THE OHIO STATE UNIVERSITY

FE0026334: ADVANCED CONTROL ARCHITECTURE AND SENSOR INFORMATION DEVELOPMENT

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

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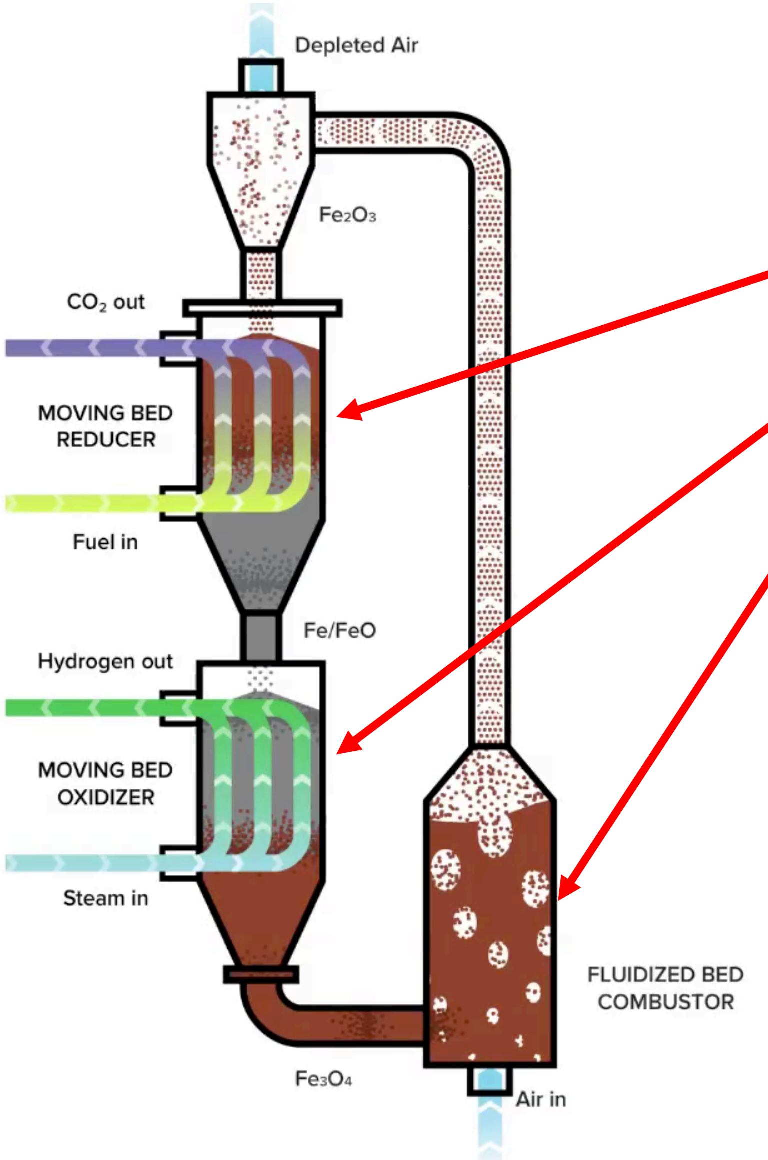
Department of Chemical and Biomolecular Engineering

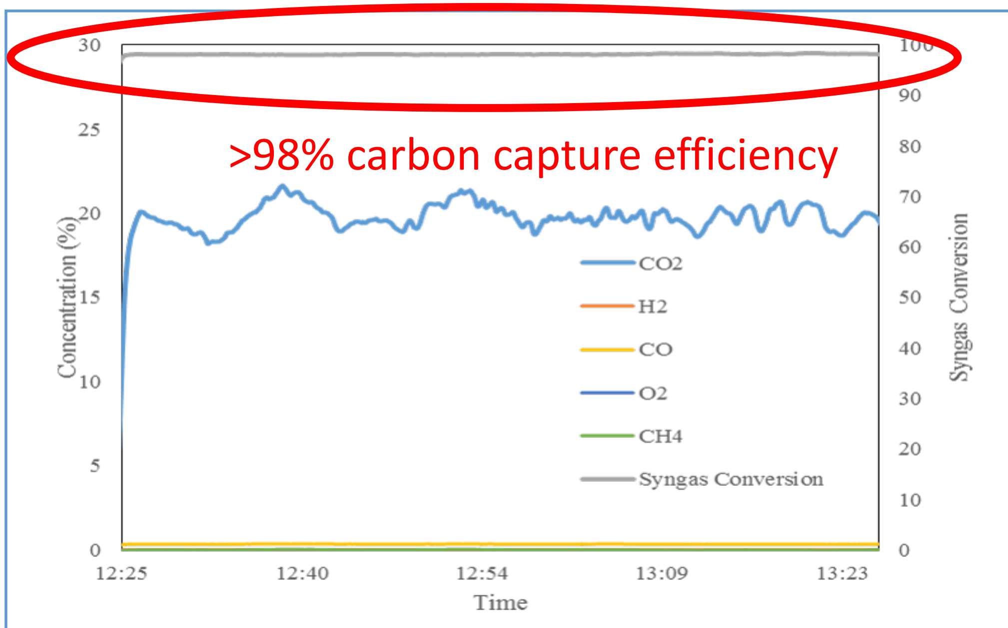
2017 Combined Project Portfolio Review| 20 March 2017

Syngas Chemical Looping (SCL) Process for H_2 Production



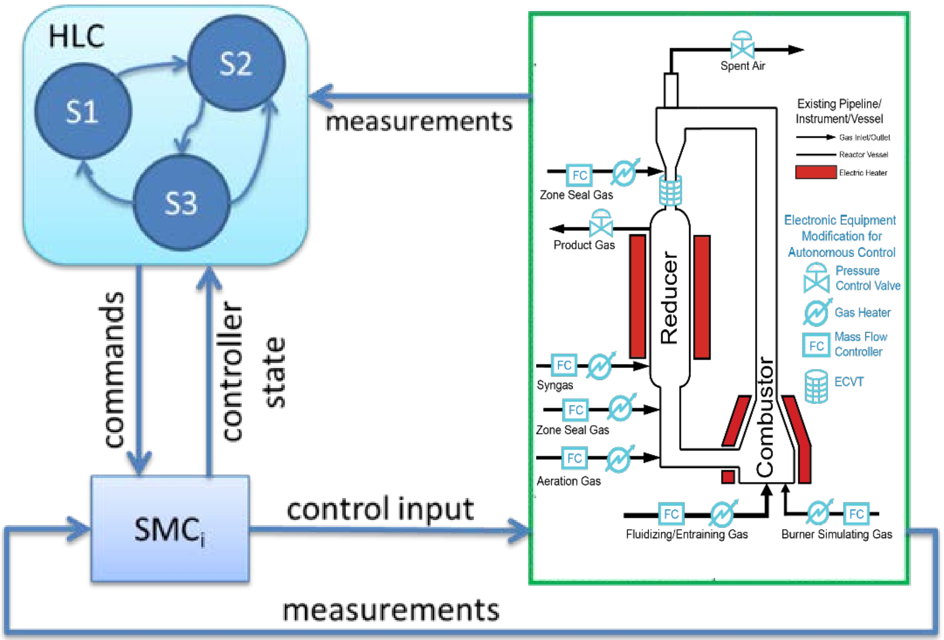
Main reactions:

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:	$C_xH_yO_z + H_2O + O_2 \rightarrow CO_2 + H_2 + Q$



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**)
    - Integrate process performance parameters with FocalPoint Optimization System (**B&W**)
    - 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

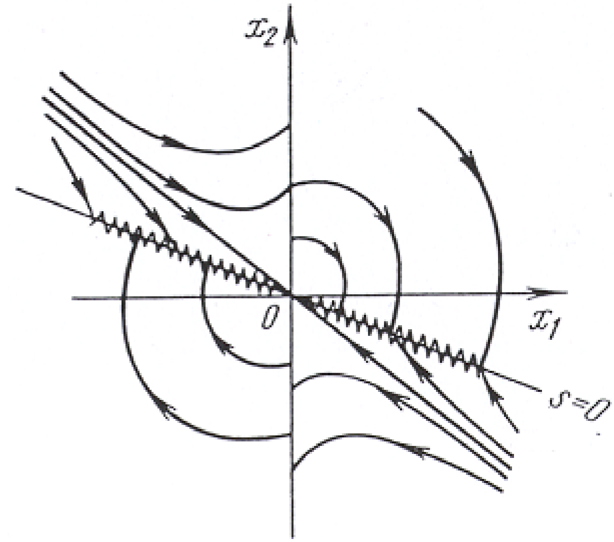
Sliding Mode Controller (SMC)

