeking control via sliding mode with periodic search signals. In: Proceedings of the Conference on Decision and Control, vol. 1, pp. 323–328 (2002)
- Y. Pan, U. Ozguner, and T. Acarman, Stability and performance ¨ improvement of extremum seeking control with sliding mode, Int.J.Control, vol. 76, no. 9-10, 2003, pp. 968-985.
- H.-H. Wang, M. Krstic, and G. Bastin, “Optimizing bioreactors by extremum seeking," International Journal of Adaptive Control and Signal Processing, vol. 13, pp. 651-669, 1999.
- Titica, M., Dochain, D., Guay, M.: Adaptive extremum-seeking control of fed-batch bioreactors. Eur. J. Control 9(6), 614–627 (2003)
- Guay, M., Dochain, D., Perrier, M.: Adaptive extremum seeking control of continuous stirred tank bioreactors with unknown growth kinetics. Automatica 40(5), 881–888 (2004)
- Cougnon, P., Dochain, D., Guay, M., Perrier, M.: Real-time optimization of a tubular reactor with distributed feed. AIChE J. 52(6), 2120–2128 (2006)
- Bastin, G., Nešic, D., Tan, Y., Mareels, I.: On extremum seeking in bioprocesses with multivalued cost functions. Biotechnol. Prog. 25(3), 683–689 (2009)

SPECIFIC TASKS: MODEL BUILDING

- In order to build a simulation model of the plant to apply SMC
  - Using the basic dynamics of each main component in the sub-pilot and pilot units
  - System equations are being modeled in Matlab/Simulink
  - Data collected from the real units are used where available
- The hybrid controllers that are being designed and tested using these models/simulations will form the basis of the sub-pilot and pilot controllers

Technical Approach – Model Equations

- Ergun Equation

$$DP_{360} = \frac{150\mu_{N_2}L_{361}}{d_p^2}\frac{(1-\epsilon)^2}{\epsilon^3}u_{361} + \frac{1.75\rho_{360}L_{361}}{d_p}\frac{(1-\epsilon)}{\epsilon^3}u_{361}|u_{361}|$$

- Valve Equation

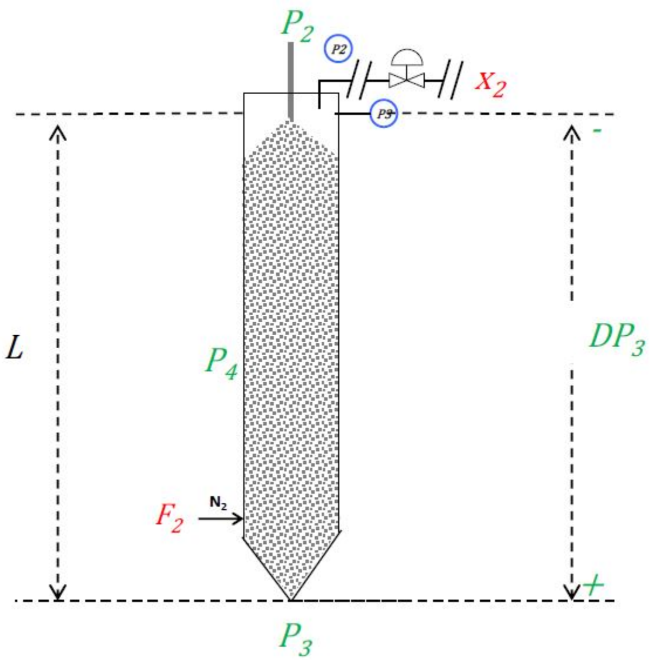
$$\begin{cases} F_{590} = 3.455\times10^{-5}\left(mol\cdot s^{-1}\cdot Tg_{490}^{\frac{1}{2}}\cdot Pa^{-1}\right)\times C_v\cdot x_{490}\cdot\sqrt{\frac{P_{490}^2-P_0^2}{Tg_{491}S_g}}\ when\ \frac{P_{490}}{P_0}<1.89 \\ F_{590} = 2.934\times10^{-5}\left(mol\cdot s^{-1}\cdot Tg_{490}^{\frac{1}{2}}\cdot Pa^{-1}\right)\times C_v\cdot x_{490}\cdot P_{490}\sqrt{\frac{1}{Tg_{491}S_g}}\quad when\ \frac{P_{490}}{P_0}>1.89 \end{cases}$$

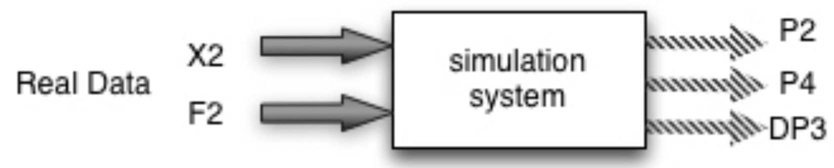
- Gas Mass Balance

$$\frac{dP_O}{dt} = \frac{R\cdot Tg_{490}\cdot(F_{420}+F_{371}+F_{362}-F_{490})}{V} + \frac{P_O}{Tg_{490}}\cdot\frac{dTg_{490}}{dt}$$

