

MODEL PREDICTIVE CONTROL AND REAL-TIME OPTIMIZATION FOR CHEMICAL LOOPING PROCESS

Xinsheng Lou, Carl Neuschaefer, Abhinaya Joshi, Herbert Andrus, Iqbal Abdulally

*Alstom Power Inc.
200 Great Pond Drive
Windsor, CT 06095, USA*

Abstract:

Alstom Power Inc. (Alstom) is developing a breakthrough “zero emission” low cost, high efficiency technology for the global energy market. This new power plant concept is based on a process utilizing high temperature chemical and thermal looping technology. The Limestone Based Chemical Looping Combustion (LCL-CTM) technology can be configured as a next generation power plant with a controlled stream of CO₂ for use or sequestration.

Because of the complexity of the technology, Alstom is developing advanced controls and optimization solutions for the chemical looping system. An R&D project on dynamic simulation and advanced controls was executed under a DOE advanced research project co-sponsorship between 2007 and 2012. Alstom’s R&D efforts were placed on dynamic modeling and simulation analysis, facility testing of new sensors and controls, and application of Model Predictive Controls (MPC) and Real-Time Optimization (RTO) to the chemical looping process. The University of Illinois supported Alstom with its advanced controls research focused on wavelet based model complexity reduction and PDE based control design and analysis during the initial stage of the development.

A key part of this project was the development of a new computational approach to process dynamic simulations for use in the controls development. The controls development initially focused on developing an understanding of the basic transport processes and the underlying process control dynamics. The effort included characterization of the chemical looping process, building solids transport process math models, and developing offline and real-time dynamic simulation software to support control investigations. These first-of-a-kind (FOAK) dynamic simulators in conjunction with Alstom’s experimental facilities were used to explore advanced controls concepts such as Model Predictive Control for application to the chemical looping process. Most recently, Alstom’s 3MWth prototype scale LCL-CTM facility in Connecticut, was used as the reference to investigate scale-up modeling, simulation and control specification development.

This paper presents Alstom’s research and development to demonstrate concepts of MPC and RTO applications to its chemical looping process. The LCL-CTM technology background and development status is provided. Then, the technical approach to first principle modeling of a multi-loop reaction flow dynamic simulation model, including: model discretization, and software and numerical simulation development, is presented. The simulation results and numerical problems resolved during the computational studies are presented at a proper technical level. Next, the design and test results obtained on Linear MPC (LMPC) as well as simulation results on Nonlinear MPC (NMPC) are shared. Further, plant level Real-Time Optimization (RTO) is introduced using a preliminary RTO example incorporating steady-state chemical looping model. It is pointed out that advanced controls operational optimization has been established as a key enhancement for the chemical looping process based power generation plant with carbon capture for utilization and sequestration. Finally, the future plan for the development of integrated control and optimization along with Alstom’s Chemical Looping technology development for clean fossil power is outlined.

Keywords: Chemical Looping, Dynamic Modeling, Simulation, Advanced Control, Model Predictive Control, Linear Model Predictive Control, Non-Linear Model Predictive Control, Real-Time Optimization

1. Introduction

Alstom is developing Chemical Looping Processes using solid oxygen carriers to transport oxygen from air to the fuel. This technology has the capability to capture CO₂ from new and existing coal-fired power plants while maintaining high plant power generation efficiency. The power plant concept is based on a hybrid combustion-gasification process utilizing high temperature chemical and thermal looping technology to produce coal-fired steam power. Chemical looping technology can also be configured as a hybrid combustion-gasification process producing a syngas or hydrogen for various applications while also producing a separate stream of CO₂ for use or sequestration [1]. Alstom is pursuing two technical approaches: one based on limestone (CaS-CaSO₄) and the other based on metal oxides (in particular Ilmenite - FeTiO₃, but generically referred to as MeO_x). Both these oxygen carriers are natural resources that are abundantly available. The limestone-based approach has been investigated in a collaboration program between Alstom and NETL (National Energy Technology Laboratories) under the US DOE. Meanwhile, the metals-based technology has been developed under the ÉCLAIR program co-funded by the European Union (EU) - Research Funding for Coal and Steel (RFCS)[3].

Since late 1990s, Alstom has committed significant resources to develop the chemical looping technologies with parallel efforts in the US and in Europe. Today, the company continues to lead product and commercialization development of the chemical looping technology. It is committed to successful demonstrating operation and optimization of the chemical looping combustion (CLC) process in the prototype facilities and to the subsequent steps for scale-up, field demonstration and eventual commercialization of a CLC product. Significant progress has been made by the company and its partners, and the next step is to develop a small (10 to 50MWe) host site demonstration unit prior to scaling up to a 100 to 200MWe commercial unit. The company's long term vision is for an advanced supercritical cycle 600MWe+ CLC boiler and steam power plant for the utility market. As an integral part of the chemical looping technology development efforts, Model Predictive Controls (MPC) and Real-Time Optimization (RTO) will be designed and tested to enhance the performance of the commercial scale chemical looping based power plants for low cost CCUS (Carbon Capture, Utilization and Storage). This investigation on advanced control and optimization of chemical looping is an ongoing effort, which is actively co-funded by Alstom and the US DOE.

The limestone chemical looping process development has progressed through four phases. The most recent Phase IVA, executed between 2008 and 2012, included designing, modifying and testing a 3MWth prototype (See Figure 1) of the Chemical Looping process that integrates all of the equipment and systems required to operate. This 3MWth prototype located at Alstom's Power Plant Laboratories in Connecticut, USA, is the first chemical looping unit in the world to achieve auto-thermal chemical looping operation in June 2011. And it has since totaled over 375 hours of operation with 75 hours of auto-thermal operation ending in October 2013 under the current 3 year project co-founded by DOE's Advanced Oxy-Combustion Program that commenced on 1st October 2013.

Due to environmental dispatch requirements and integration of more and more renewable units onto the Grid system, the power generation market will become more competitive and units will be required to provide higher megawatt flexibility. As such, there is a significant demand to economically optimize the thermal and emission performance of the power generating units, improve load-changing flexibility, improve reliability and availability through robust controls, and to reduce the overall plant operating cost. In order to investigate and identify the potentials for optimizing the overall performance and reliability of the chemical looping process by integrating the application of advanced controls, the company launched a project involving dynamic simulation, sensing and advanced control design with co-sponsorship from DOE NETL's Advanced Research Program in 2007.

It was expected that adoption and integration of advanced controls in the early stages of process development would help to address the inherent process control and operating challenges associated with a complex interacting multi-loop chemical looping process. Please refer to Figure 2 for the research and technology development flow chart as was first developed by the company in 2007. This technology map was used to guide the research and development efforts in this collaborative R&D program that involved Alstom, University of Illinois and Taft Engineering Inc.

