MODELING, SIMULATION AND ADVANCED CONTROLS FOR PROTOTYPE CHEMICAL LOOPING

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Agenda

1  Introduction

2  CL Advanced Control Development Plan

3  CL Prototype Dynamic Model

4  MPC Design and Simulation Results

5  Conclusions and Future Work
What is Chemical Looping (CL)?

- **Chemical Looping (CL)**
  - A multi-loop coal combustion/gasification process
  - Using a solids oxygen carrier for separating $N_2$ and $O_2$ in air
  - Easy $CO_2$ capture for use or sequestration

Alstom’s MeOx Based Chemical Looping

Alstom’s Calcium Based Chemical Looping
What is Advanced Controls?

- **Advanced Controls**
  - Computer based algorithm/strategy/system that deviates from PID control
  - Usually an optimization solution involved in controller action
  - **Model-Based Predictive Control (MPC)** is a typical advanced controller – fit in modern enterprise optimization hierarchy

- **Why Advanced Controls**
  - Improve capacity and product yield
  - Reduce energy consumption
  - Improve process safety and reduce environmental emissions
  - Increase responsiveness
Why Advanced Controls for CL?

- Multivariable control for better coordination of multi-loop interactions in CL

- Robust control to reject disturbances such as fuel and solids flow variations

- Enable fast load change in wide range operation to better support smart grid

- Enable economic optimization for production cost, energy cost saving and emission (CO\textsubscript{2}) cost reduction
What is this Project about?

• **Project Title**
  Development of Computational Approaches for Simulation & Controls for Hybrid Combustion-Gasification Chemical Looping (CL) Plant

• **Project Goal**
  To characterize the Chemical Looping process dynamics, and apply advanced multivariable controls to enable optimization of future CL plant operating performance and overall economics.

• **Project Sponsorship**
  - DOE/NETL (Virtual Engineering of Advanced Power Generation Systems Area1: Sensors & Controls Systems)
  - Alstom – Thermal Power
DOE/Alstom Project Tasks

Phase I: Jul 2007 - Sep 2009 (Completed)

- Milestone 1. Process and Control Performance Benchmark (Taft Engineering)
- Milestone 3. Develop PDU Model and Simulation
- Milestone 4. Validate Process Model
- Milestone 5. Advanced Modeling and Controls work @ UIUC
- Milestone 6. Design and Build APC Control Modules and Link to Simulator
- Milestone 7. Project Management, Reporting and Presentations
- Milestone 8. Investigation and development of sensors for controls
CL Controls Project Milestones

• DOE/Alstom Project Tasks

Phase I Extension: Oct 2009 ~ July 2012

Milestone 1. Prototype Process Characterization/Specification
Milestone 2. Extend Modeling & Simulation to Prototype Process
Milestone 3. Control Analysis for Prototype Scale
Milestone 4. Advanced Sensor Development and Testing
Milestone 5. Project Management, Reporting and Presentations
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Chemical Looping (CL) Simulation and Advanced Controls is aligned with CL Process Development in Alstom's Chemical Looping Program.
CL Advanced Controls Development Plan
Phase I: Modeling & Control of CL Solids Transport

• Step 1: Solids Transport Controls

• Step 2: Hot Loops with CL PDU
CL Advanced Controls Development Plan
Phase II: Modeling and Control of CL Prototype Plant

Chemical Looping Prototype System

Simulation and Control of CL Prototype Facility

CL Prototype (3MW) Process Design by Alstom’s CL Process Team

Optimization System
Advanced Control
Simulators
Models
Integrated Controls Optimization of Utility Scale Plants

**Inputs**
- Fuel
- Sorbet
- Air
- Water
- Others

**CL Based CO₂ Ready Plant**

**Outputs**
- Electric Power
- Emissions Credit
- Life Extending
- Process Steam as Product
- CO₂ utilized for commercial products
- CO₂ Capture and Storage – Negative Income

**Costs**
- \(-\sum C_i X_i\)

**Clean Power System Optimizer**

**Incomes**
- \(\sum P_i Y_i\)

**New Control System Platform with Optimization Functionalities**

- Operating Constraints
- Others
- Environmental Constraints
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The Governing Equations for Gas Phase:

\[
\frac{\partial}{\partial t} (\varepsilon \rho_g) + \frac{\partial}{\partial z} (\varepsilon \rho_g v_g) = 0
\]

\[
\frac{\partial}{\partial t} (\varepsilon \rho_g v_g) + \frac{\partial}{\partial z} (\varepsilon \rho_g v_g^2) + \varepsilon \frac{\partial P}{\partial z} + \varepsilon \rho_g g + \frac{\varepsilon \rho_g v_g^2 f_g}{r} + (1 - \varepsilon) \rho_s F_D (v_g - v_s) = 0
\]

\[
\frac{\partial}{\partial t} \left[ \varepsilon \rho_g \left( h - \frac{P}{\rho_g} + \frac{v_g^2}{2g} \right) \right] + \frac{\partial}{\partial z} \left[ \varepsilon \rho_g v_g \left( h + \frac{v_g^2}{2g} \right) \right] + \frac{\partial}{\partial z} \left( k_g \frac{\partial T_g}{\partial z} \right)
\]

\[-\frac{6}{d_p} (1 - \varepsilon) h_{sg} (T_s - T_g) + \frac{2 h_{wall} (T_g - T_{amb})}{r} + S_{rg} = 0\]