- Fludized Bed/Riser Correlation

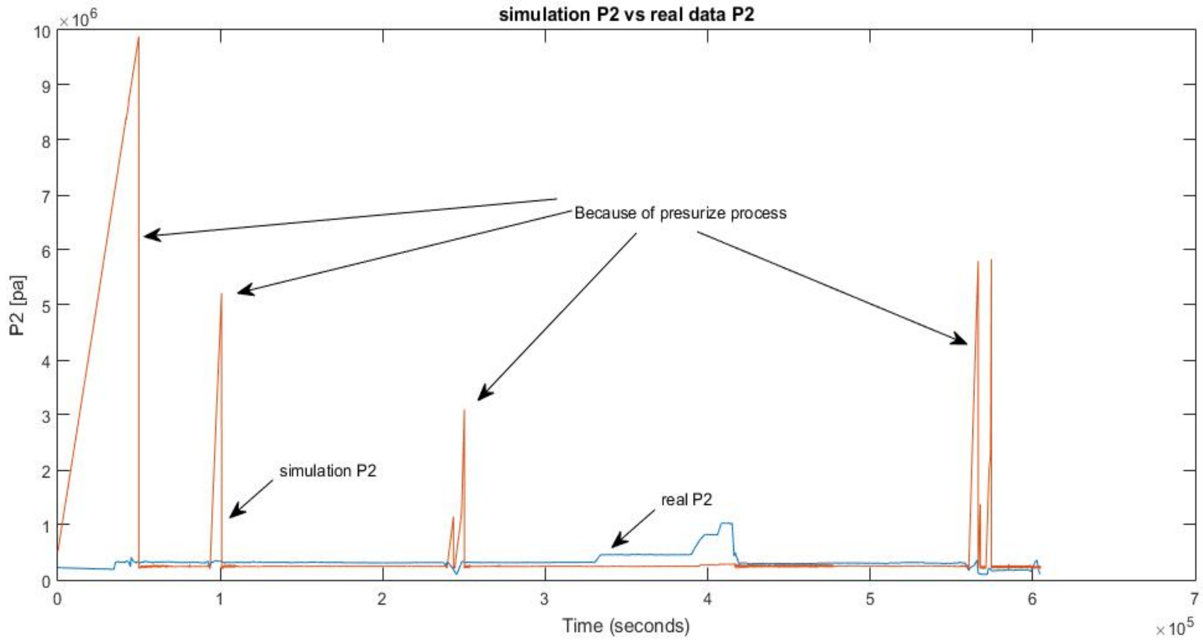
One tank system modeling & validation



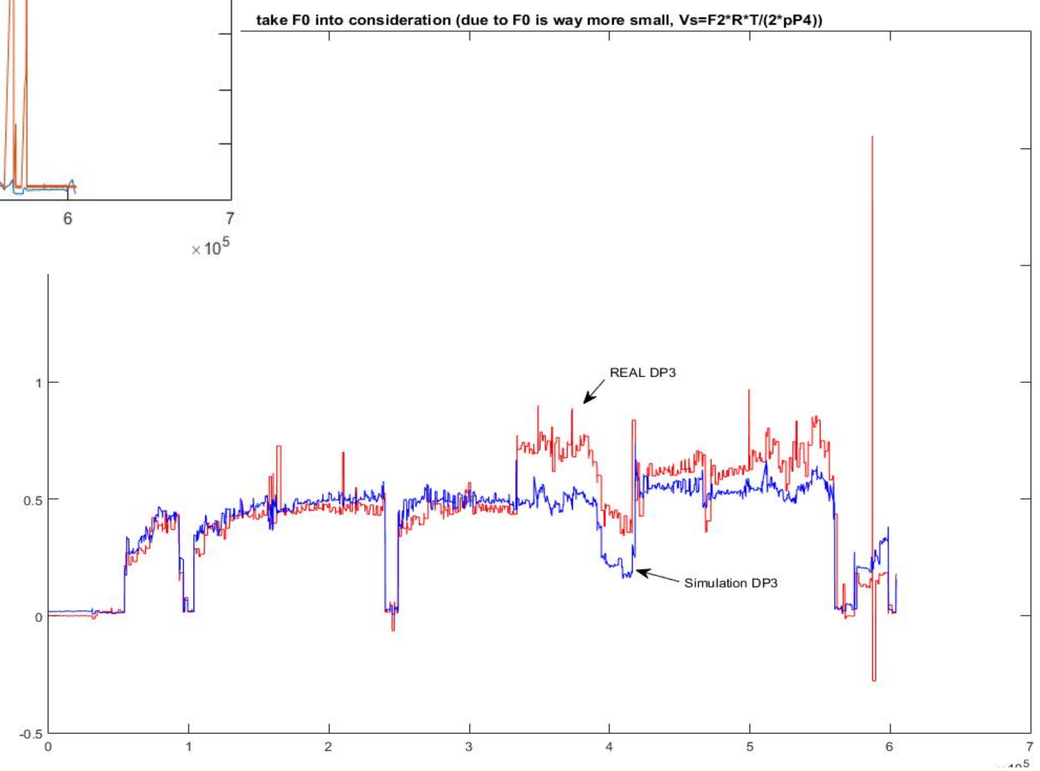


- **Test input (experimental data):**
- X2(valve 2), F2(air flow 2)
- **Test output(simulation outcome):**
- P2, P4, DP3

MODEL BUILDING - 3



Simulation P2 vs real P2



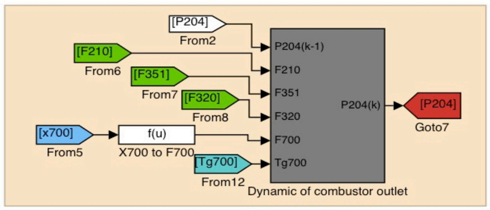
Simulation DP3 vs real DP3

SIMULATION METHOD 1 - SIMULINK
THREE TANK SYSTEM MODEL

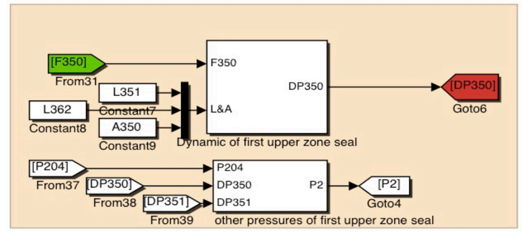
THE OHIO STATE UNIVERSITY
CENTER FOR AUTOMOTIVE RESEARCH

Green : airflow input
Light blue: valve open percentage
Cyan: temperature
Red: main states