This dynamic modeling, simulation, and advanced sensing and controls project ran in parallel to the chemical looping process development. In the first project execution period of the chemical looping controls project (i.e. 2007-2009), research was focused on solids transport dynamic modeling and simulation studies as well as advanced controls development using the simulation models and the cold flow test facilities [4][5][6]. In the extended project execution period of the controls project (2010-2012), dynamic simulation, sensing and advanced controls tasks were extended to the 3MWth chemical looping prototype process [7].

The Phase I and the Phase I Extension of the project on chemical looping dynamic simulation and advanced controls have been completed. The Phase I Extension period was created in order to enable a smooth transition from the Phase I (simulation and controls of the pilot lab-scale process) project to the next phase of technology development (scale-up CL prototype process - 3MWth in Windsor, CT, USA). In the Phase I project execution, several first-principles dynamic-process-model-based simulators were developed for dynamic analysis and control study purposes [4]. Based on the simulations, real time simulation kernels were generated. Different control strategies including benchmark PID, linear model predictive control (MPC), nonlinear MPC (NMPC) and so on were developed and tested on the simulators to investigate control of the solids transport process. Some promising control algorithms were further physically implemented on the pilot-scale test facilities. Based on the simulation model, a preliminary framework was developed for testing the method for designing Real-Time Optimization (RTO) applications. Advanced sensor systems were developed and tested in Windsor, Connecticut, to support the chemical looping advanced control technology development.

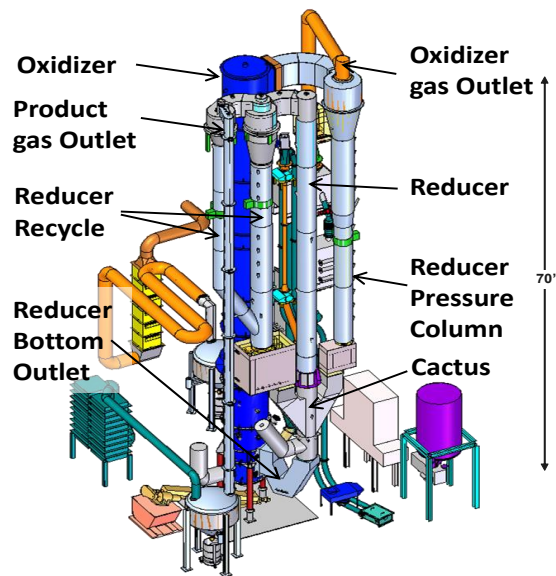


Figure 1 Isometric View of 3MWth LCL-C™ Prototype

Technical Flow Chart for Chemical Looping System Simulation and Controls

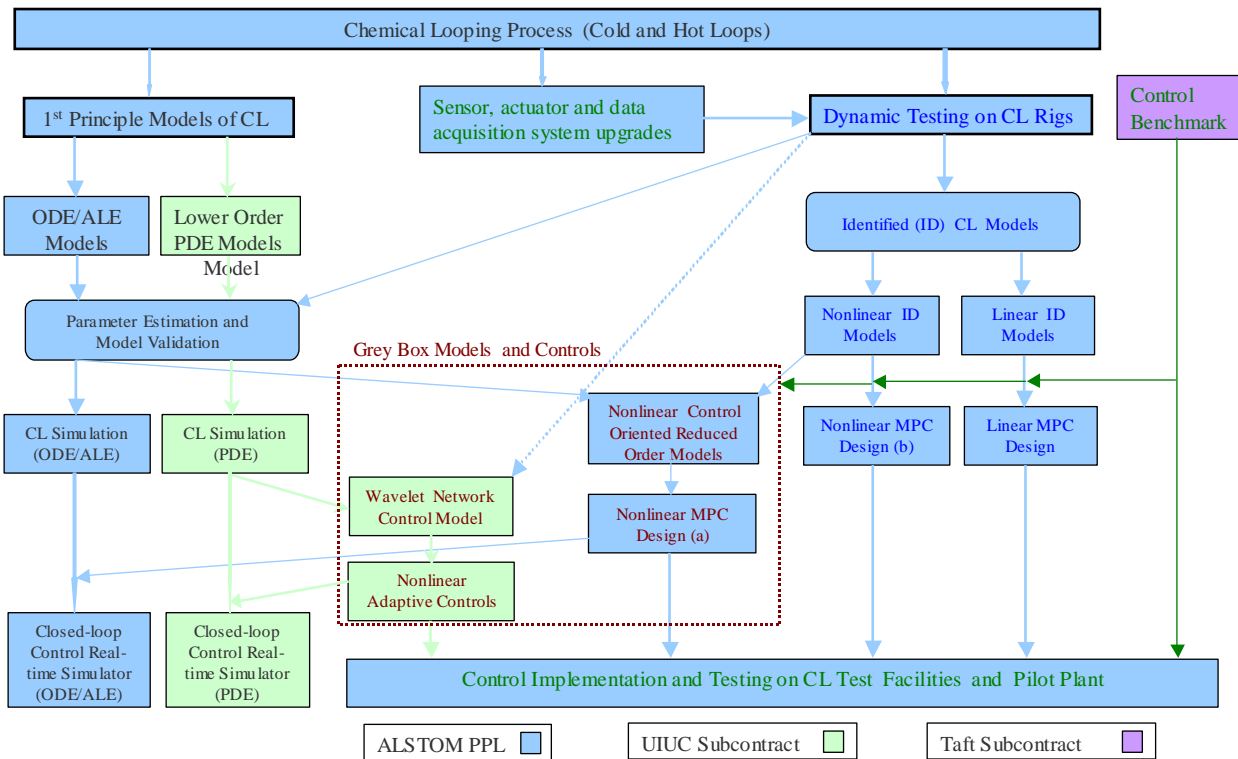


Figure 2 Research and Technology Development Flow Chart

Two subcontract projects were defined in the first project execution of the simulation and controls tasks. Taft Engineering Inc. was asked to conduct a survey on the current status of dynamic operations and controls for typical types of thermal power plants to help establish a benchmark for CL controls and other future clean power generation plants with carbon capture. The University of Illinois at Urbana-Champaign (UIUC) participated in the first project execution period (2007-2009) as a subcontractor to Alstom. UIUC was focusing on investigating more theoretical future control approaches including: (a) complexity reduction of the PDE's (Partial Differential Equations) models for the single loop solids transport process using multi-resolution wavelet approximation; and (b) advanced controls using the reduced order PDE models. The university continues on this work, and has produced results on multi-resolution wavelet network model based predictive controls [8][9].

2. Dynamic Modeling and Simulation of Prototype Chemical Looping Process

In modern systems and controls engineering, dynamic simulation is a critical tool in the early stage of advanced process and controls technology development. In the DOE/Alstom CLC Advanced Controls project, a significant amount of the efforts have been spent on the development of the first principle mathematical dynamic models for the chemical looping processes, investigating model order reduction using appropriate technical approaches, performing model validation using test data collected from the CLC process facilities, and developing and deploying real-time simulation platform for control work.