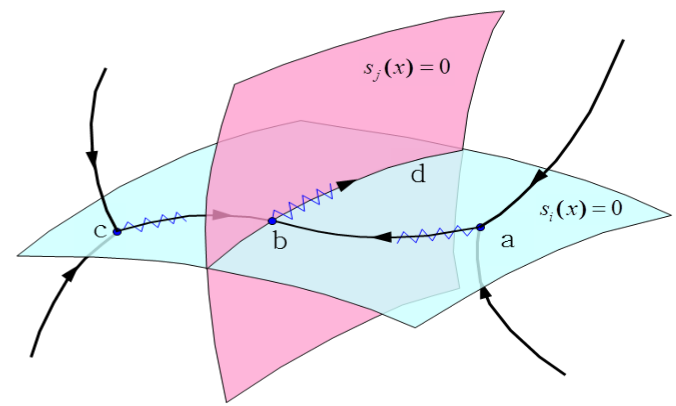
- Advantage: State trajectory control, robustness
- Controller changes behavior as the state trajectory crosses the surface
- Exemplary mathematical form:

$$\ddot{x} + a_2\dot{x} + a_1 x = u,$$

$$u = -M\text{sign}(s), \quad s = cx + \dot{x}, \; a_1, a_2, M, c \text{ - const}$$

- Two stages:
  - Reaching mode: to get to the sliding surface
  - Sliding mode: reduced order motion on the surface
- Disadvantage: chattering ➔
  - actuator wear-and-tear
  - potential plant excitement

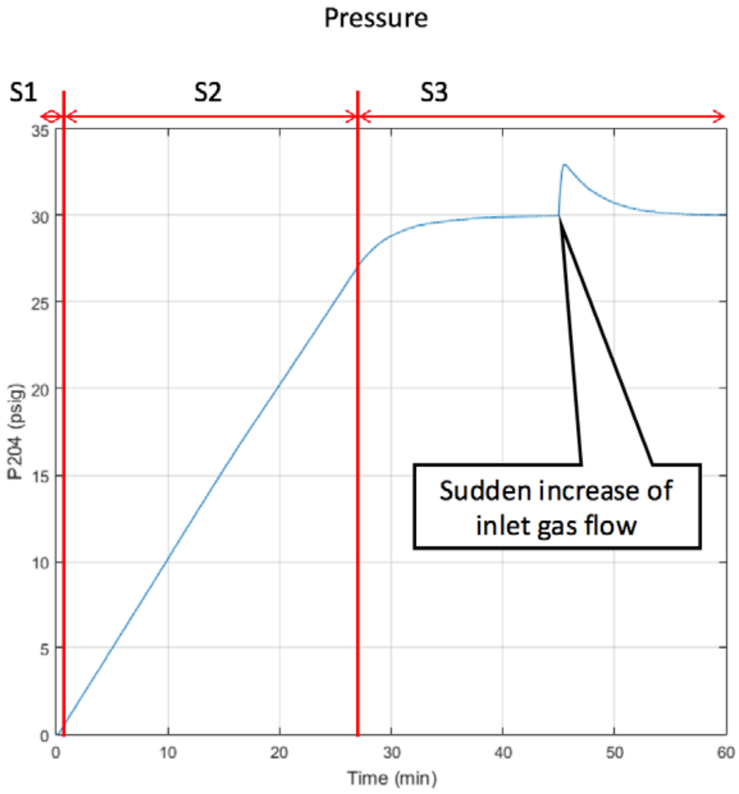




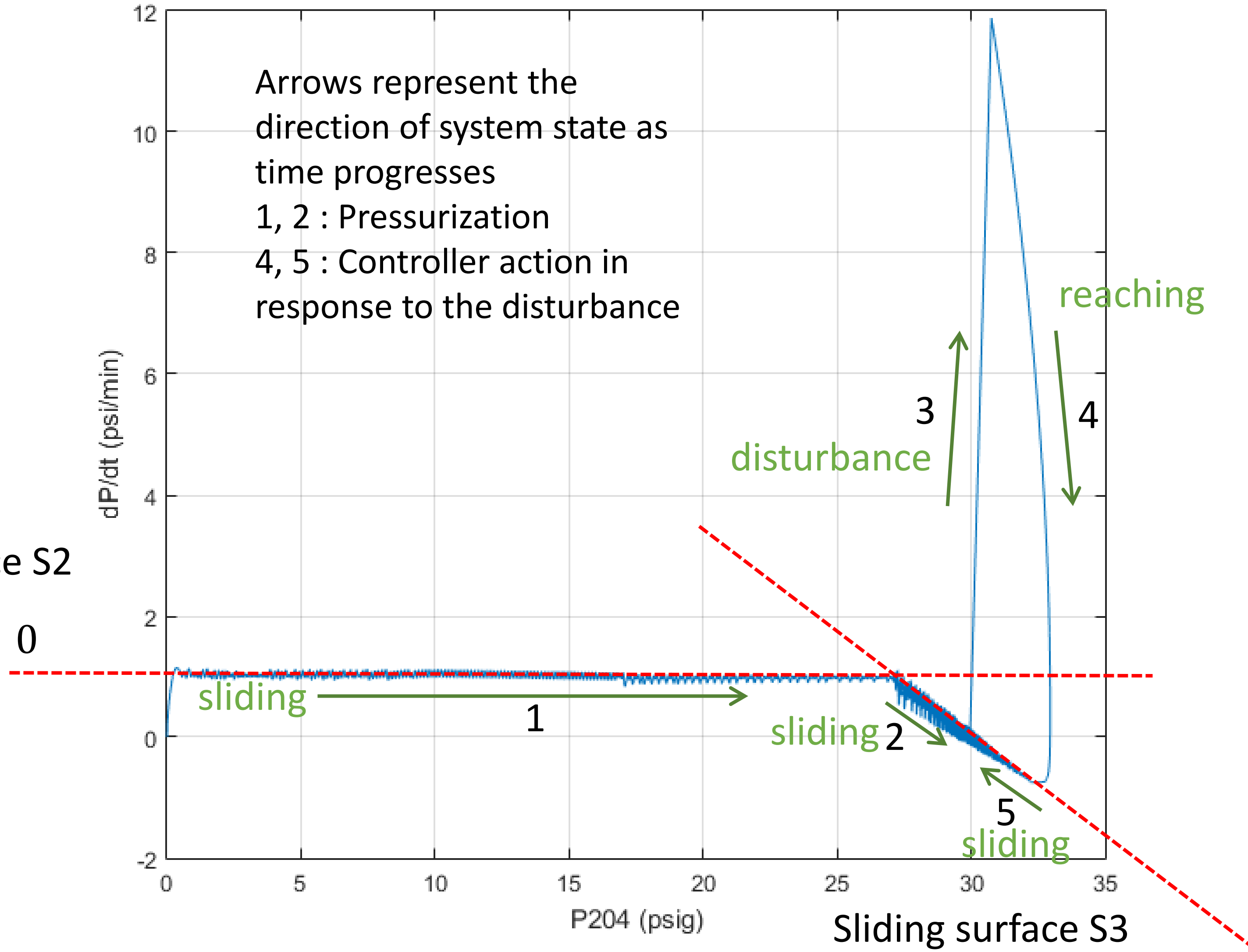
Utkin, V., "Variable structure systems with sliding modes," *Automatic Control, IEEE Transactions on* , vol.22, no.2, pp.212,222, Apr 1977

Matlab simulation of a sliding mode controller design for pressure control

- Control law: rate of valve opening change
  - $u = \frac{dx}{dt}$
- S2 Controller:
  - $u = M_2 \cdot sign(S_2)$
  - $S_2 = \frac{dP}{dt} - RR$
  - $RR = 1\,psi/min$
- S3 Controller:
  - $u = M_3 \cdot sign(S_3)$
  - $S_3 = \frac{dP}{dt} + \left(P - P_{sp}\right) \cdot K$
  - $P_{sp} = 30psig, K = \frac{1}{3}min^{-1}$