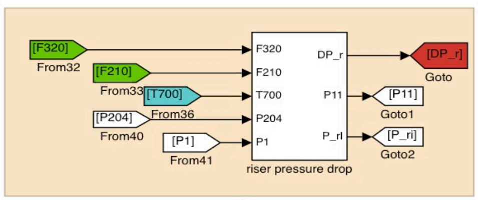

input generator



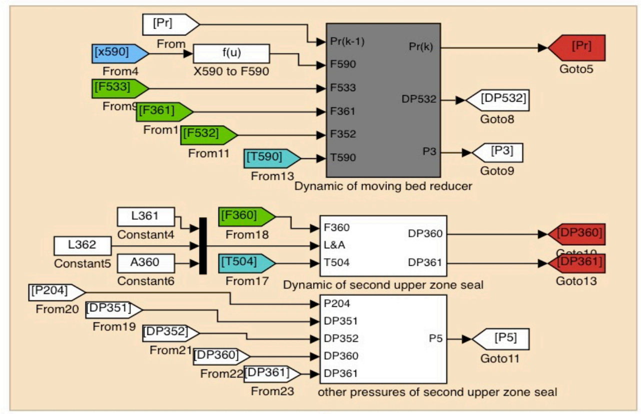
combustor outlet



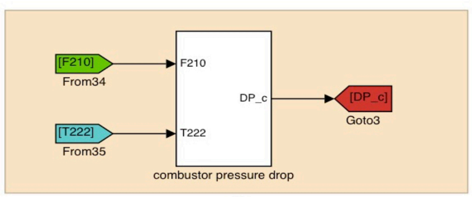
first tank



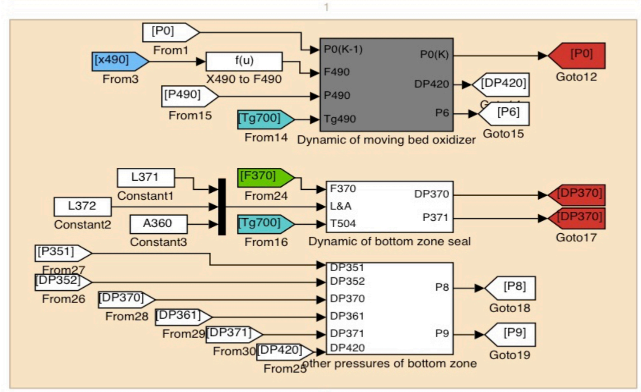
riser



second tank

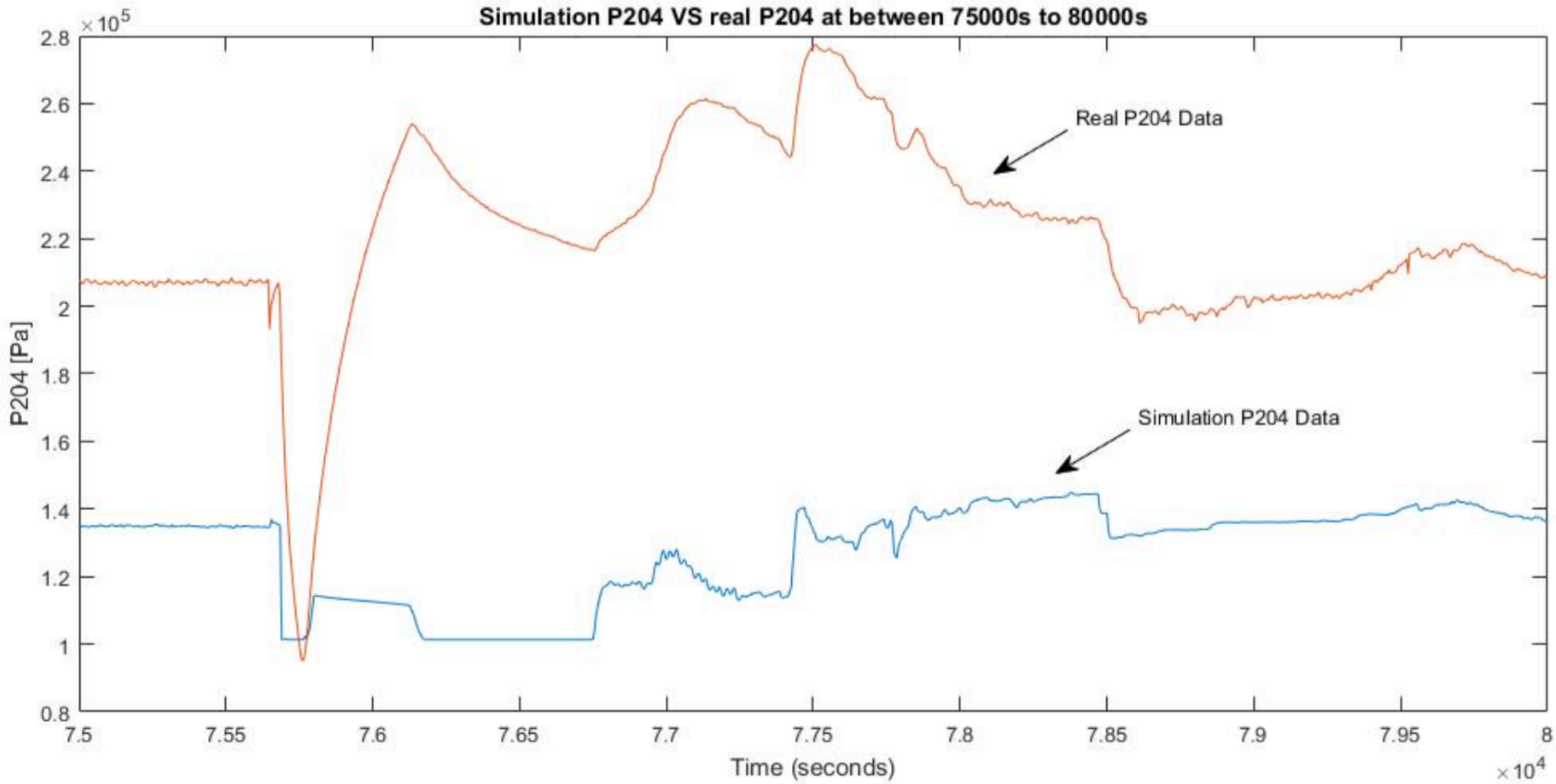


combustor

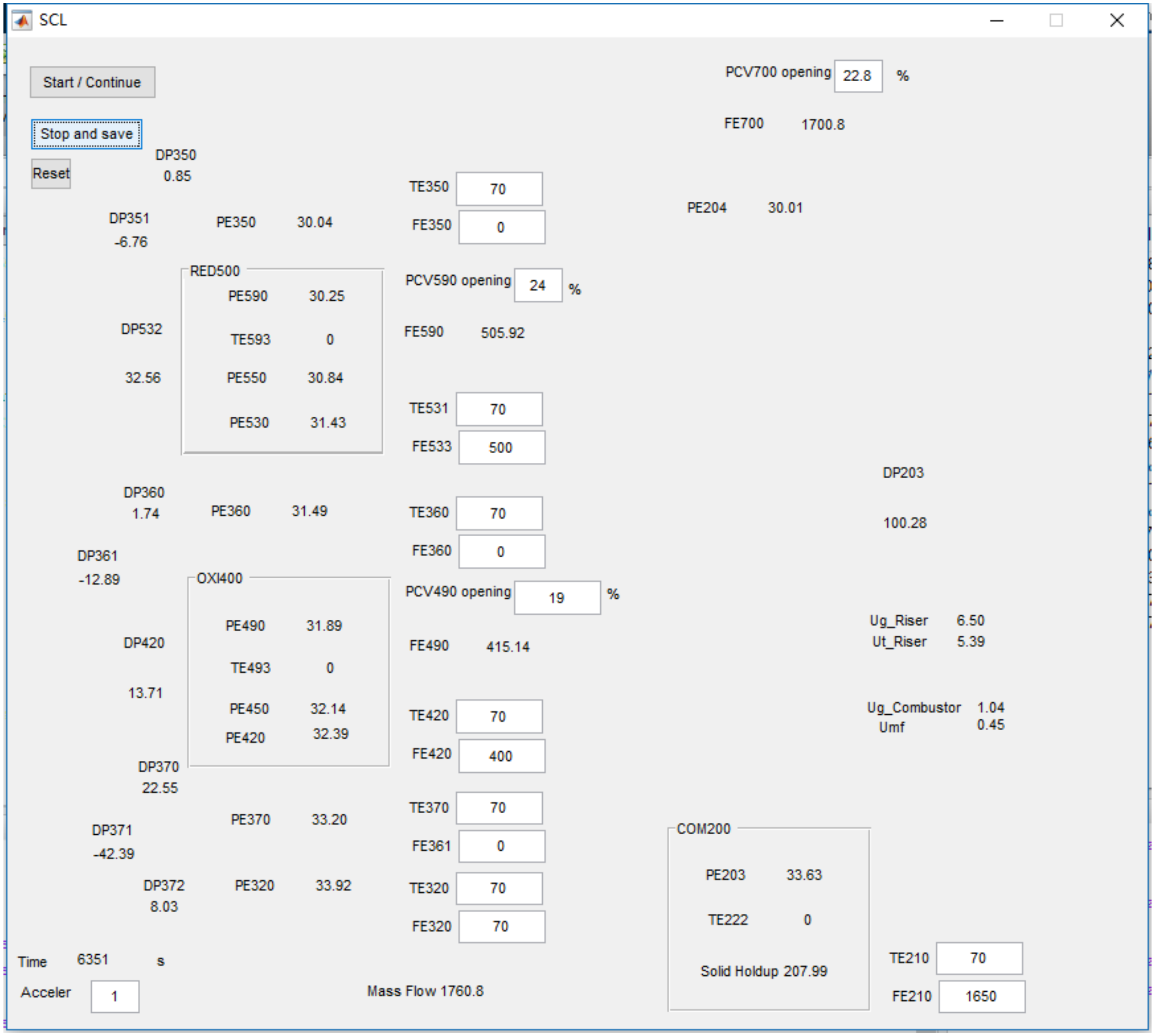


third tank

SIMULATION METHOD 1 – SIMULINK SAMPLE RESULT



Simulation Method 2 - Matlab



Technical Approach – Tasks and Schedule

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3.0	**Visualization Software Development for High Temperature ECVT**	**10/1/15**	**12/31/16**																		
