Dynamic Power Plant Modeling for Flexible Operations

Stephen E. Zitney, NETL
Elijah Hedrick, WVU
Katherine Reynolds, WVU
Vinayak Dwivedy, WVU
Debangsu Bhattacharyya, WVU

2021 Crosscutting Research and Advanced Energy Systems Project Review Meeting

Artificial Intelligence & Machine Learning Session

Co-sponsored by Transformative Power Generation and Crosscutting Research Sensors & Controls Programs

May 13, 2021

Motivation

Flexible Plant Operations

- **Thermal power plants** are **required to operate more flexibly** as renewable penetration increases
- Conventional plants were originally designed to operate at full load and **do not perform optimally during load-following**
  - **Decreased efficiency** (increased heat rate)
  - **Leads to poor control**
  - **Increased environmental emissions** (e.g., CO_2, NO_x)
  - **Increased equipment damage and O&M costs**

R&D Objectives and Technical Approach

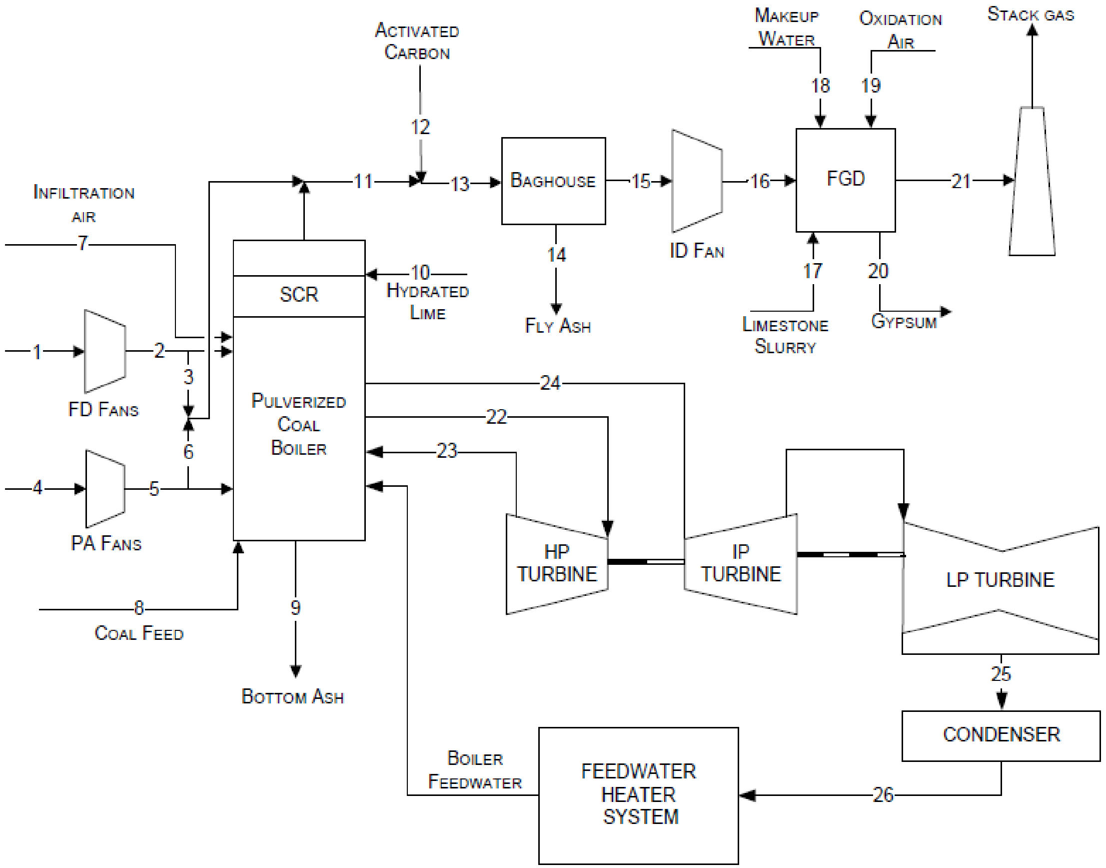
- **R&D Objectives**
  - Improve plant **performance** and **reliability** under **flexible operations**
- **Technical Approach**
  - Develop and **validate** high-fidelity **dynamic power plant models**
  - Develop plant-wide regulatory and supervisory **controls** and augment with **reinforcement learning**
  - Quantitatively assess flexible **operation and control approaches**
  - Develop **creep and fatigue damage models** for key equipment items
  - Assess and mitigate negative impacts of flexible operations on **plant health**