Phase Plane



Sliding surface S2

$$\frac{dP}{dt} - 1 = 0$$

Sliding surface S3

$$\frac{dP}{dt} + \frac{P - 30}{3} = 0$$

SCL Pilot Unit Pressurization/Depressurization

Ramp surface:

$$u = M_2 \cdot sign(S_2)$$

$$S_2 = \frac{dP}{dt} - RR$$

$$RR: Ramp\ rate$$

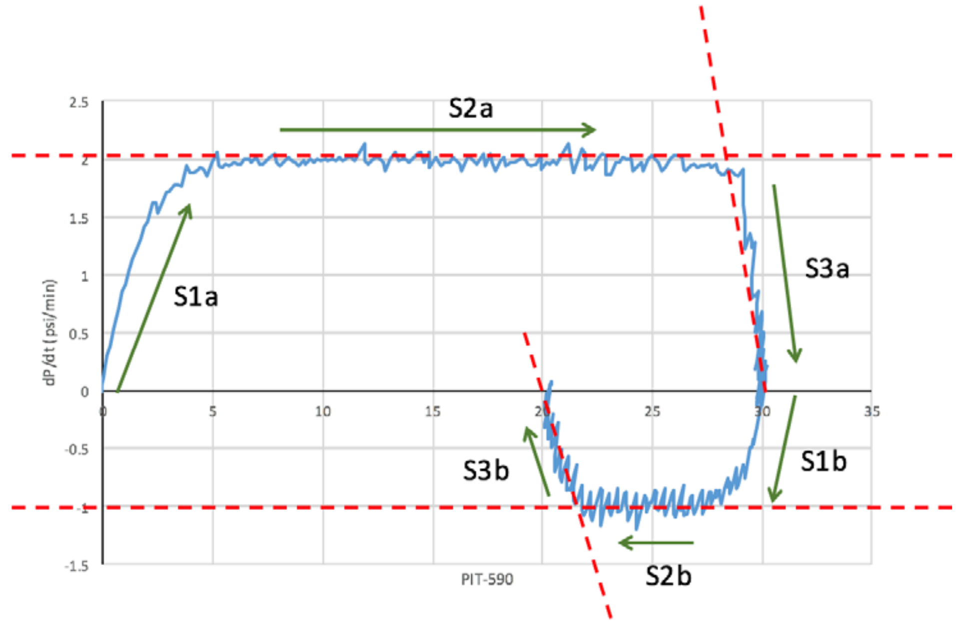
SS surface:

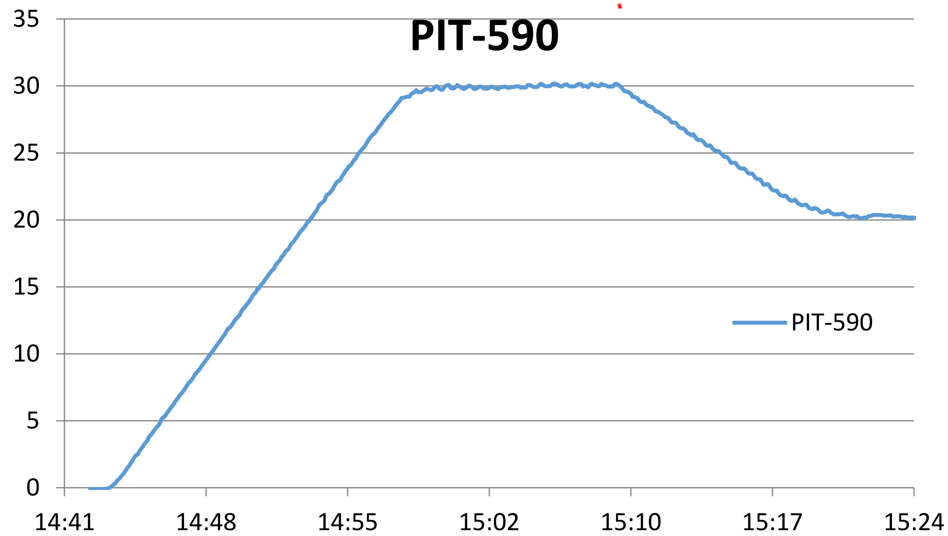
$$u = M_3 \cdot sign(S_3)$$

$$S_2 = \frac{dP}{dt} + \left(P - P_{sp}\right) \cdot K$$

$$P_{sp} = setpoint, K = const$$

$$u = \frac{dx}{dt}$$





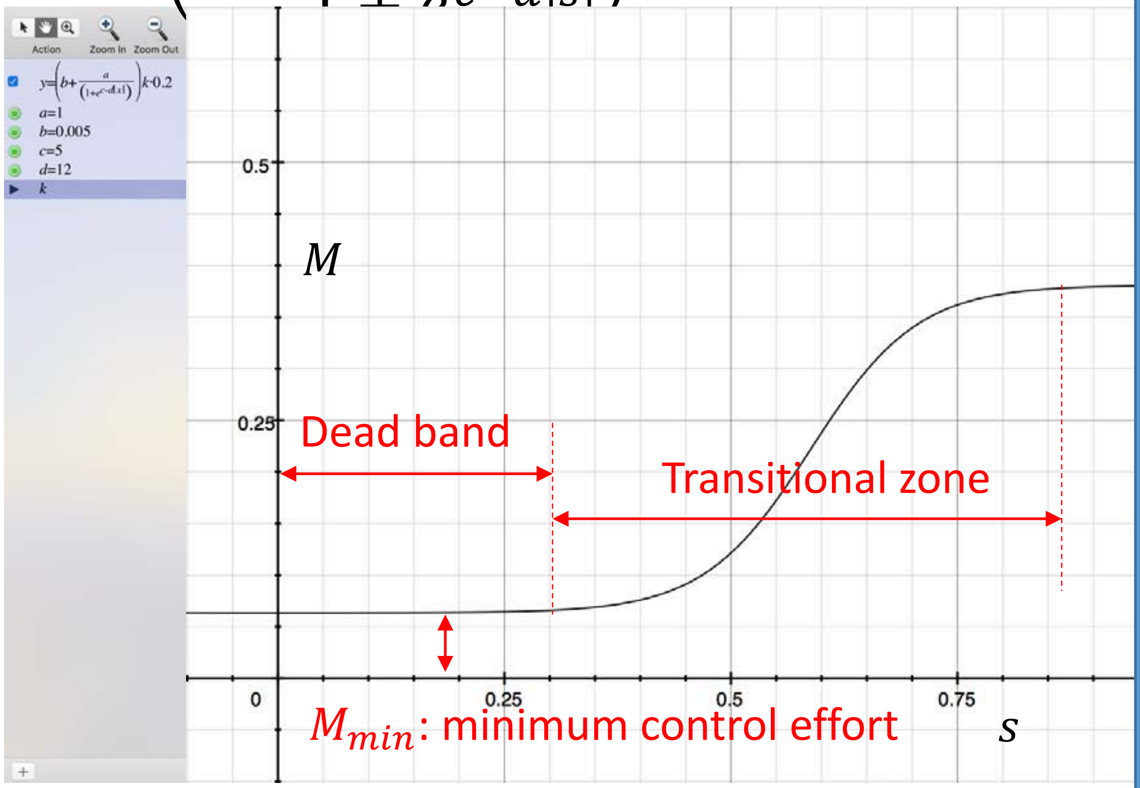
Design of adaptive M

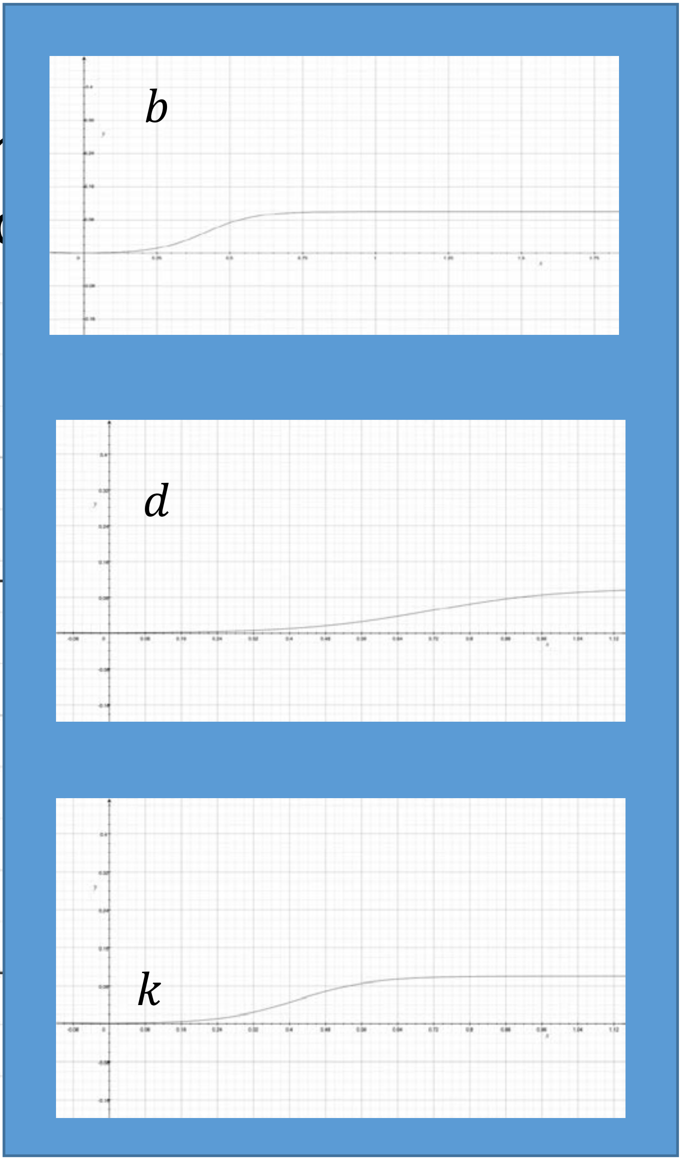
Modified sigmoid function:

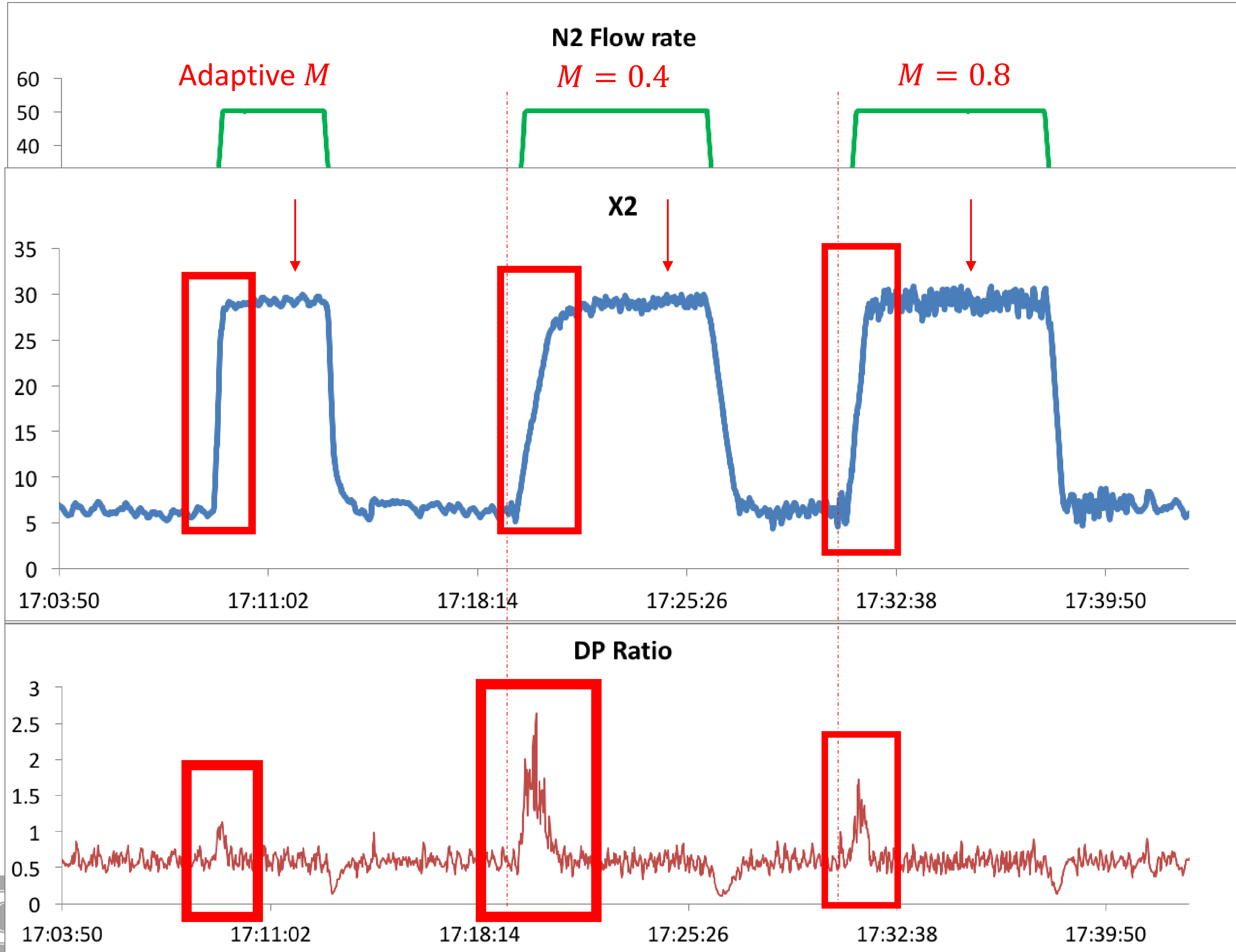
$$M = \left(b + \frac{a}{\ldots}\right) k$$

Goal:

- Reduce ch
- Enhance c



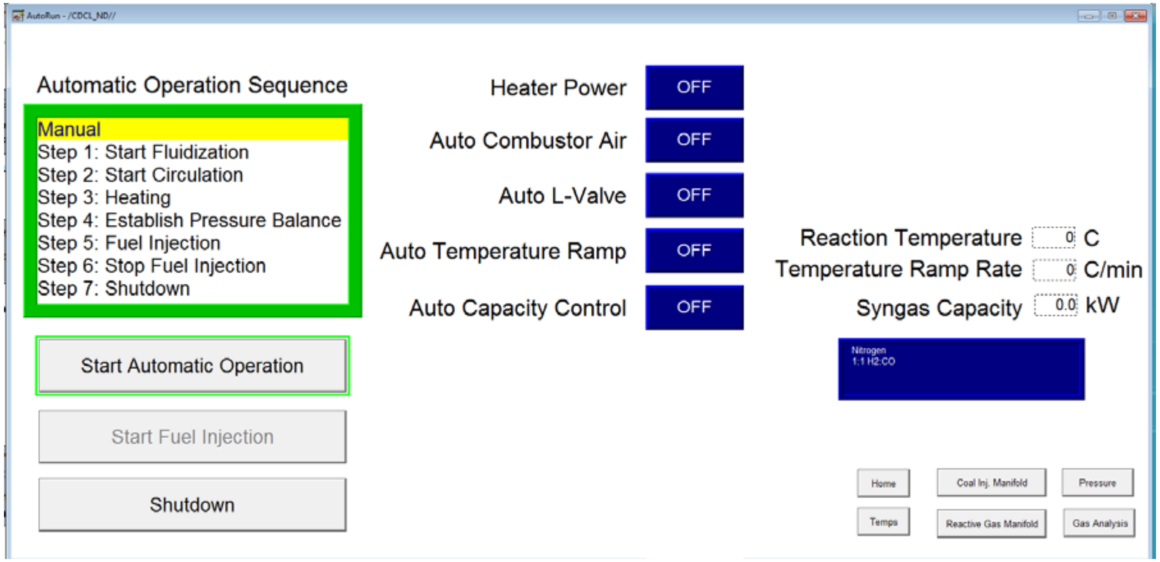




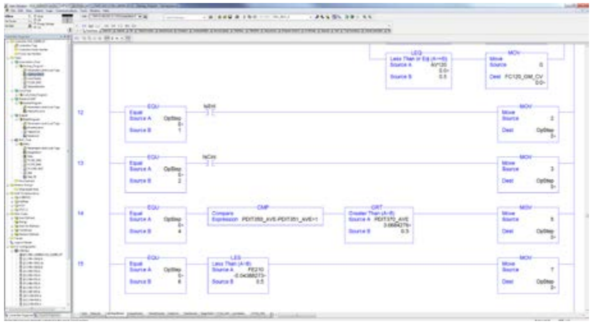
N2 Flow rate
Adaptive M
$M = 0.4$
$M = 0.8$
60
50
40
X2
35
30
25
20
15
10
5
0
17:03:50
17:11:02
17:18:14
17:25:26
17:32:38
17:39:50
DP Ratio
3
2.5
2
1.5
1
0.5
0
17:03:50
17:11:02
17:18:14
17:25:26
17:32:38
17:39:50

Implementation of automatic start-up algorithm

- Pre-set operation goals
- HLC-SMC structure
- 1-click startup for fluidization, entrainment and maintaining circulation during heat-up
- Fuel injection upon reaching reaction temperatures and operation 1-click acknowledgement