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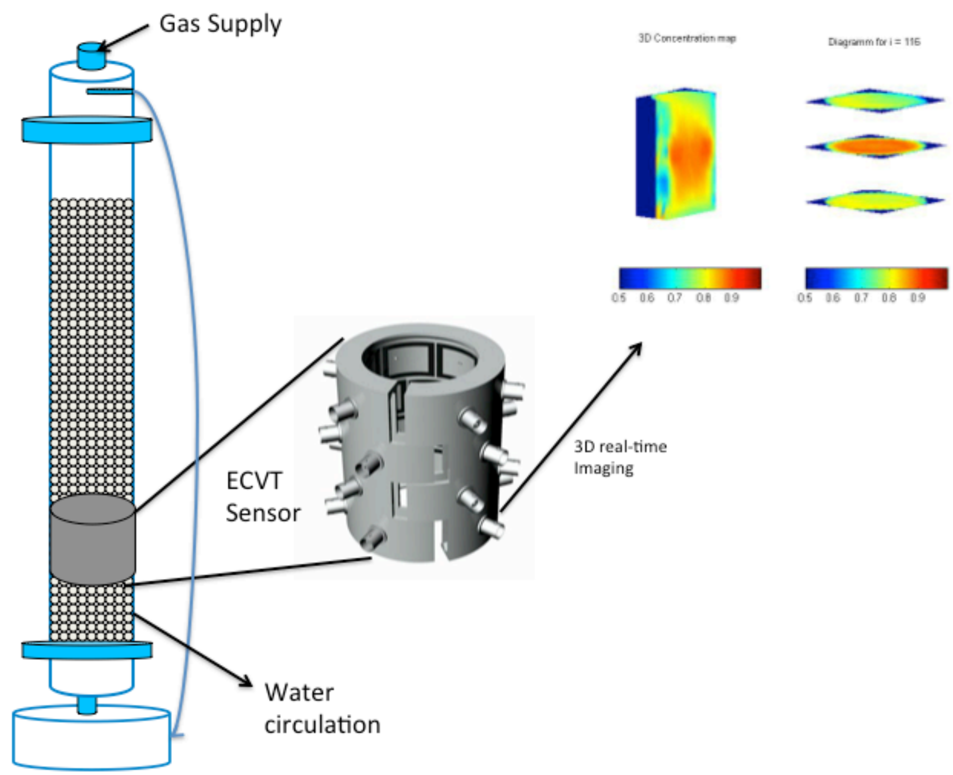
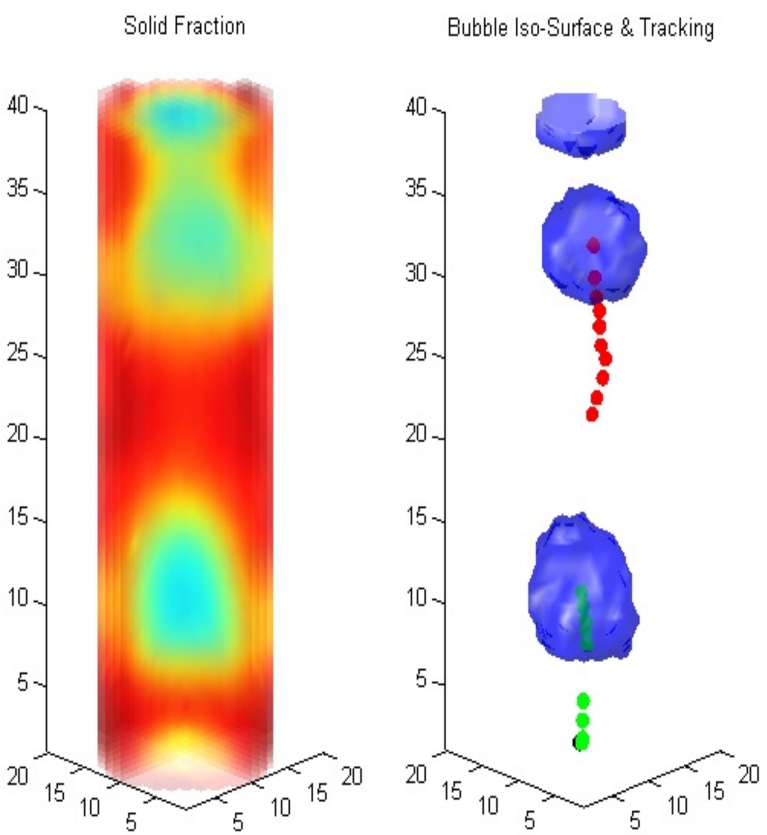
	Milestone 6 - Demonstrate Complete Automated Chemical Looping Operation		*3/31/17*																		◆

Technical Approach – Task 3

Develop high-temperature Electrical Capacitance Volume Tomography (ECVT) sensor and software for real-time solid flow rate measurement



ECVT System



- non-invasive sensors are used to measure changes in electrical capacitance in response to flow dynamics
- measured changes are mapped into phase concentrations using image reconstruction techniques