The overall main chemical looping process takes place in two steps and keeps the air away from the fuel in two separate reactors with the help of oxygen carriers [2]. As stated before, there are two kinds of oxygen carriers under investigation at Alstom (see Figure 3). One is calcium based and the other is metal-oxide based. Without loss of generality, the models presented in this paper are derived by using calcium-based process.

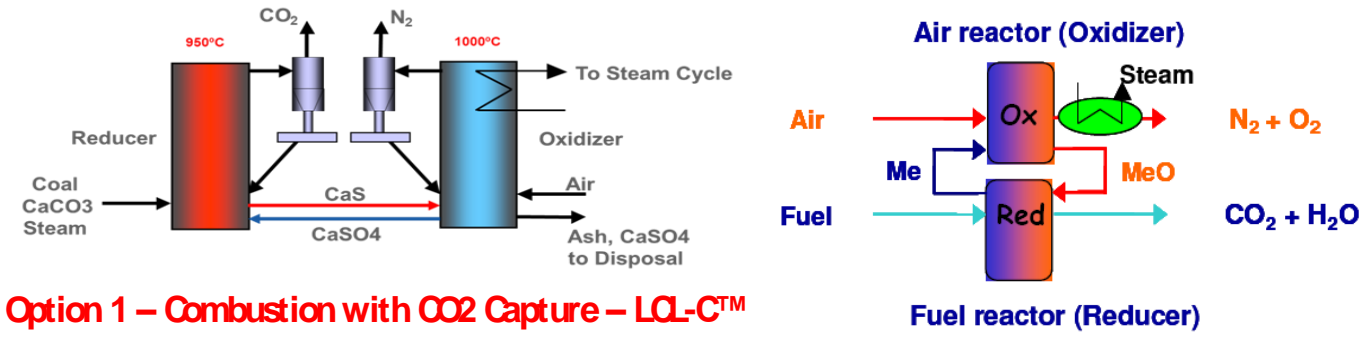


Figure 3. Calcium Based (Left) and Metal Based (Right) Chemical Looping Processes

In order to have successive chemical reactions in the chemical looping system, it is very important to maintain a continuous circulation of the solids in the loops at a certain desired rate. Therefore, how to regulate and maintain a stable solids mass flow in the chemical looping process is one of the major tasks to operate the process. In Phase I and the Extension project, the process simulation focused on studying the dynamic responses of the solids transport between loops under different operation conditions.

To build a mathematical model and subsequent dynamic simulation for a process system like chemical looping, it is necessary to define boundaries, inputs and outputs. The model is built up from the cause-effect relationships between inputs and outputs at certain boundary conditions. For the chemical looping process, the inputs are the operational parameters, e.g., input gas and solids flows, design parameters such as the reactor geometry and other physical properties. The process model outputs are thermal, mechanical and reaction performance parameters, such as the change of temperatures, solids mass flow, pressure and chemical composition in the system.

The governing equations in the current one-dimensional approach for the gas-solids flow are described as follows:

Gas phase:

$$\begin{aligned} \frac{\partial}{\partial t}(\varepsilon \rho_g) + \frac{\partial}{\partial z}(\varepsilon \rho_g v_g) &= 0 \\ \frac{\partial}{\partial t}(\varepsilon \rho_g v_g) + \frac{\partial}{\partial z}(\varepsilon \rho_g v_g^2) + \varepsilon \frac{\partial P}{\partial z} + \varepsilon \rho_g g + \frac{\varepsilon \rho_g v_g^2 f_{gF}}{r} + (1-\varepsilon) \rho_s F_D (v_g - v_s) &= 0 \\ \frac{\partial}{\partial t} \left[\varepsilon \rho_g \left(h - \frac{P}{\rho_g} + \frac{v_g^2}{2g} \right) \right] + \frac{\partial}{\partial z} (\varepsilon \rho_g v_g \left(h + \frac{v_g^2}{2g} \right)) + \frac{\partial}{\partial z} \left(k_g \frac{\partial T_g}{\partial z} \right) \\ - \frac{6}{d_p} (1-\varepsilon) h_{sg} (T_s - T_g) + \frac{2h_{wall} (T_g - T_{amb})}{r} + S_{rg} &= 0 \end{aligned}$$

Solids phase:

$$\begin{aligned} \frac{\partial}{\partial t}((1-\varepsilon) \rho_s) + \frac{\partial}{\partial z}((1-\varepsilon) \rho_s v_s) &= 0 \\ \frac{\partial}{\partial t}((1-\varepsilon) \rho_s v_s) + \frac{\partial}{\partial z}((1-\varepsilon) \rho_s v_s^2) + (1-\varepsilon) \rho_s g - (1-\varepsilon) \rho_s F_D (v_g - v_s) &= 0 \\ (1-\varepsilon) \rho_s c_{ps} \frac{\partial T_s}{\partial t} + (1-\varepsilon) \rho_s c_{ps} v_s \frac{\partial T_s}{\partial z} + \frac{6}{d_p} (1-\varepsilon) h_{sg} (T_s - T_g) + S_{rs} &= 0 \end{aligned}$$

where ε is the void fraction of gas, ρ is the density, v is the velocity, P is the pressure, h is the enthalpy, T is the temperature, S_r is the external heat source, r is the radius of the pipe, d_p is the diameter of the solids particle, c_p is the specific heat, and $g, f_{gF}, F_D, k_g, h_{wall}, h_{sg}$ are different physical coefficients in the system. The subscripts g and s stand for gas and solids phases, respectively.

A general species balance model used in the current model for gas and solids can be written as follows:

$$\begin{aligned} V \frac{d}{dt} (x_i^g \varepsilon \rho_g) &= \dot{m}_{in_i}^g - \dot{m}_{out_i}^g + VM_{gw}^i R_i^g \\ V \frac{d}{dt} (x_i^s (1-\varepsilon) \rho_s) &= \dot{m}_{in_i}^s - \dot{m}_{out_i}^s + VM_{sw}^i R_i^s \end{aligned}$$

with

$$\sum_i x_i^g = 1$$

$$\sum_i x_i^s = 1$$

where V is the volume of the system, x_i is the mass fraction of species i (gas or solids), ε is the void fraction of gas, ρ is the density of gas or solids, \dot{m}_{in_i} is the mass flow rate into the system, \dot{m}_{out_i} is the mass flow rate out of the system, and R_i is the net rate of production per unit volume of species i by chemical reaction.