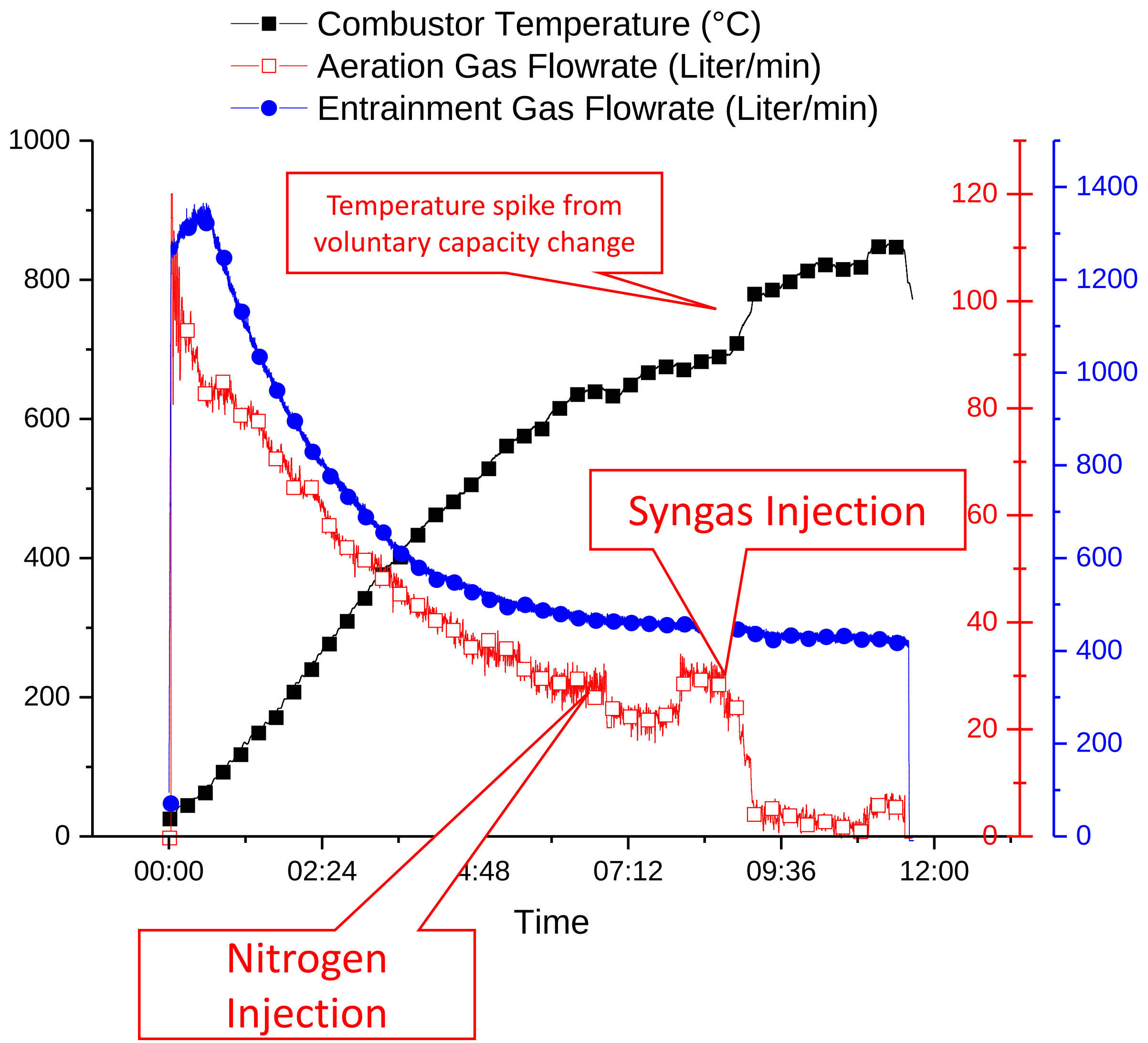



```
(* Calculate Ut based on riser top temperature, 1atm correlation *)
AIR_VIS_R:=((TE243/10)**2/10**6+(TE243/10)*0.0041+1.7669)/10**5; (* The unit of TE tags in
AIR_DEN_R:=353.32/((TE243/10)+273.15);
Ut1:=0.154*(0.0015**1.6*2500*9.8/AIR_VIS_R**0.6*AIR_DEN_R**0.4)**(5/7);
Ut2:=1.74*SQRT(0.0015*2500*9.8/AIR_DEN_R);
If Ut1<Ut2 then
    Ut := Ut1;
else
    Ut := Ut2;
end_if;
Ft_ent := Ut/(273+TE234/10)*298*0.002*60000;

(* Decide whether combustor gas flow is sufficient to start L-valve*)
if FT210*(273+TE234/10)/298/0.002/60000-0.5 >= Ut then
    IsEnt := 1;
    else
    IsEnt := 0;
end_if;

(*  Decide whether the bed is circulating based on riser DP fluctuation *)
if PDIT231_STD>=1 then
    IsCirc := 1;
else
    IsCirc := 0;
end_if;
```



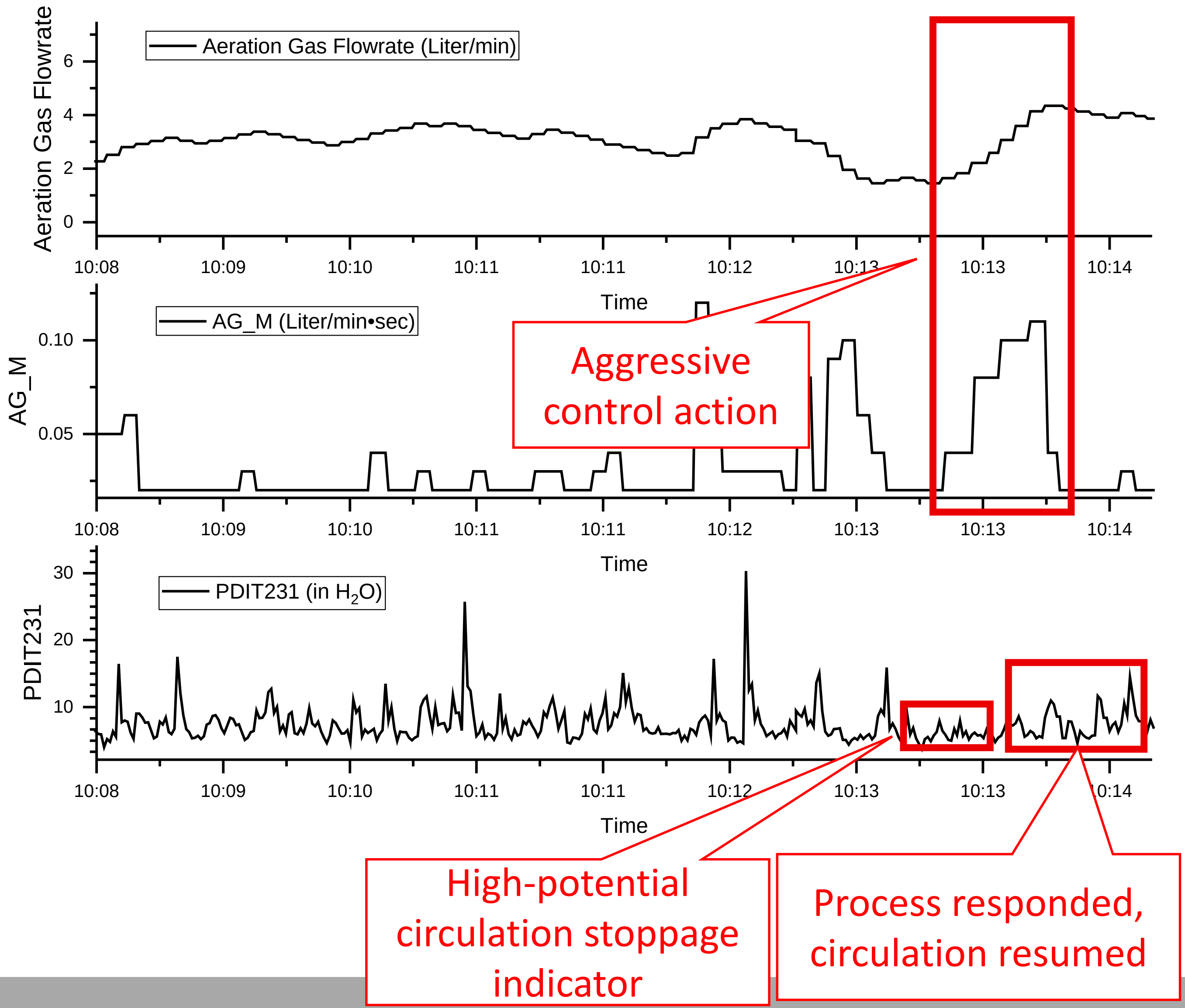
Start-up sequence test drive

- Achieved automatic startup with zero operator intervention
- Maintained oxygen carrier circulation at minimal solid flow rate using self-regulating aeration and entrainment gases