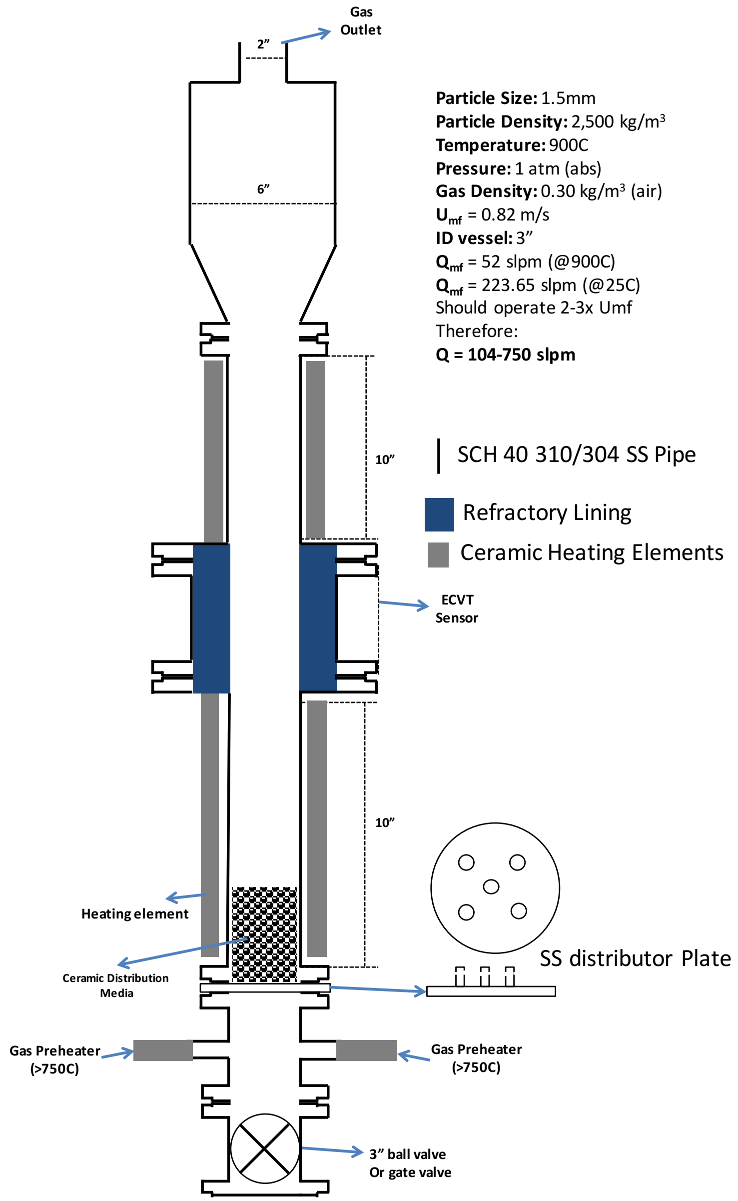
3D images of Multi-Phase Flow

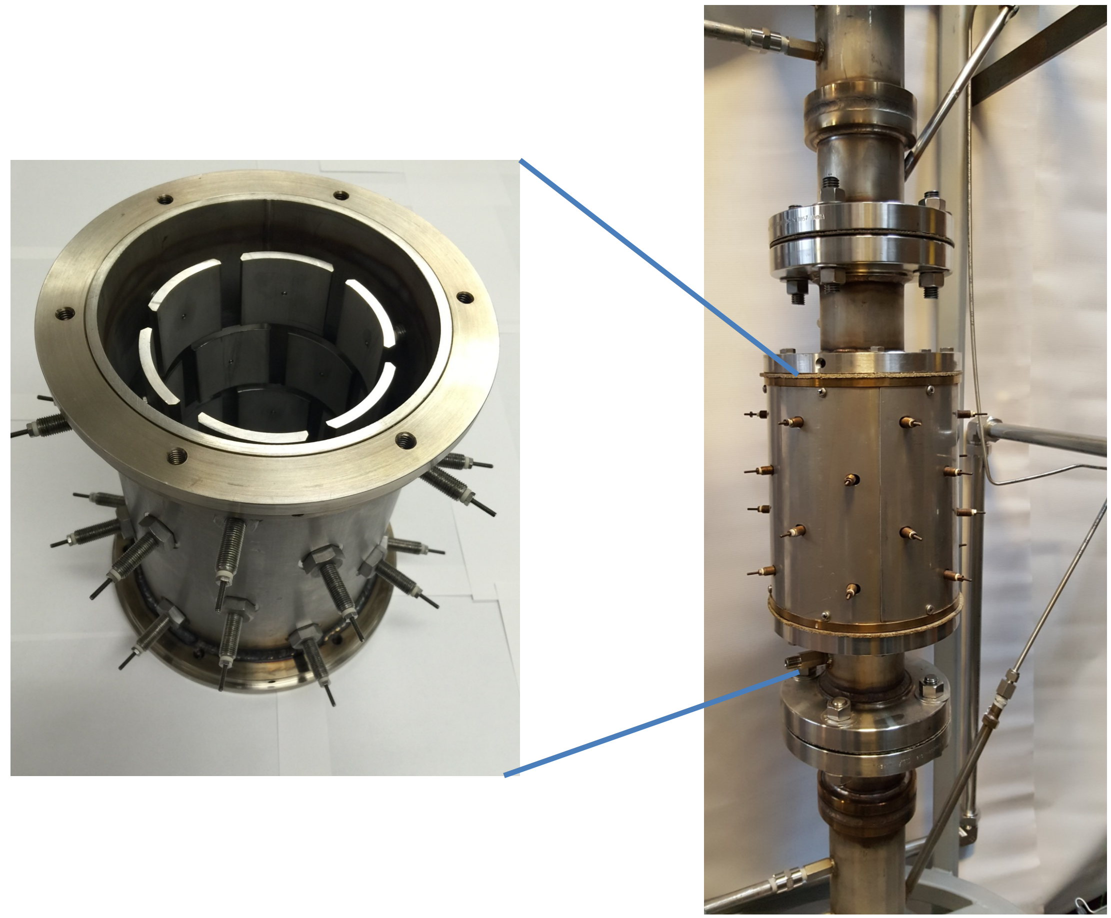
Data Acquisition and ECVT Sensor

TECH 4 IMAGING

ECVT Hot Unit Design and Assembly

Particle Size: 1.5mm
Particle Density: 2,500 kg/m^3
Temperature: 900C
Pressure: 1 atm (abs)
Gas Density: 0.30 kg/m^3 (air)
U_{mf} = 0.82 m/s
ID vessel: 3"
Q_{mf} = 52 slpm (@900C)
Q_{mf} = 223.65 slpm (@25C)
Should operate 2-3x Umf
Therefore:
Q = 104-750 slpm





TECH 4 IMAGING

ECVT Hot Unit Design and Assembly

- Temperature controller integrated
- Fluidization gas with flow control
- Manual valve for solid discharge to simulate moving bed mode