To simulate the dynamic process using derived mathematical CLC process models, it is necessary to solve the aforementioned time dependent PDE's. Many numerical techniques have been developed in the literature to solve PDE's. One of the most widely popular numerical technique is the finite difference method. The finite difference method can be applied to elliptic or parabolic PDE's and generate linear or nonlinear algebraic equations. The aim of this method is to replace the derivatives in the governing equations by finite difference approximations. However, the finite difference methods may generate high order equations due to fine mesh and is not suitable for on-line control design. The numerical method of lines is a better alternative method to solve PDE's, which is similar to the finite difference method. Unlike the finite difference method, the numerical method of lines does not discretize the time variable. As a result, it produces a set of ordinary differential equations (ODE's), which can be easily solved by using some standard commercial solver packages. Hence, the numerical method of lines is the method of choice going forward in simulator development for real-time controls.

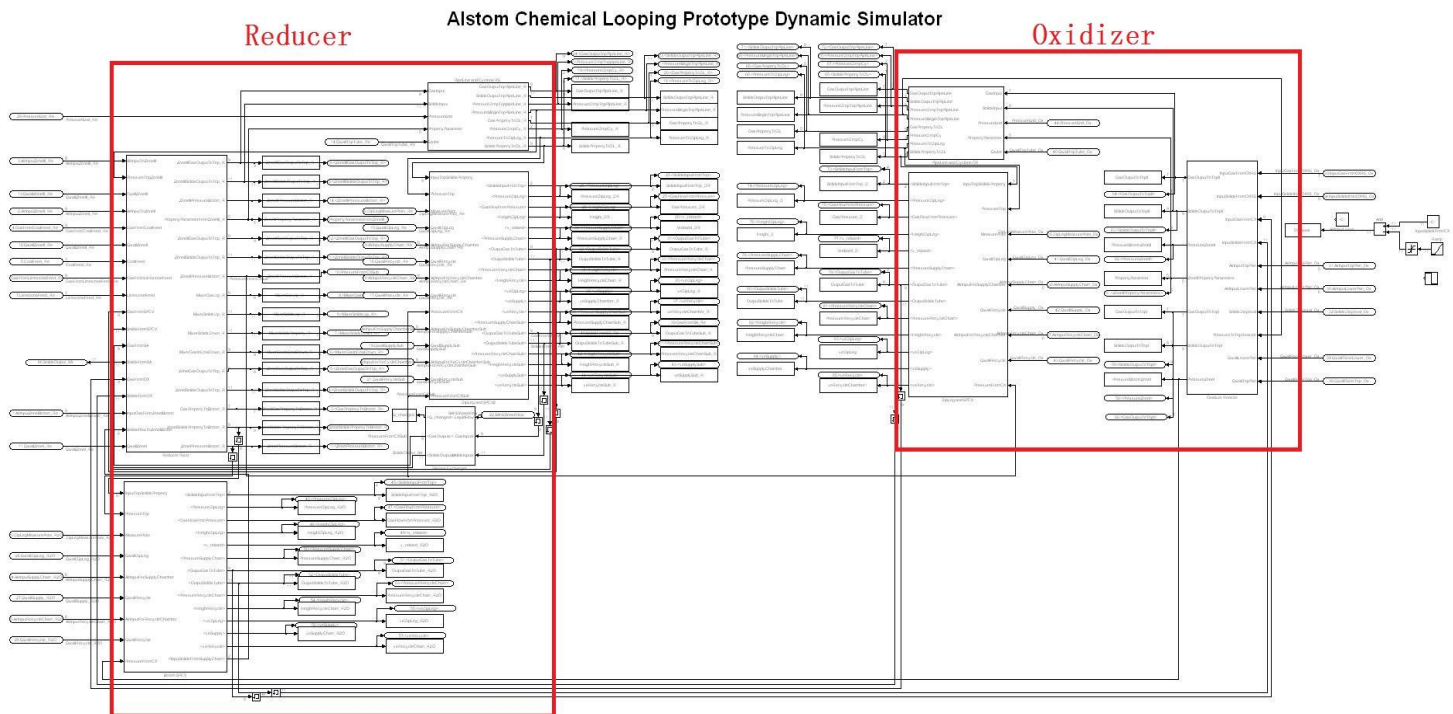


Figure 4. Alstom's Dynamic Offline Simulator for Prototype Chemical Looping Process

A flow sheet from the offline simulator for the 3MWth dual loop prototype chemical looping process in MATLAB/Simulink is shown in Figure 4. This dynamic simulator can be used to simulate and study the chemical looping reaction kinetics and the solids transport dynamics between two loops under changes of temperatures. Different control scenarios related to temperatures, e.g., how to maintain the solids mass flow rate and the solids residence time in the reactors under the change of temperatures and how to regulate the reactor temperatures, etc., can be investigated in this simulator. Before the mathematic models were applied to the 3MWth process simulation, they had been validated against the test data from: (a) the 15ft dual loop solids transport test facility; (b) Process Development Unit (PDU) of the same scale with thermal capacity of 65kWth. Both of these pilot scale test facilities are located in Connecticut.

The company has completed construction, shakedown and initial testing of the prototype chemical looping test facility. A series of tests have been conducted on the 3MWth prototype test facility totaling 375 hours of operation with 75 hours of auto-thermal operation. Design data and facility operation data to date were used to estimate model parameters, validate the model and support the

simulation work. A real-time simulator has been developed by compiling the MATLAB/Simulink model into real-time Dynamic-Link Library (DLL) target to support the controls development and evaluation.

3. Model Predictive Control

3.1 Model Predictive Control Design

MPC is a model-based, advanced multivariable optimal control algorithm that uses an internal dynamic model (linear or nonlinear) of the process and an optimization routine to calculate a set of optimum control moves. A structural block diagram of a MPC is depicted in Figure 5.

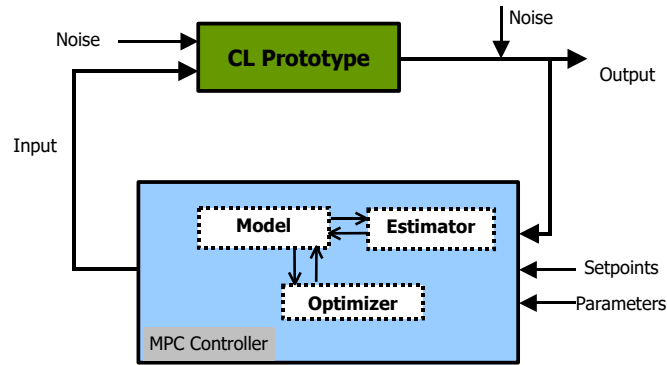


Figure 5. A Supervisory MPC Input-Output Structure for CL Prototype

Compared with conventional model free control algorithms, the integration of an internal dynamic model in the control design enables MPC more intelligent control capabilities. For example, MPC can coordinate the interactions in the multi-input-multi-output (MIMO) case and deal with different features of the process dynamics. Moreover, because of the prediction capability of the process models, MPC can tackle the effects of feedforward and feedback disturbances, and provide more accurate control actions. The most distinguished feature of MPC is that it can handle process input, state, and output constraints explicitly in each control calculation cycle; as a result it is capable of driving a process to optimal constrained condition without violating them.