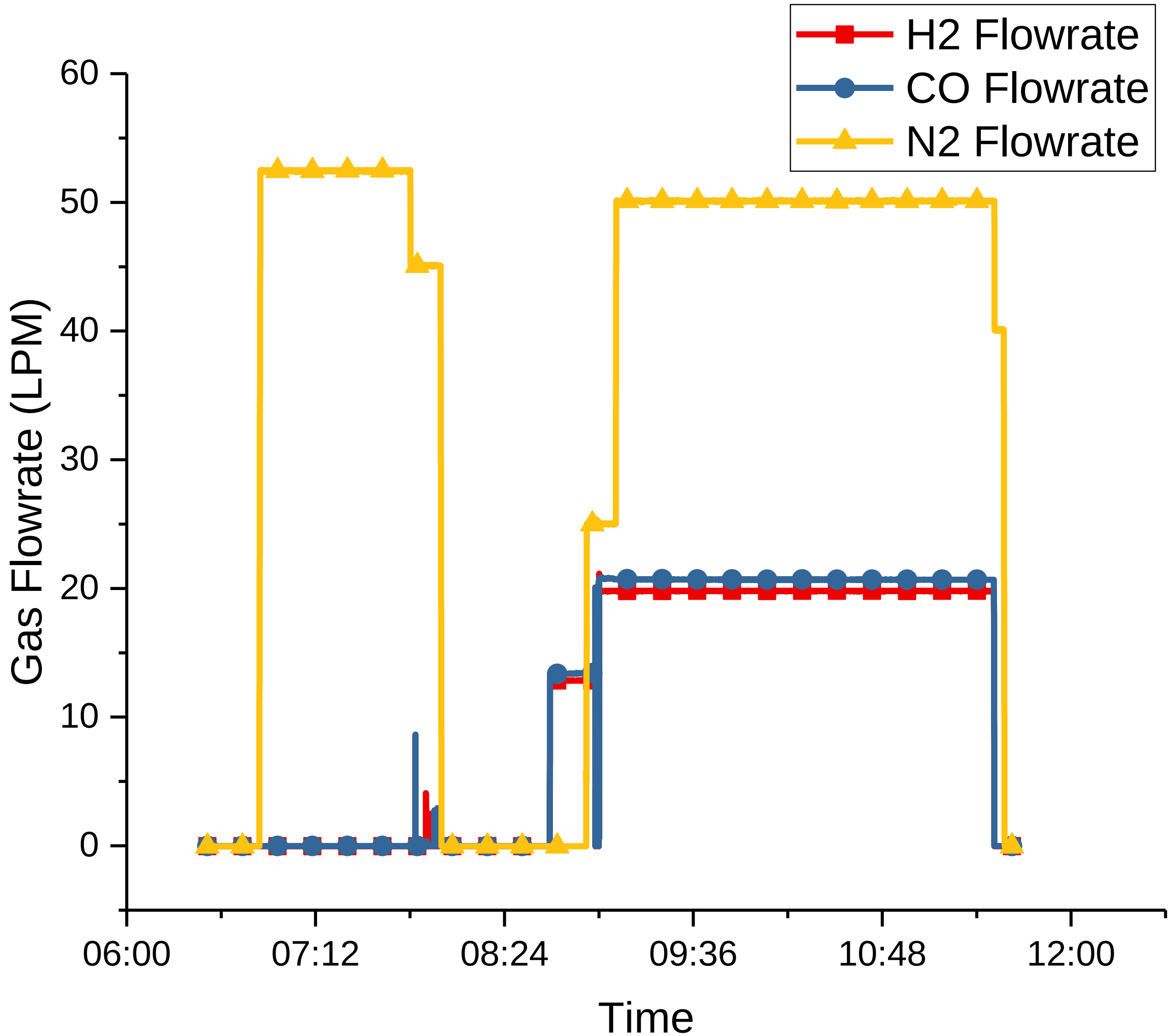
Circulation rate control

- SMCs attempt to minimize attrition by controlling circulation rate

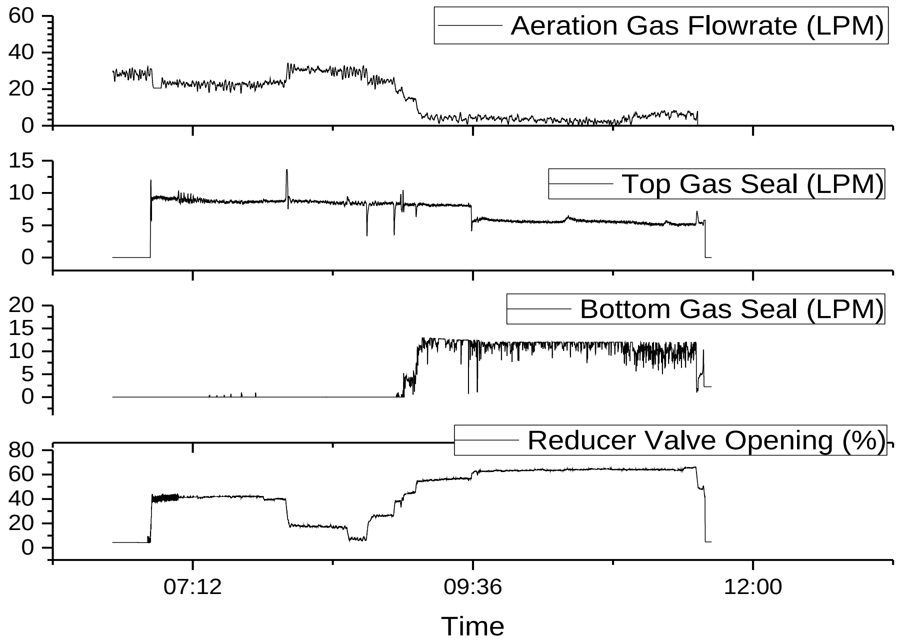


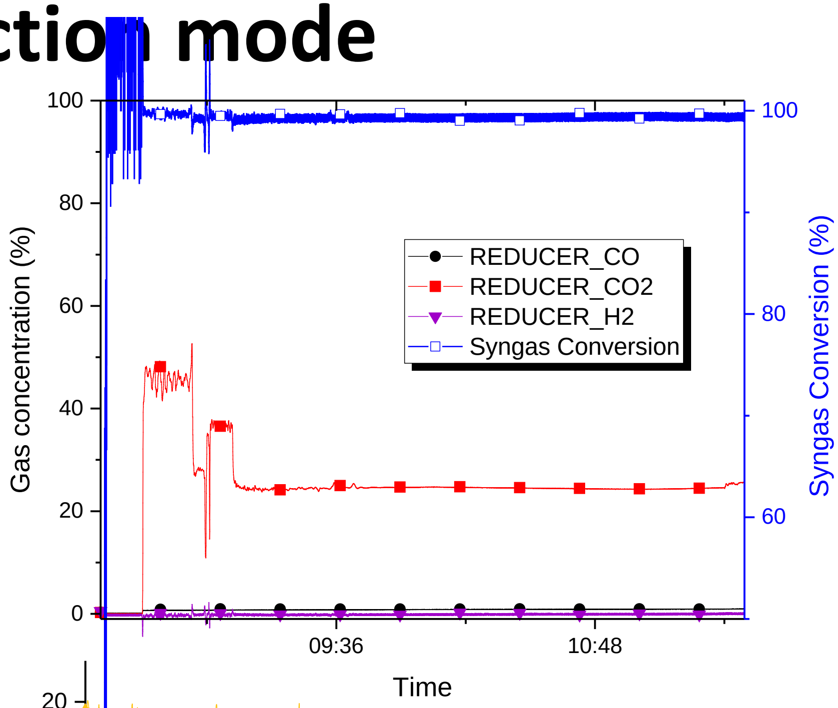
Fuel injection mode

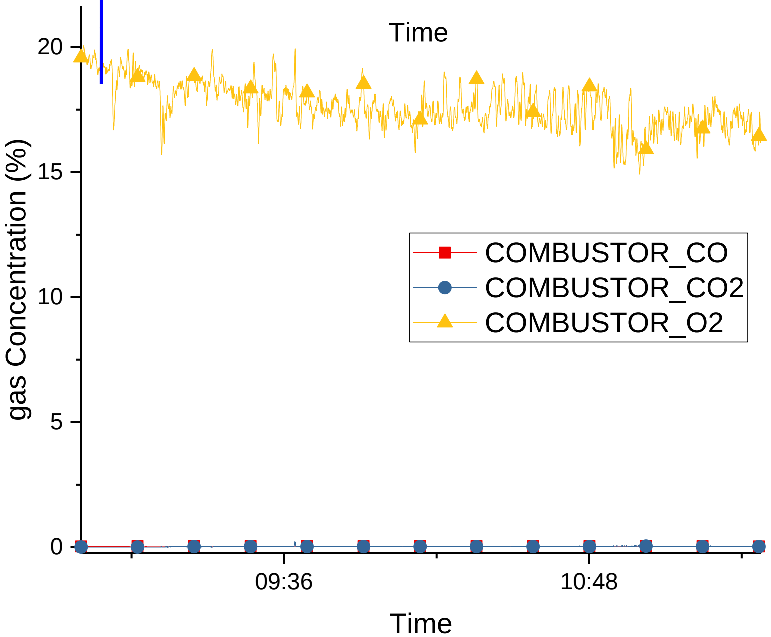
- Nitrogen injection to verify behaviors for individual SMCs
- Extreme capacity change to test disturbance rejection performance