Presentation Overview

- **Dynamic Power Plant Modeling**
  - Process, Control, and Health
- **Model Validation under Load-Following Operation**
- **Reinforcement Learning-Augmented Control Results**
  - Main steam temperature control
  - NOx control in SCR unit
- **Boiler Health Modeling Results**
- **Concluding Remarks and Future Work**

Dynamic Power Plant Modeling

Overview



Plant Configuration – Major Equipment

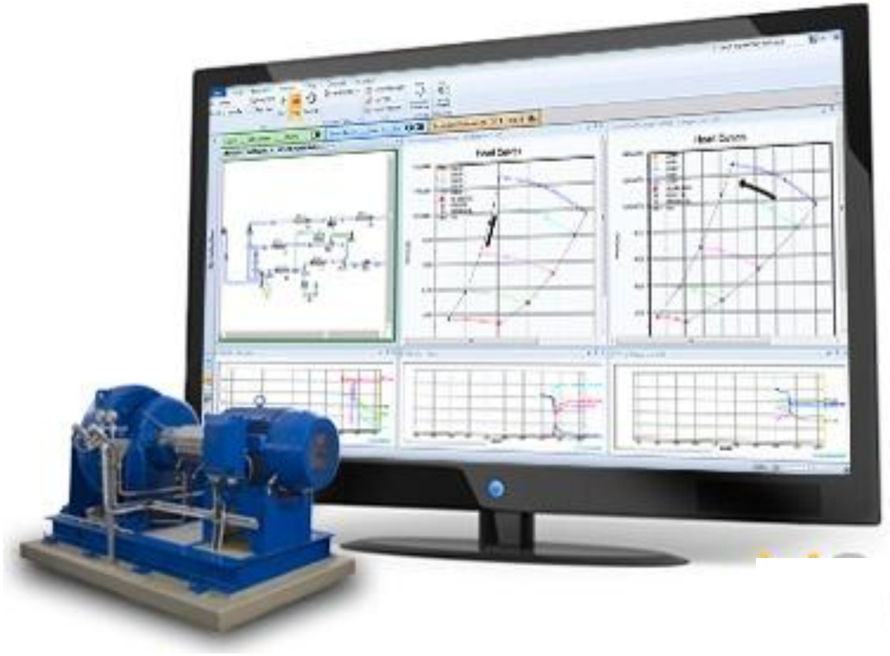
- **Plant-wide model**
  - Supercritical pulverized coal (SCPC) system
  - Case B12A, NETL Cost and Performance Baseline*
- **Equipment Models**
  - First-principles dynamic mass and energy balances
  - Boiler System
    - Gas-side: combustion, radiation, convection
    - Water/steam-side: convection, volumetric and thermal holdups
    - Waterwall, Superheaters, Reheaters, Economizer
  - Steam Cycle
    - Multistage Turbine: Sliding-pressure operation, efficiency calculations, moisture detection
    - Units with volumetric and thermal holdups: Condenser, Feedwater Heaters, Deaerator, …
  - Flue Gas Treatment
    - Selective catalytic reduction (SCR) for NOx control

* Case B12A, Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3, National Energy Technology Laboratory, www.netl.doe.gov, DOE/NETL-2015/1723, July 6, 2015.

Dynamic Power Plant Modeling

Modeling Software and Physical Properties

- **Modeling Software**
  - Aspen Plus Dynamics®
    - Plant-wide model and controls
    - Equation-oriented, pressure-driven
  - Aspen Custom Modeler® (ACM)
    - Equipment models
    - 1-2D Partial Differential Equations (PDEs)