In general, MPC problem is formulated to solve an on-line finite horizon open-loop optimal control problem subject to system dynamics and other constraints involving inputs and outputs. The optimization problem in MPC is given by

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

subject to

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

$$u_{\min} \leq u_k \leq u_{\max},$$

$$\Delta u_{\min} \leq \Delta u_k \equiv u_k - u_{k-1} \leq \Delta u_{\max},$$

$$y_{\min} \leq y_k \leq y_{\max},$$

where \hat{y} is predicted output vector; y_s is output setpoint vector; u is input vector; Δu is input move vector; N_p and N_c (with $N_c \leq N_p$) are prediction and control horizons; $Q (>0)$ and $R (\geq 0)$ are symmetric weighting matrices; and $\hat{y}_{k+1} = f(\cdot)$ is the process (prototype) model with a set of model parameters θ .

An appropriate model structure for the CLC MPC has been defined based on process control objectives and a MPC controller has been designed for the chemical looping prototype process. The MPC uses a linear dynamic prediction model consisting of three inputs (Manipulated Variables or MV's) and four outputs (two Controlled Variables or CV's and two constraints). The main objective of this MPC is to maintain reactor temperatures and other key state variables in the system at their setpoints or within a narrow range to enable and maintain stable operation during steady state, and to drive these controlled variables to closely follow a given trajectory during load change conditions. System pressures are maintained at fixed setpoints by using PID controllers for all control simulation cases presented in this paper. The MPC control simulation modeled in Simulink is shown in Figure 6. An NMPC was also developed by using a nonlinear process model developed based on a reduced order first principles approach.. The input-output structure for the NMPC design is identical to the linear MPC design.

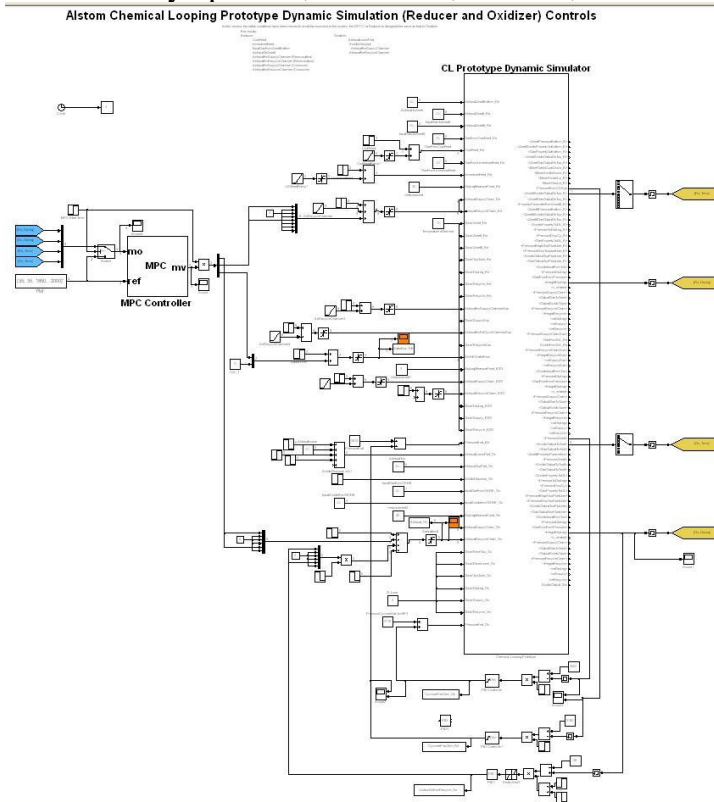


Figure 6. MPC Control Simulation for the CLC Prototype in MATLAB/SIMULINK

In the UIUC portion of the project, the model based control designs were extended to the use a) linearized PDE and b) multi-resolution wavelet network based dynamic model. In 2007-2009, the preliminary model based control algorithms were implemented and tested on the company's test facility to prove the feasibility of the newly derived control design methodology. In 2010-2013, this scientific part of the controls research continued with the university's focus on the theoretical aspects on (a) PDE model order reduction, and (b) wavelet model based predictive control designs (with optimization constraints applied or relaxed)[8][9].

3.2 Summary of MPC Simulation Results

Linear MPC, multi-model linear MPC and nonlinear MPC were all tested on the 15ft scale chemical looping dynamic simulator. Two types of nonlinear MPC were designed and implemented for simulation testing: a) Reduced Order Model based nonlinear MPC design; b) Neural network nonlinear MPC design. In both cases, the nonlinear controllers were tuned to achieve stable control performance and their control performance data were recorded for further analysis[4][5][6].

The MPC was also tested on the 3MWth CLC prototype simulator under two direct control case scenarios [7]. Comparative analysis of simulation results between MPC and PID controllers were conducted. For both test case scenarios, all the simulations are started with PID controllers. For a PID response test, the simulation is continued, however, for MPC response test, MPC takes over control from selected relevant PIDs

It was concluded from the simulation case studies that MPC is able to maintain the controlled variables close to their setpoints and satisfy all the constraints. It can also be seen that MPC is able to carry out setpoint changes with much less overshoot and with a faster settling time compared to PID control. Analysis revealed that the better results from MPC are because of two reasons. First, because of its prediction capability, MPC can 'foresee' future effects of current MV changes and therefore, move MV's accordingly. Second, because it is a multivariable controller, it can use multiple MV's to better control the CV's. Further simulation case studies with disturbances suggested that MPC has its advantages in deploying multiple Manipulated Variables, for example, its awareness of MV saturation before that actually happens and its ability to understand the future effects of the current control moves [7].

An NMPC based on a reduced order model was also tested using the CLC prototype simulator for different control scenarios. A control simulation result for NMPC is shown in Figure 7, which shows good control performance on the controlled variables. The NMPC design and control test results so far have been going well. The NMPC work will be continued and test implemented in real-time simulation and in the prototype facility in the next phase work.

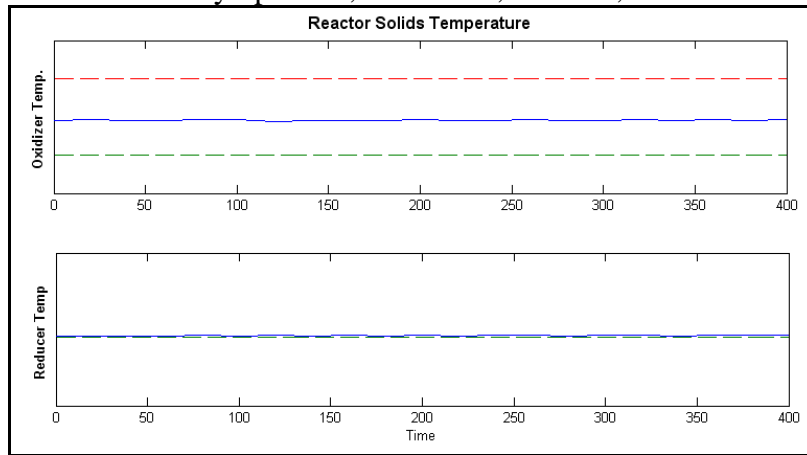


Figure 7. NMPC Simulation – Reactor Temperatures Controls for CLC Prototype Model

3.3 Facility Testing of Model Predictive Controls (MPC)

3.3.1 Implementing MPC On Dual Loop Facility

The MPC testing was conducted on the 15ft dual loop solids transport facility as shown in Figure 8 [4].