Fuel injection mode

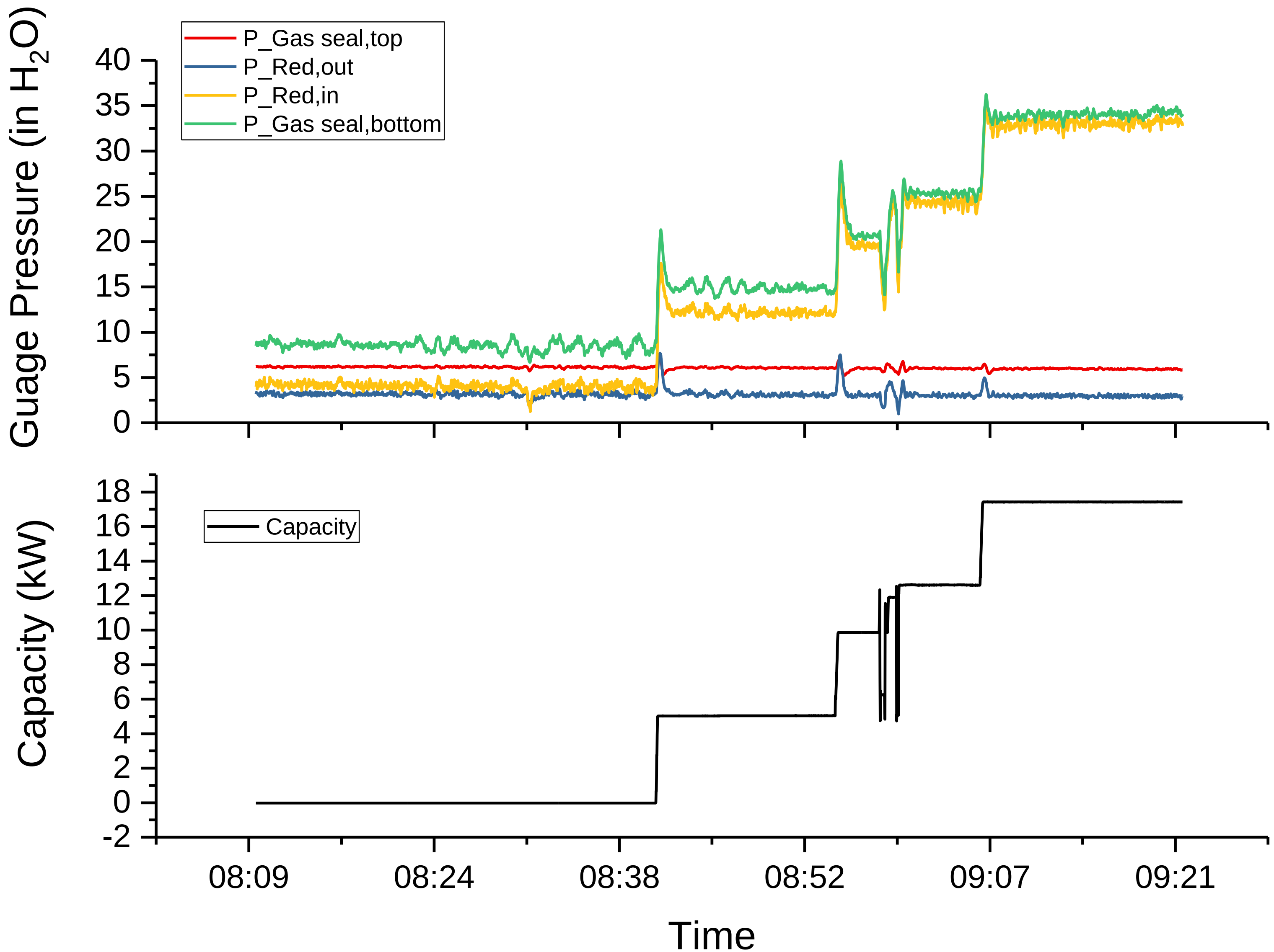






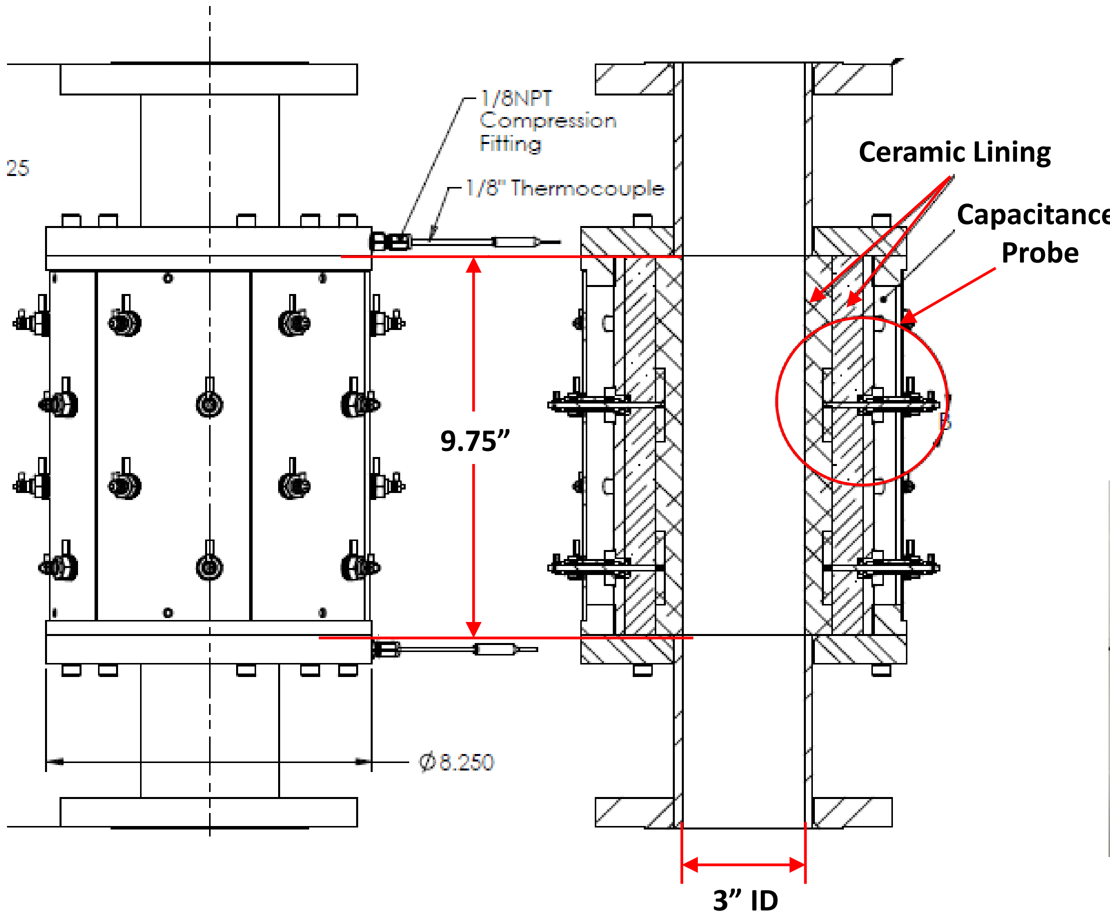
- Simultaneous control actions correctly executed by all SMCs with no operator intervention
- Achieved ~99% syngas conversion
- No gas breakthrough was observed in either reactor