TECH 4 IMAGING

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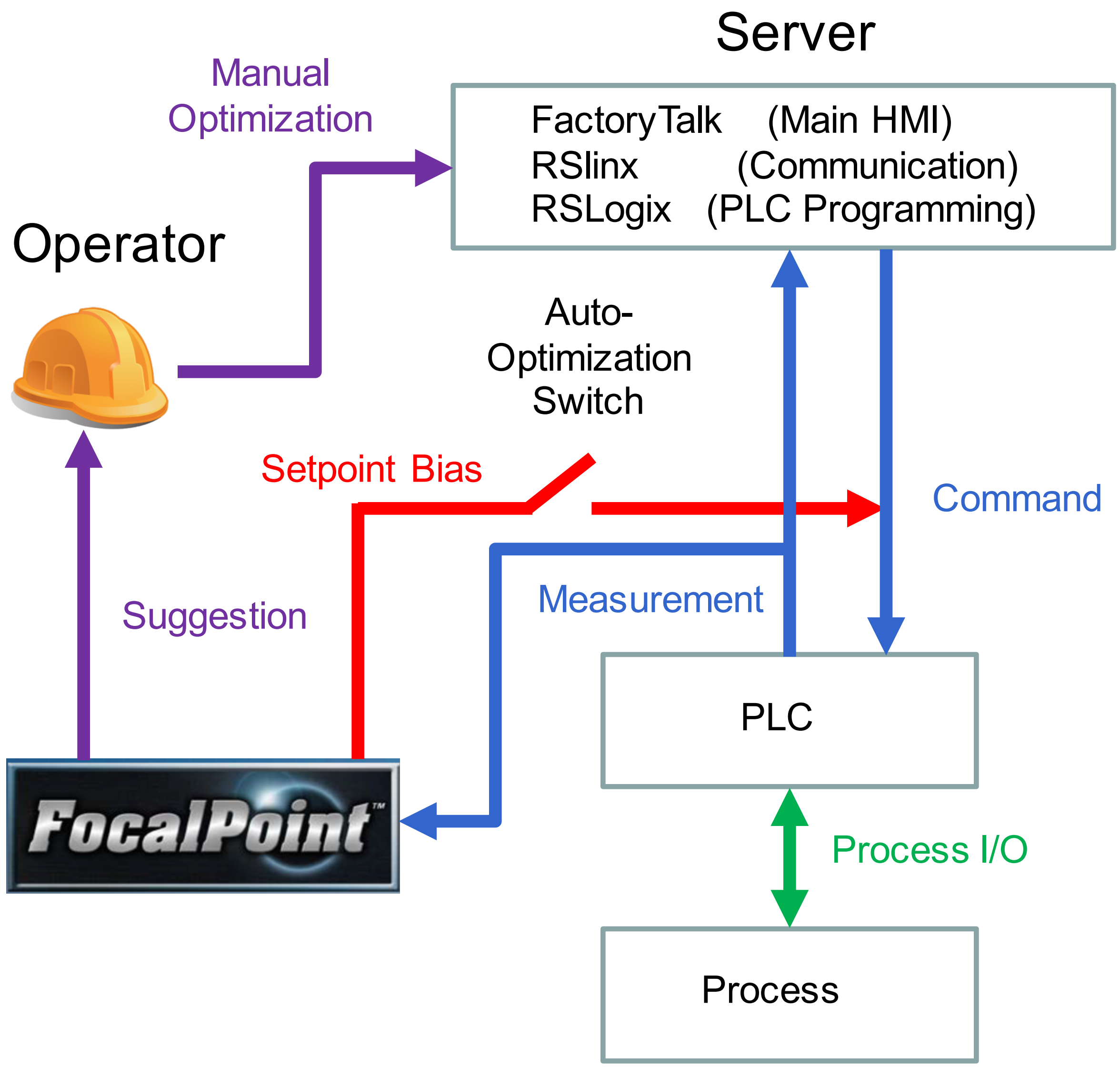
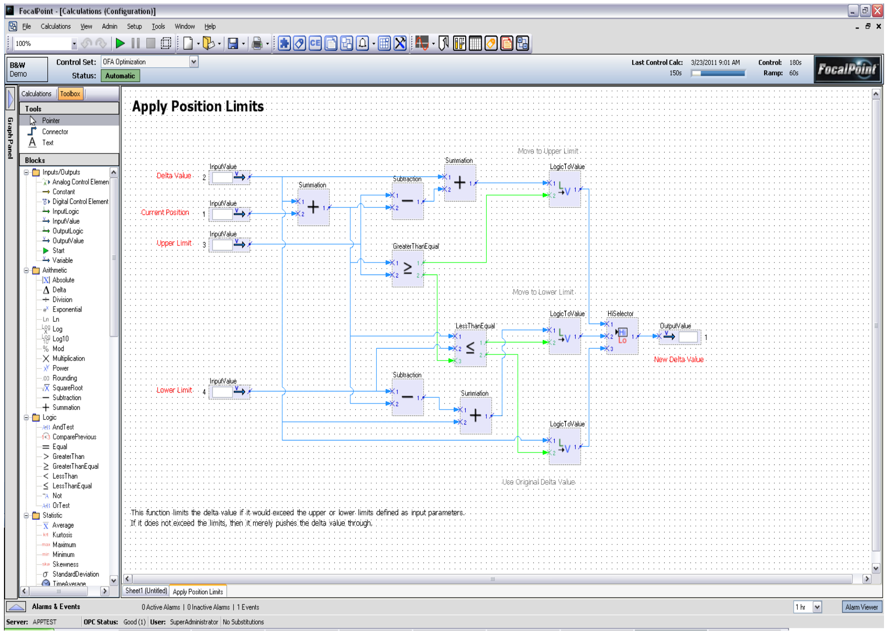
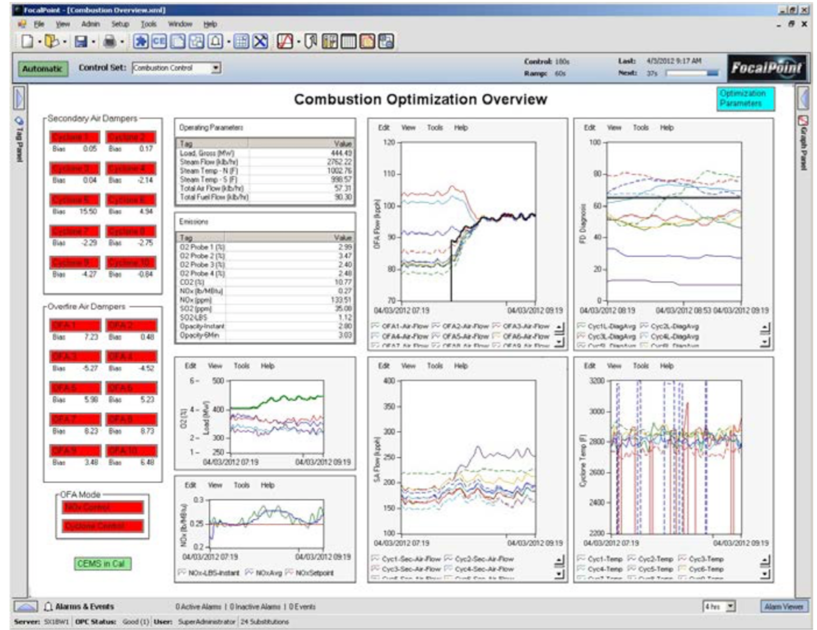
Technical Approach – Task 4