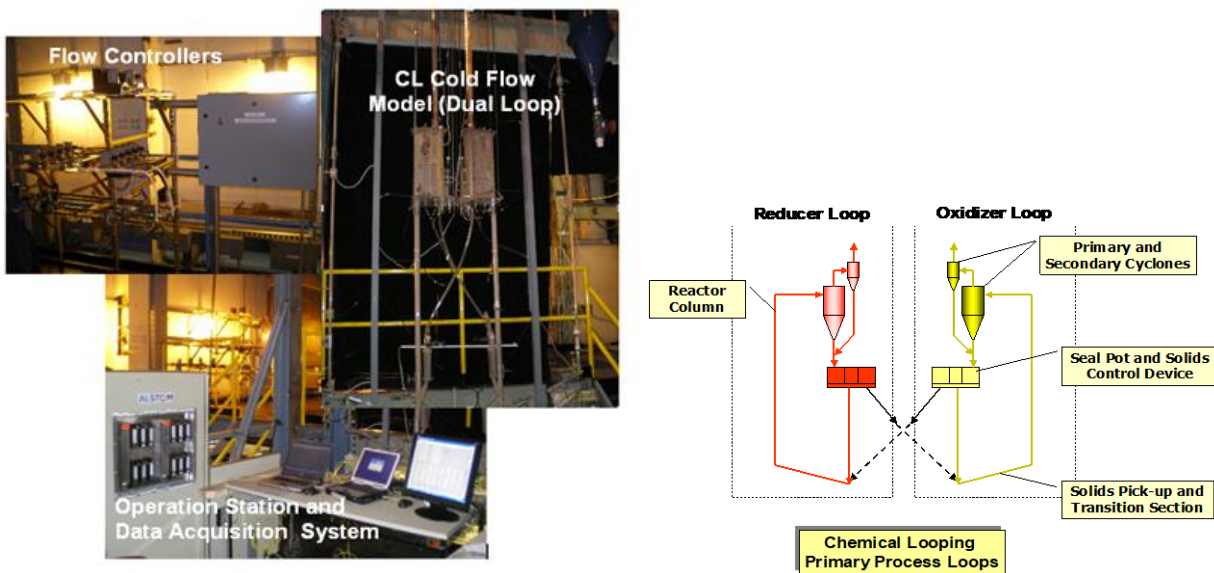


Figure 8. Chemical Looping Cold Flow Test Facility for Solids Transport Control Investigations

Building on previous controls designs that were already tested on the dynamic simulator, linear model based MPC controllers were developed for the CLC cold flow single and dual loop test facilities and were embedded to the LabVIEW facility data acquisition (DAQ) program module. The MPC designed for the control of CLC 15-foot facility was developed as a dynamic optimization problem incorporating a quadratic cost function in MATLAB and interfaced with LabVIEW by using its MATLAB script node. The optimization problem in the MPC was solved by using MATLAB Optimization Toolbox.

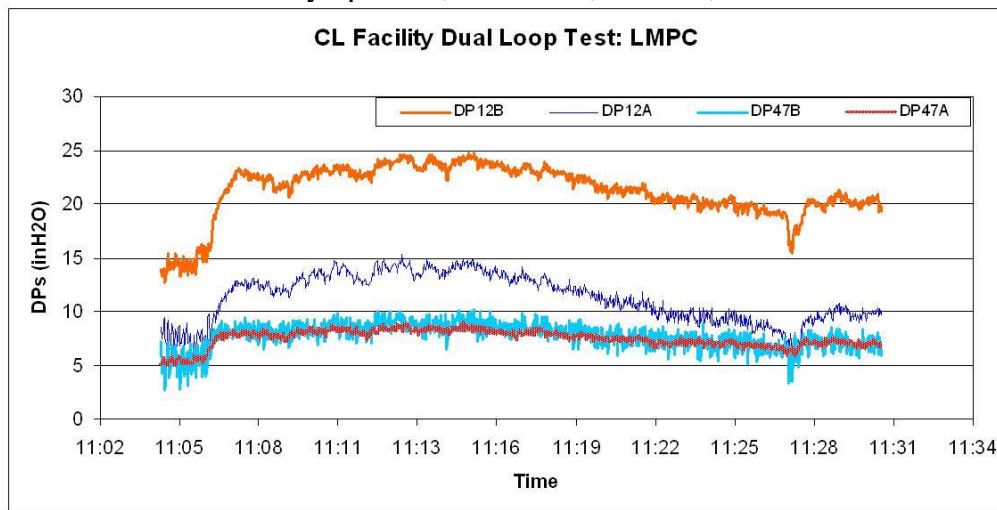


Figure 9 MPC Test Result from CL 15-foot Cold Flow Dual Loop Facility

The dynamic linear models in the MPC controllers for single and dual loops were identified based on the facility test data. The prediction and control horizons were 10s and 1s, respectively. In the single loop case, the controller was able to drive the CV to its changing setpoints reasonably well. In the dual loop case, the test was carried out with solids flow only through crossover but not through the main loops, which went well in terms of maintaining stabilized cross-over solids flows between the two loops. The test result for the dual loop is plotted in Figure 9.

3.3.2 Implementing Control Designs from University Research

Two advanced control designs by the UIUC research group were tested on this 15ft test facility in Windsor, Connecticut. As this was aimed to test the feasibility of the new algorithm, the focus was placed on the controls of the single loop solids flows. The first control algorithm was a linearized PDE model based controller; the second control algorithm was a wavelet model based controller. Both controllers were tuned to control the single loop solids transport flows circulation in the flow network for long enough time while unmeasured disturbances were observed during the control experiments.

3.3.3 Implementing Industrial MPC on Dual Loop Test Facility

DMCplus (or simply DMC) is a commercial model predictive control software package from AspenTech Inc. A DMC controller was designed for the Alstom CLC 15-foot cold flow solids transport facility as a supervisory controller on top of the regulatory PID controllers. The DMC controller was designed to compute optimal setpoints for the PID's. The controller was successfully tested on the facility to control the key pressure variables and maintain the system flow stability.