SMC Response to Capacity Change

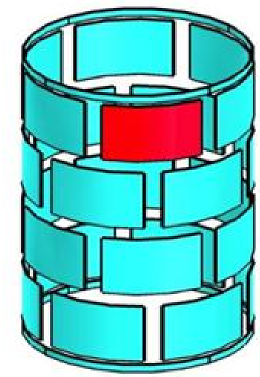


Combustor Performance Investigation - ECVT

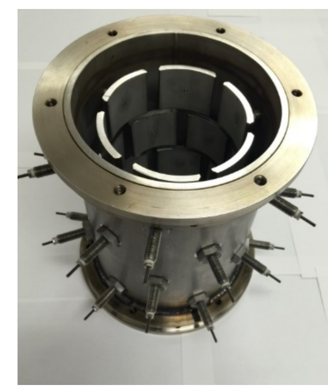
Sensor Assembly



Capacitance Probe Arrangement

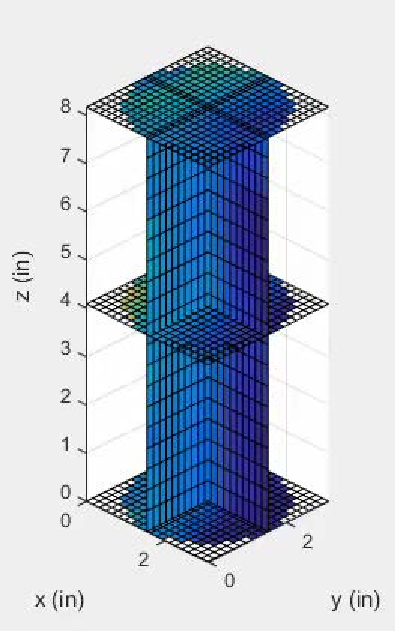


24 channel Sensor

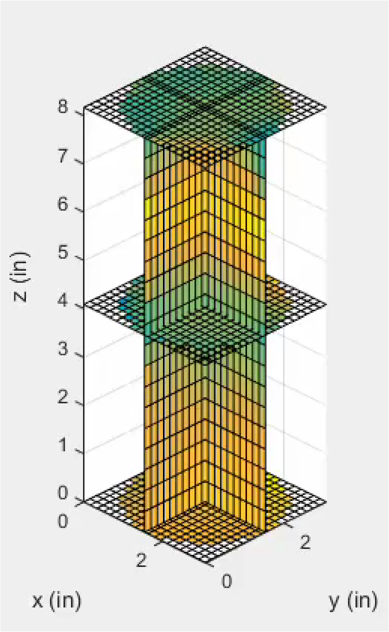


Combustor Performance Investigation - ECVT

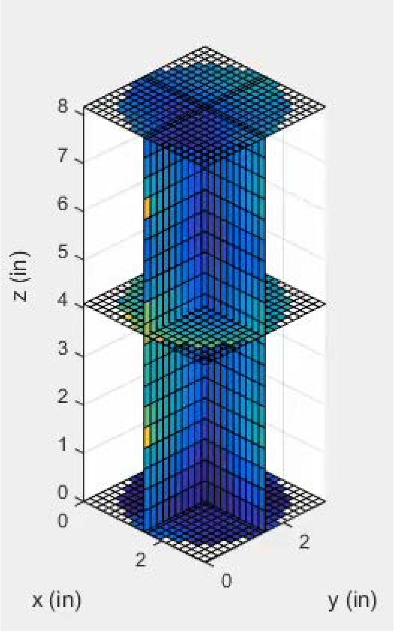
Image Reconstruction:



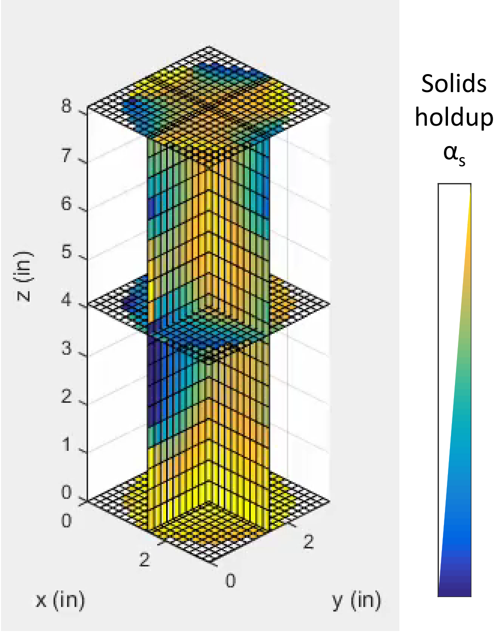
23 C, 600 slpm
U_g-U_{mf} = 1.49



335 C, 300 slpm
U_g-U_{mf} = 1.5



640 C, 220 slpm
U_g-U_{mf} = 1.80

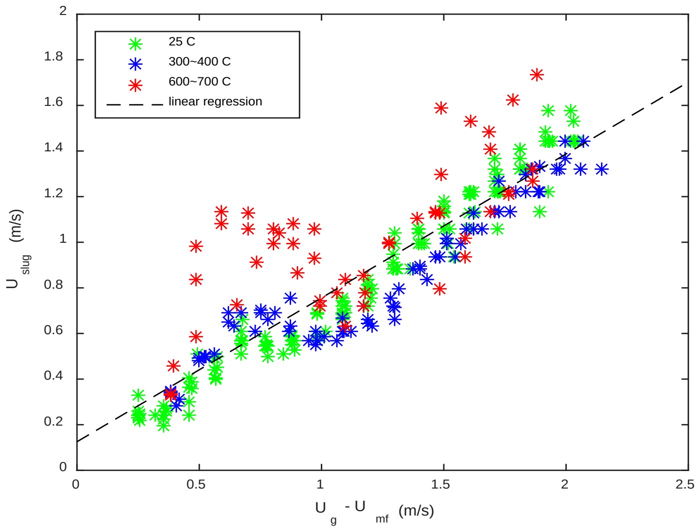


720 C, 176 slpm
U_g-U_{mf} = 1.47

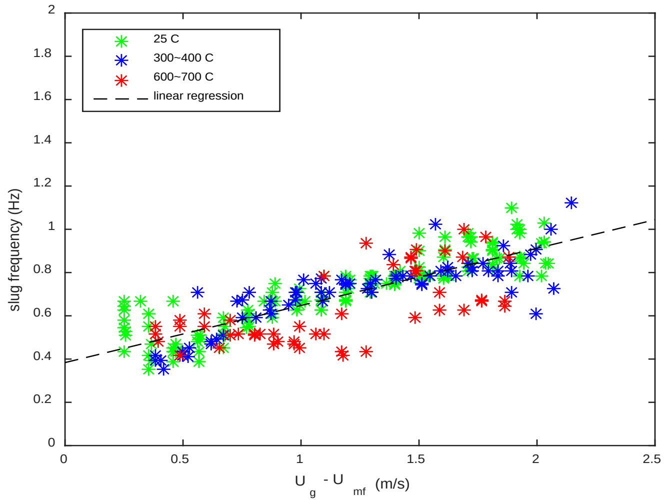
Image reconstruction frame rate: 80 Hz ~ 260 Hz

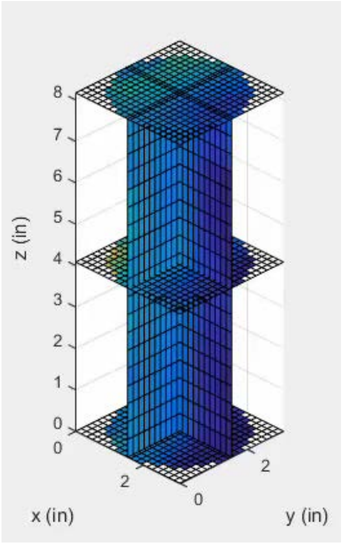
Combustor Performance Investigation - ECVT

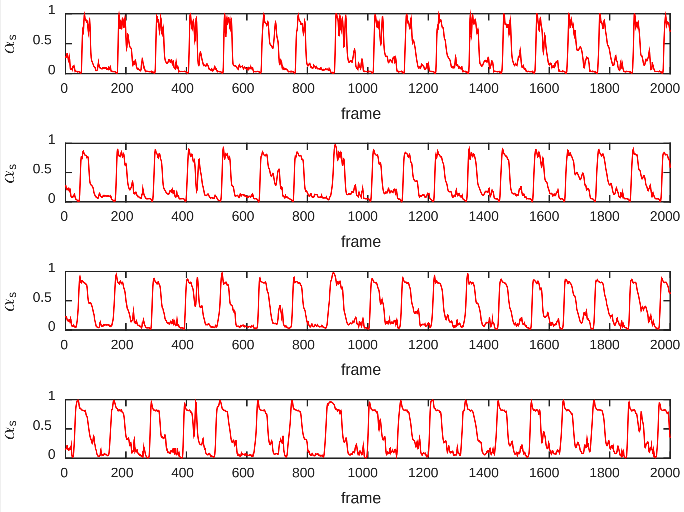
Slug Velocity vs. Gas Velocity



Slug Frequency vs. Gas Velocity







23 C, 600 slpm

Additional Work

- Continued sub-pilot demonstration
  - Tuning adaptive SMC
  - Comparative testing with conventional controls
- FocalPoint Integration
  - HLC Performance
  - Sensor fault detection
  - Thermodynamic Optimization parameters
- ECVT Solid flow control development
  - Moving bed flow characterization
  - Electrical characterization of ceramic and oxygen carrier material

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Fan Research Group Members