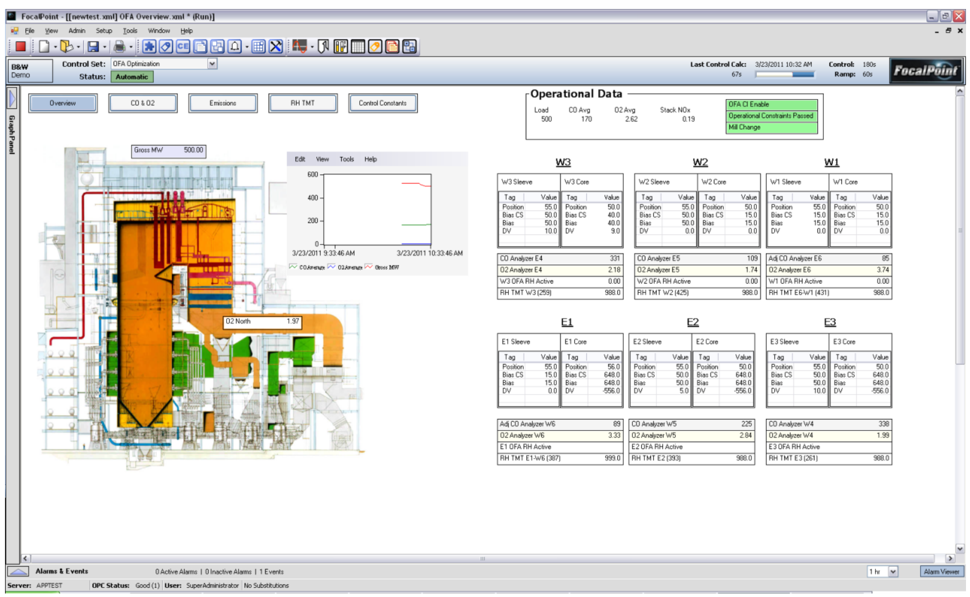


- B&W's commercial real-time, closed-loop optimization system
- Realize modeling techniques, optimization algorithms and knowledge-based strategies
- Features more advanced function blocks such as fuzzy logic for control purposes
- Will be used to optimize
  1. solid circulation rate
  2. sealing gas usage

Technical Approach – Task 4







the babcock & wilcox company

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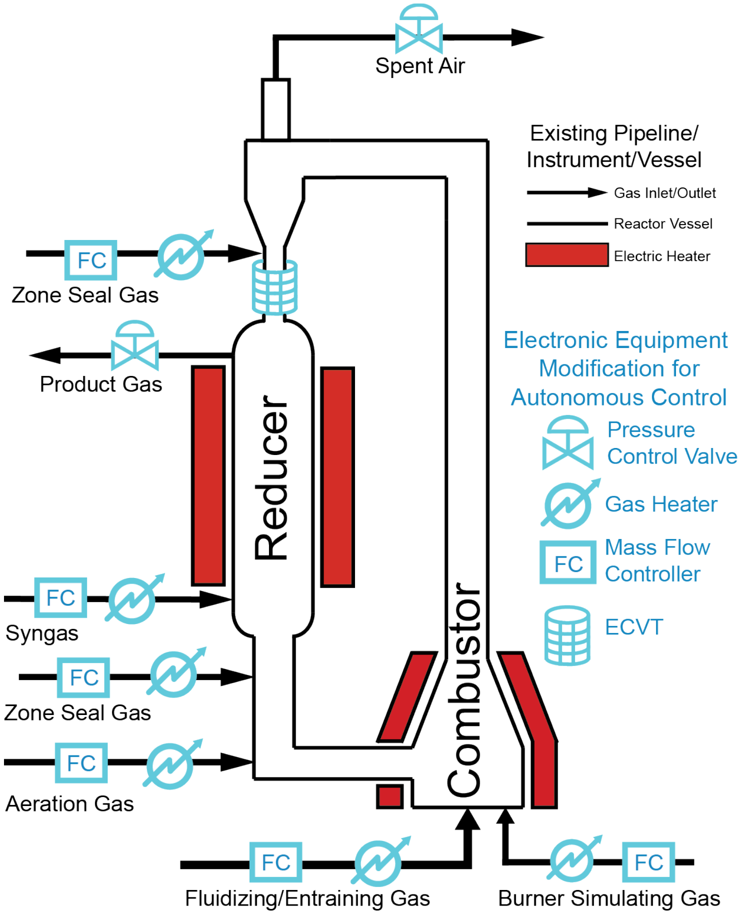
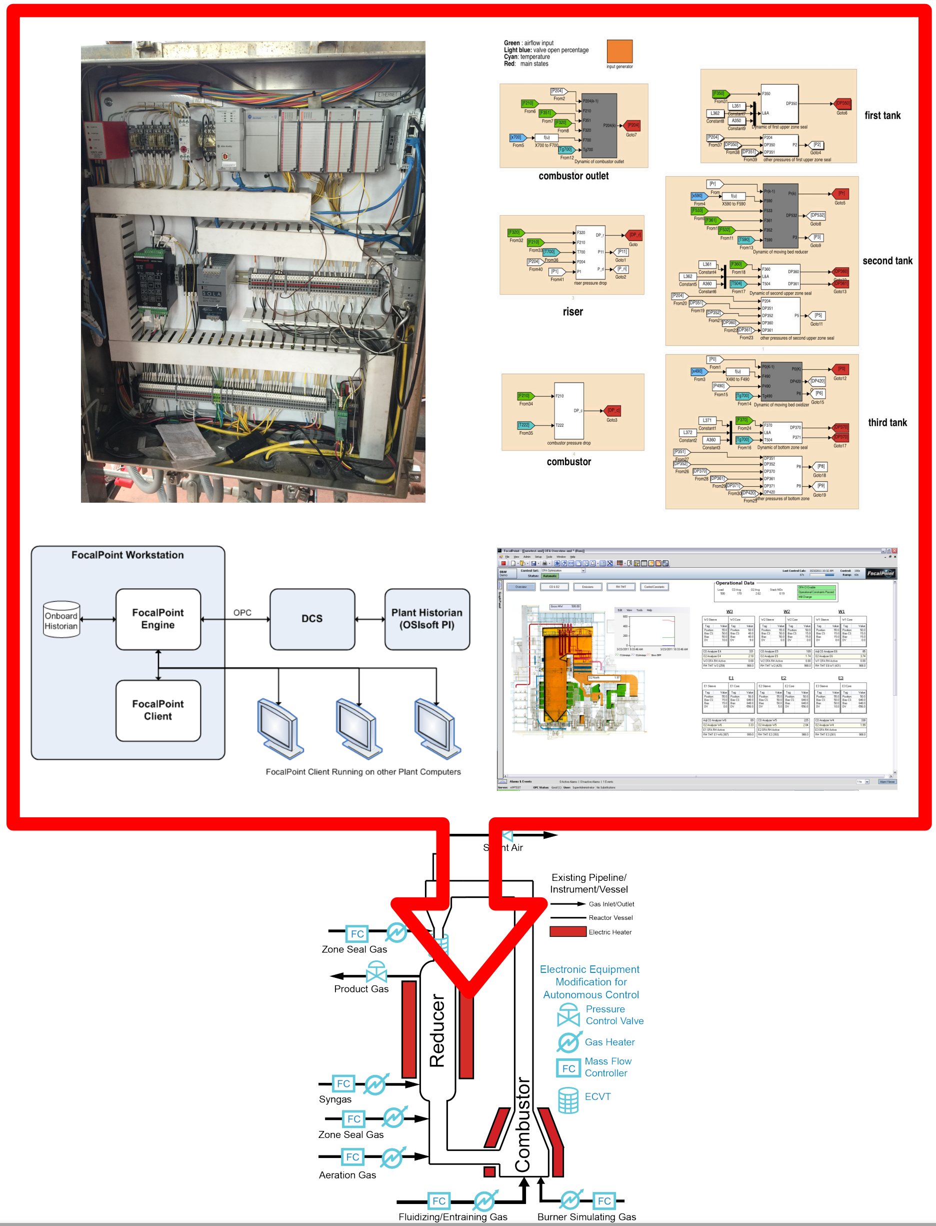
Technical Approach – Task 5