The results for this test case have been reported to DOE NETL. In this test, the dual loop process was well controlled with continuous crossover solids flows for extended period of time under the control of MPC and PID. Compared with the sole PID controls of the dual loop process, this MPC/PID design demonstrated salient control advantages with multivariable tuning flexibility to achieve different control goals. With continuous crossover solids flows, the values of the two differential pressures for the diplegs were maintained in reasonable ranges. This proved that MPC is capable of changing the setpoints for the key variables within desired operating ranges. This control test showed that the MPC was able to balance the solids transport in two loops by controlling crossover differential pressures (DP's) within the desired operating ranges.

Later, the same MPC test results were reproduced with another model predictive controller, which uses the standard MPC design for today featured by SQP solver for solving constrained optimization problems on-line.

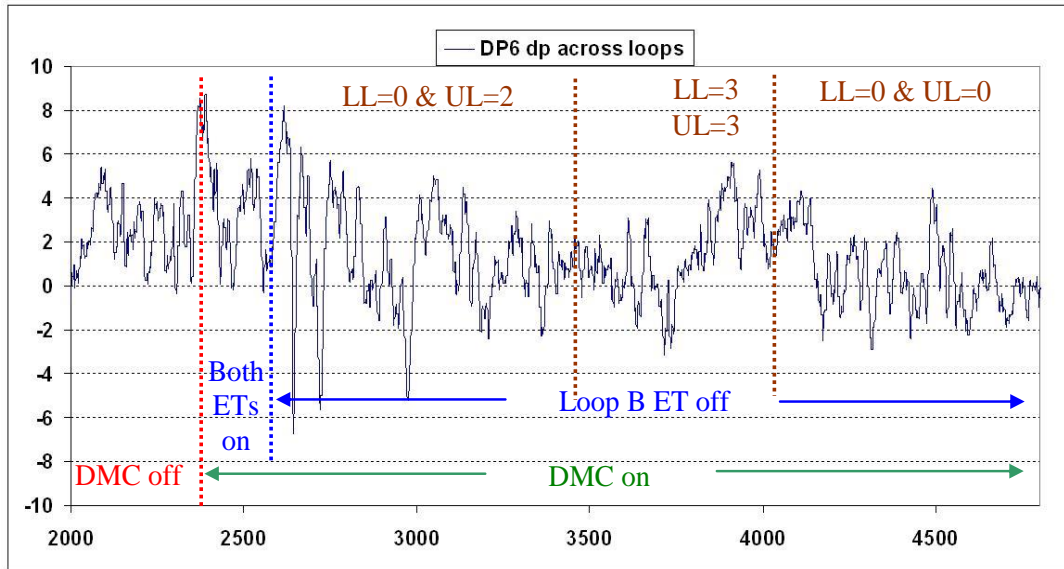


Figure 10 DMC Testing Results from CLC 15-foot Cold Flow Dual Loop Facility

3.4 Control Test on 3MWth CLC Test Facility

The 3MWth CLC test facility is equipped with a set of DCS control system. All the basic PID control loops have been coded into the DCS to support the operation and controls of the process test facility. An OPC server has been added to the DCS as the interface with the MPC controller to be implemented and tested. The MPC testing work will be conducted along with future facility testing programs to be co-sponsored by US DOE.

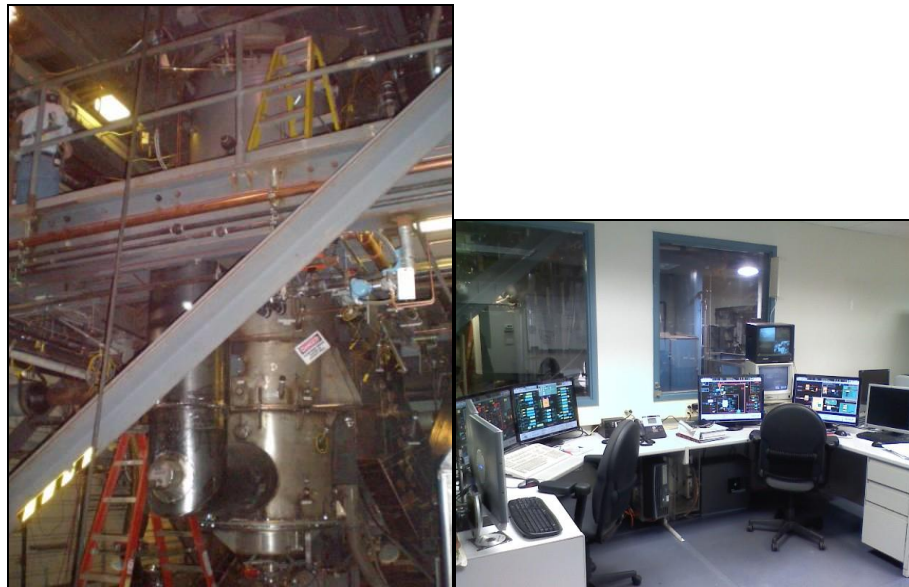


Figure 11 Chemical Looping Prototype Facility and DCS Control Room

5. Real-Time Optimization (RTO)

Nowadays, a standard automation hierarchical structure provides a systematic way to integrate the multiple tasks in plant controls and operation. In this hierarchy, an upper optimization layer called RTO focuses on the economic objectives, while the lower layer called Advanced Process Control (APC, typically MPC is used), deals with controls performance optimization. The objective of the RTO is to optimize the plant operation based on an economic performance measure under changing production schedule, power price, prices

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of fuel and sorbent, emission credits availability and trading mechanisms, etc. It holistically calculates setpoints and sends to the advanced process control layer to implement the optimal operation strategy.

As a promising technology for the next generation power plant, achieving the cheapest operation cost under a strict environment regulation is one of the objectives for the chemical looping process. Therefore, the implementation of hierarchical control structure with RTO and advanced control layers is necessary for control system design of chemical looping process.

An exploratory study of RTO for a Chemical Looping Plant was conducted with following objectives:

- Understanding the general procedure of dealing with the real time optimization problem for prototype chemical looping process;
- Identifying the optimization opportunities and problems to solve;
- Proposing future research directions.

Figure 12 depicts a technological vision of the control system for this chemical looping based clean power generation plant with carbon capture, utilization and sequestration as a next generation power plant solution.

Although RTO is not limited only to steady-state optimization, a typical RTO system calculates the most profitable operating points under steady state plant operations with a given set of conditions (e.g. unit load demand, fuel and limestone costs, ambient factors, etc.). In this exploratory RTO study, the focus is to develop and evaluate a conceptual RTO design for steady state economic performance optimization for the 3MWth Chemical Looping process.

As such, building on the past experiences and ongoing effort in developing a dynamic simulation model for the CLC prototype, a steady-state model for RTO construction has been developed by using mass, energy and species balance equations. The unknown parameters in the RTO model are estimated based on the process design data for the CLC prototype at the full load condition. The estimation results indicate that the steady state model prediction matches the design data at the full load condition with reasonable accuracy for the RTO feasibility study.