The Governing Equations for Solids Phase:

\[
\frac{\partial}{\partial t} ((1 - \varepsilon) \rho_s) + \frac{\partial}{\partial z} ((1 - \varepsilon) \rho_s v_s) = 0
\]

\[
\frac{\partial}{\partial t} ((1 - \varepsilon) \rho_s v_s) + \frac{\partial}{\partial z} ((1 - \varepsilon) \rho_s v_s^2) + (1 - \varepsilon) \rho_s g - (1 - \varepsilon) \rho_s F_D (v_g - v_s) = 0
\]

\[
(1 - \varepsilon) \rho_s c_{ps} \frac{\partial T_s}{\partial t} + (1 - \varepsilon) \rho_s c_{ps} v_s \frac{\partial T_s}{\partial z} + \frac{6}{d_p} (1 - \varepsilon) h_{sg} (T_s - T_g) + S_{rs} = 0
\]
The Governing Equations for Species Balance:

\[ V \frac{d}{dt} \left( x_i^s (1 - \varepsilon) \rho_s \right) = \dot{m}_{in\_i}^s - \dot{m}_{in\_i}^s + VM_{sw\_i}^i R_i^s \]

\[ V \frac{d}{dt} \left( x_i^g \varepsilon \rho_g \right) = \dot{m}_{in\_i}^g - \dot{m}_{out\_i}^g + VM_{gw\_i}^i R_i^g \]

with

\[ \sum_i x_i^s = 1 \quad \text{and} \quad \sum_i x_i^g = 1 \]
The dynamic simulation model has been validated by using design data and preliminary test data from the prototype facility.
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CL Prototype Process MPC Design

- MPC designed to control
  - Reactor temperatures
  - Reactor Inventories

- Test data from the simulator used to build a dynamic model for MPC

- Different cases of control simulations carried out for MPC and PID controllers and compared

\[
\min_{\Delta u} J, \quad with \quad J = \sum_{k=1}^{N_p} (\hat{y}_k - y_{s,k})^T Q (\hat{y}_k - y_{s,k}) + \sum_{k=0}^{N_c-1} \Delta u_k^T R \Delta u_k
\]

Subject to

\[
\hat{y}_{k+1} = f(y_{past}, u_{past}, u_k, \theta)
\]

\[
u_{min} \leq u_k \leq u_{max}
\]

\[
y_{min} \leq y_k \leq y_{max}
\]

\[
\Delta u_{min} \leq \Delta u_k \equiv u_k - u_{k-1} \leq \Delta u_{max}
\]
Control Simulation Results – Case 1

- Case 1: Reactor temperature setpoint changed @ t = 700
- MPC controlled the reactor temperature with less overshoot
- Dynamic model in MPC able to predict the process response and pre-act accordingly
Control Simulation Results – Case 2

- Case 1: Unmeasured step disturbance in a heat exchanger introduced between $t = 700$ and $t = 1200$
- MPC controlled the temp. with less fluctuation
- MPC able to predict responses to current control actions, utilize multiple variables and monitor MV saturation to better handle the disturbance in the process
CL Prototype Process NMPC Design

- A nonlinear MPC (NMPC) based on reduced order first principles model designed and developed

- NMPC controller being tested and tuned on the CL Prototype dynamic simulator

- Simulation results show good control performance

- Work underway to prepare for real-time application in the 3MWth CL Prototype facility
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Summary and Conclusions

• Technical approach to modeling and controls of CL pilot scale and 3MWth Prototype proved feasible

• CL 3MWth Prototype dynamic simulator developed and validated with design data

• CL 3MWth Prototype control schemes (PID and MPC) tested on the dynamic simulator

• Advanced sensors are also prepared to be installed and tested in the 3MWth CL Prototype facility
Future Work

• The CL Prototype dynamic simulator will be further refined by using operation and test data from the 3MWth CL Prototype facility

• The MPC design is planned to be installed and tested in the 3MWth CL Prototype facility

• Work on nonlinear MPC based on reduced order first principle model and empirical models will be continued

• Integrated advanced controls designs for commercial demonstration CL project
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