Demonstrate continuous operation on existing SCL sub-pilot and pilot units



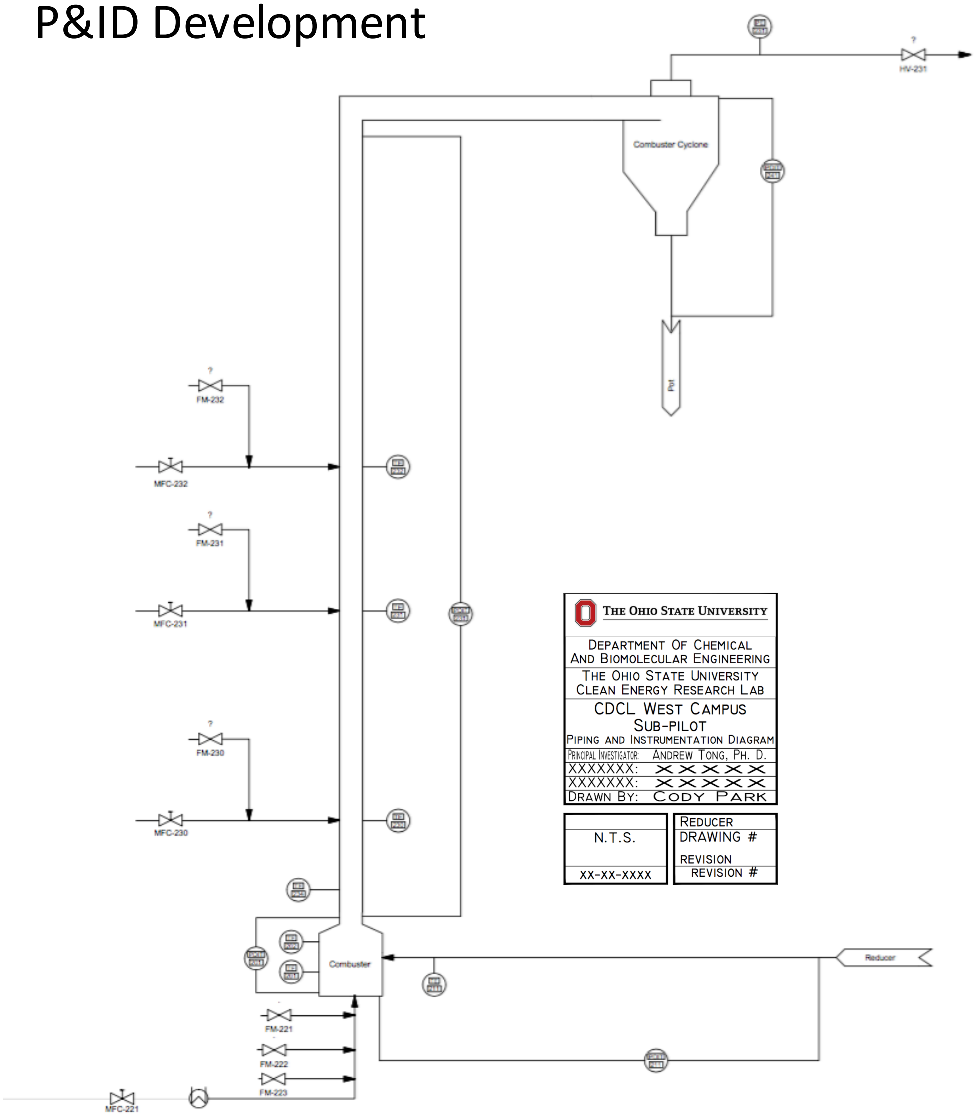
Technical Approach – Task 5

- Replace current manually-controlled components with controller-compatible components (ex: electronic mass flow controllers, control valves, gas heaters with relays) for autonomous control
- Upgrade the control system (HMI, PLC, client software) to industrial grade
- Integrate HLC-SMC control algorithm and FocalPoint with the standard system
- System assembly commissioning, instrument calibration
- Perform continuous operation and controller testing

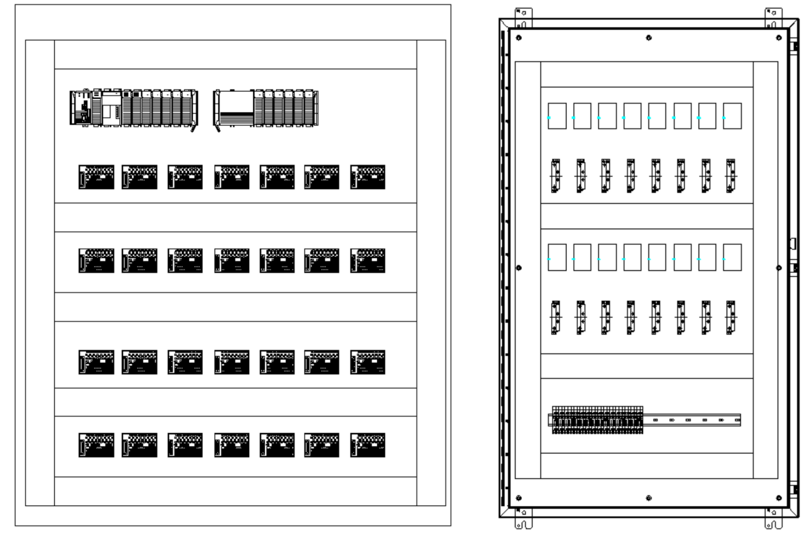


Task 5 status

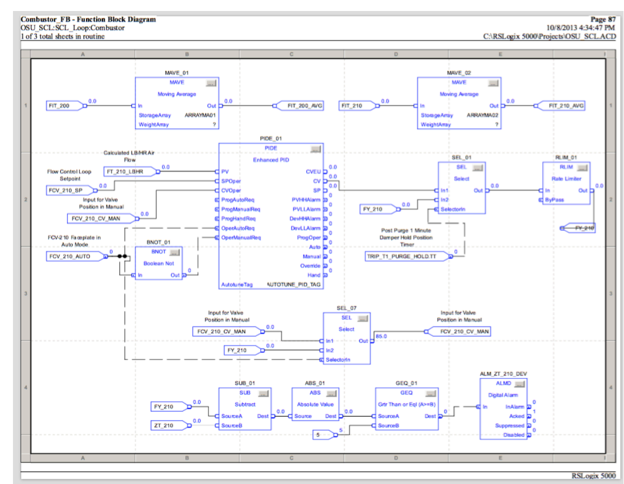
P&ID Development



Control Panel Design



PLC Control Programming



Progress summary

- Developed dynamic models of the 3-reactor system based on the SCL-Pilot Unit at NCCC, qualitative characteristics validated
- Hot ECVT testing apparatus built
- FocalPoint incorporated in the server, training on-going
- Procured PLC, control software and control instruments

Future work

- Develop HLC-SMC
- Calibrate and test the Hot ECVT unit in fluidized bed/moving bed mode
- Program interface between FocalPoint and control softwares
- Assembly testing units

Acknowledgements

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- **Tech4Imaging**
- **American Electric Power**