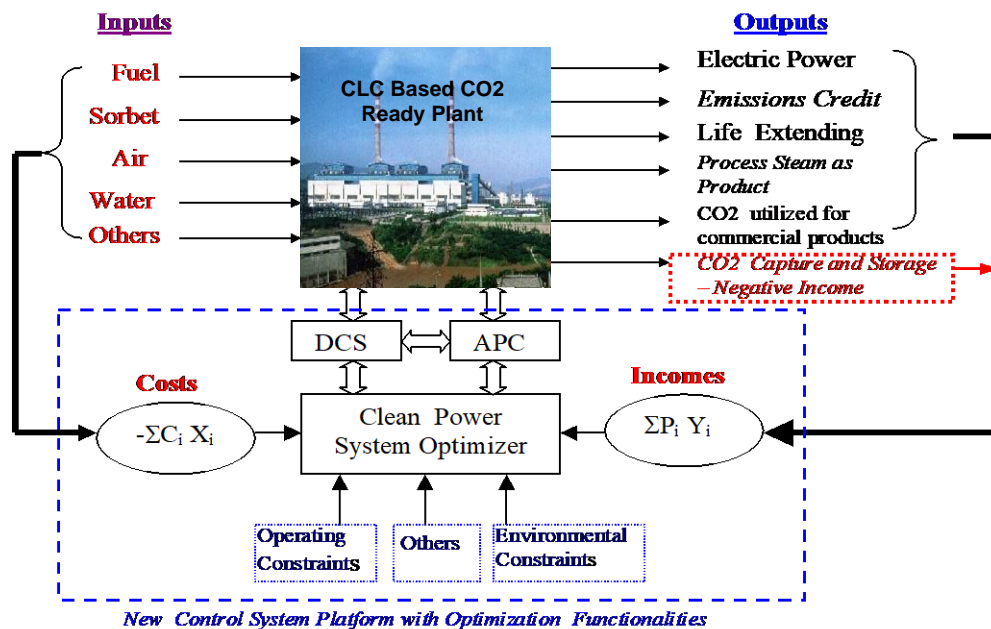


Figure 12 Schematic for Real-Time Optimization of CLC Based Power Plant

A typical RTO calculates the most profitable points to run the plant under steady state operations with a given set of conditions (e.g. unit load demand, fuel and limestone costs, ambient factors, etc.) and constraints, e.g., zero emissions, nevertheless, RTO is not necessarily limited to steady-state optimization only. The objective function in RTO is based entirely on operating profit, which is the sum of all product values minus the sum of all operation and maintenance costs. These costs could include both short term costs and life time costs on the long time horizon, which can be summarized as:

$$\text{Maximize (Total Profit = Total Income - Total Cost)}$$

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In the CLC plant as a CO₂ ready power plant, the cost/value of providing pure CO₂ for sequestration and use will have a big impact on the overall economic performance of the power plant with Carbon Capture, Utilization and Sequestration (CCUS) capability. Therefore, it should be integrated into the cost function for optimization.

In this RTO study, in order to simplify the situation at this stage, only the cost of the raw materials and the cost of CO₂ are considered. Therefore, the objective function used in this RTO case study can be simplified as follows:

$$\text{Minimize } (J = \text{Fuel Cost} + \text{Limestone Cost} + \text{CO}_2 \text{ Tax or Sequestration Cost})$$

A couple of optimization cases were simulated and the feasibility of RTO design was considered proved, which has been included in the technical report issued to the DOE NETL.

6. Conclusions and Future Work

The paper summarizes Alstom's advanced controls technology developments on chemical looping. The paper highlighted the activities in dynamic simulation and advanced controls for the past 5-6 years, evolving from pilot scale to 3MWth prototype scale test support. In this project, several first-principles based dynamic simulators for LCL-CTM pilot and prototype facilities have been developed for different purposes. MPC and PID based CLC control strategies were designed and tested on the dynamic simulators and also on physical test facilities in Connecticut. This paper focused on preliminary modeling, simulation and control designs for the LCL-CTM process. This approach can be conveniently adapted to the metal oxide (MeOx) or other oxygen carrier solids chemical looping process.

An extensive effort went into developing an integrated multi-loop simulation model for the prototype chemical looping process based on first principles incorporating solids transport, energy balance and reaction kinetics. The dynamic models and simulation tools proved invaluable during the program both in terms of providing process dynamics insight as well as in supporting the development and evaluation of various control schemes. The technical approach to first principle modeling of a multi-loop reaction flow model, model discretization and software and numerical simulation development were presented. The simulation results and numerical problems resolved during the computational studies are presented at a proper technical level.

MPC and PID based control designs were evaluated for multiple control scenarios using the dynamic simulation programs that have been configured to match the company's chemical looping pilot facility as well as the 3MWth prototype facility. The test results obtained so far clearly indicated that MPC has capabilities to compensate for disturbances, manage different manipulated variables by optimizing a multivariable control objective, and dealing with multiple operating constraints explicitly during control optimization. Comparative analysis of simulation results showed a number of advantages MPC can offer over the conventional PID designs for the chemical looping process, either as a direct controller or as a supervisory controller. For example, MPC can: (a) simultaneously manage the multiple process variables (temperatures, pressures, etc.) associated with the interacting loops of the CLC process, (b) predict dynamic process changes due to control actions and/or measured disturbances, (c) anticipate future constraint violations and make pre-emptive adjustments to maintain certain state variables within their constraint limits, and (d) drive certain state variables very close to but within economically optimal operating limits. The economic limits provided to the MPC are generated based on process designs, operating experience and/or a higher-level economic optimization. Besides, the model-based approach can support state estimation or soft sensing for control purposes. These MPC control advantages can be essential for stable, reliable and efficient operation of the multi-loop, multimode chemical looping processes.

A concept design of CLC RTO was briefly introduced. The next phases of the chemical looping control project are aimed at further developing an industrial quality control design that involves advanced sensors, advanced controls, and RTO solutions at the 3MWth CLC process prototype scale. Control designs are planned to be implemented and tested on the 3MWth prototype chemical looping test facility during hot-reactive auto-thermal operation and testing. To achieve the project goals, it is desired that the prototype model and simulator will be further refined using the latest operational and test data from the prototype test facility. In the future, continuations of reduced order modeling (ROM) will still be a major work-topic to support the development of real-time simulation, nonlinear model based state estimation, and nonlinear model predictive controls. The company's long term vision is for an advanced supercritical cycle 600MWe+ CLC boiler and steam plant with CCUS for the utility market with the latest optimizing controls. Application of all of these linear and non-linear advanced control schemes, with in-built multivariable process models and real-time optimizing control algorithms, to the next generation near zero-emission fossil power technologies are expected to enhance the CLC integrated plant performance and reliability.

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For Presentation at ISA POWID 2014 Symposium, Scottsdale, Arizona, USA

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