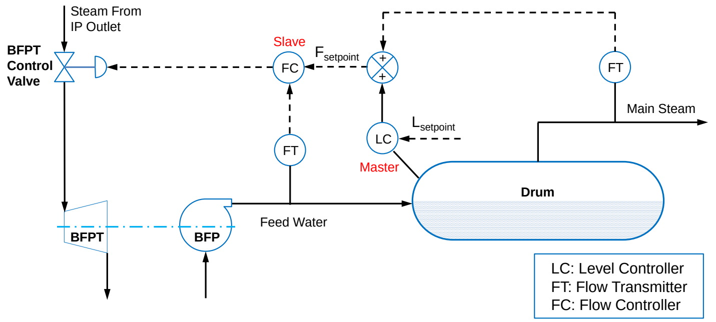
- **Physical Properties**
  - Flue Gas: PENG-ROB (Peng-Robinson Equation-of-State*)
  - Water/Steam: IAPWS-95 Steam Tables**

* D.-Y. Peng and D. B. Robinson, "A New Two-Constant Equation-of-state," Ind. Eng. Chem. Fundam., Vol. 15, (1976), pp. 59–64.

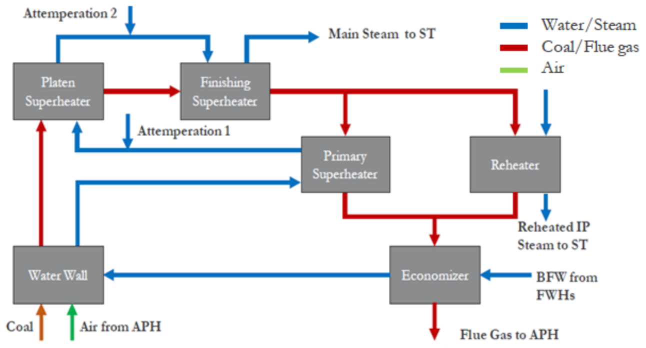
** Wagner , W. and A. Pruß, "The IAPWS Formation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use," J.Phys. Chem. Ref. Data, 31(2), 387- 535, 2002.

Regulatory and Supervisory Controls

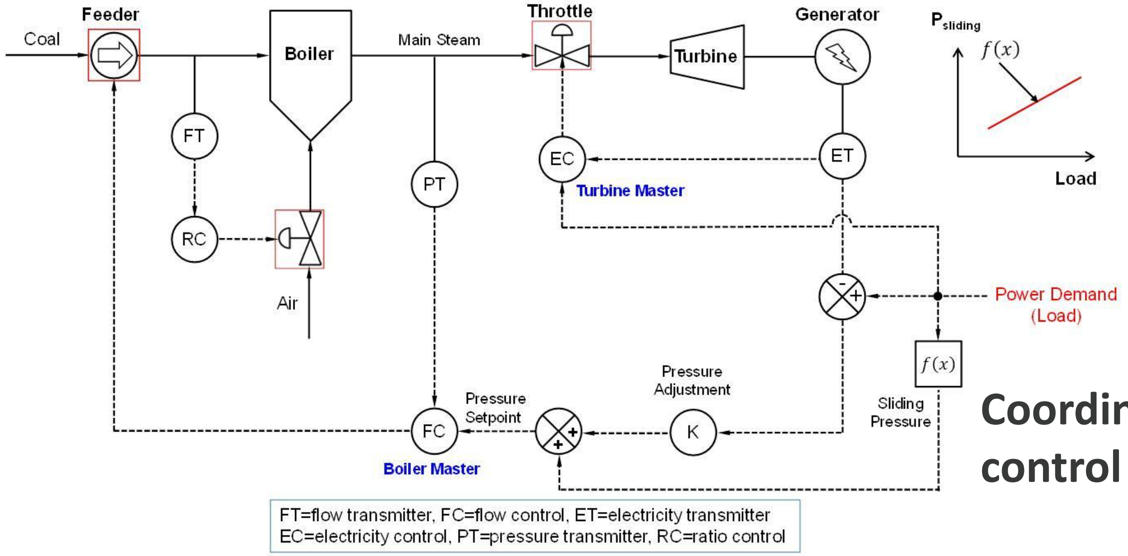
- **Regulatory controls**
  - ~30 proportional-integral-derivative (PID) control loops
    - Inventory controllers
  - 3-element drum level control
    - Two cascaded control loops
    - Drum level, main steam flow (FB), and feed water flow (FF)
  - Main steam temperature (MST) control
    - Two-stage attemperation
- **Supervisory Controls**
  - Coordinated Control System (CCS)
    - Boiler and turbine masters
  - Fixed- and sliding-pressure operation



3-element drum level control



2-stage attemperation for MST control



Coordinated control system

Sarda, P., E. Hedrick, K. Reynolds, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Development of a Dynamic Model and Control System for Load-Following Studies of Supercritical Pulverized Coal Power Plants," *Processes*, 6(11), 226, Nov. 2018.

Boiler Health Models

- **Transient pressure and temperature profiles throughout the boiler**
  - Superheaters and reheaters
  - 1D P/T profiles along length of tubes
  - Through-wall temperature profiles
- **Thermo-mechanical stresses**
  - Stress evolution over time
  - Axial, radial, and tangential stresses, as well as equivalent (von Mises) stress
  - SH/RH: Tube wall, header, header/wall junction
  - Material dependent
- **Creep and fatigue damage**
  - Load-following operation scenarios
  - Estimated time to rupture (Creep – high T)
  - # of cycles until likely failure (Fatigue – high ΔT)
    - Rainflow counting method
    - Effect of ramp rate

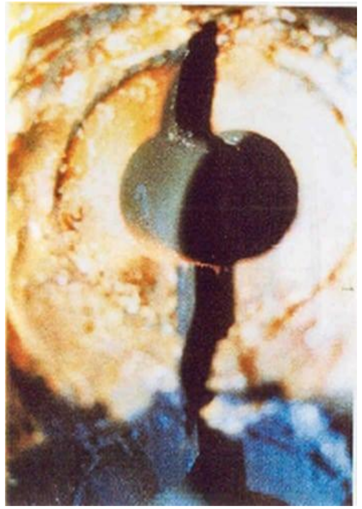
Supercritical Steam Boiler

Source: Babcock & Wilcox

Superheater

Tube Failures

Source: Power Magazine



Header Crack

Source: Power Magazine

Presentation Overview

- **Dynamic Power Plant Modeling**
  - Process, Control, and Health
- **Model Validation under Load-Following Operations**
- **Reinforcement Learning-Augmented Control Results**
  - Main steam temperature control
  - NOx control in SCR unit
- **Boiler Health Modeling Results**
- **Concluding Remarks and Future Work**

Steady-State Parameter Estimation and Model Validation using Plant Data

NATIONAL ENERGY TECHNOLOGY LABORATORY

- Dynamic power plant model adapted to match **industry partner plant**
- Equipment sizing performed using plant design data
- Operating data obtained for steady-state and part-load operation
- Model parameters estimated where not available
  - Steam turbine isentropic head parameter estimated to match full-load power
- Model validated at steady-state full-load and part-load (~70%) operation

Full-Load	Error (Model - Plant)
Economizer Inlet Temperature	-0.30%
Gross Power Production	0.09%
Main Steam Temperature	-0.12%
Main Steam Pressure	-0.16%
Main Steam Flow	-0.02%
Coal Feed Rate	0.66%
Boiler Feedwater Flow	0.00%

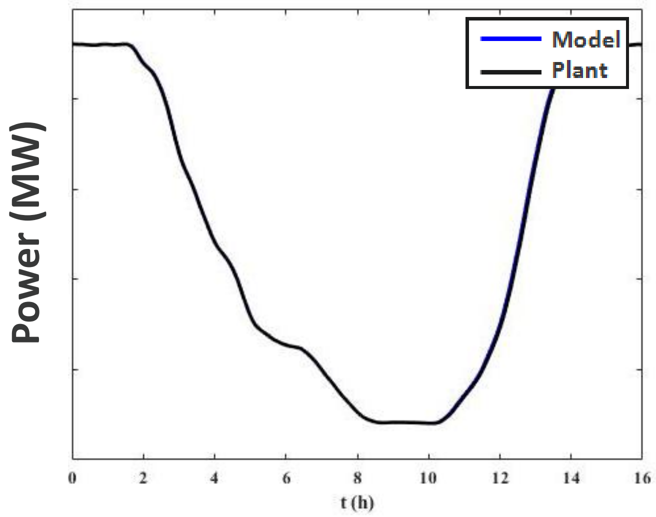
Part-Load	Error (Model - Plant)
Economizer Inlet Temperature	0.01%
Gross Power Production	0.11%
Main Steam Temperature	0.00%
Main Steam Pressure	0.63%
Main Steam Flow	0.88%
Coal Feed Rate	-1.86%
Boiler Feedwater Flow	0.34%

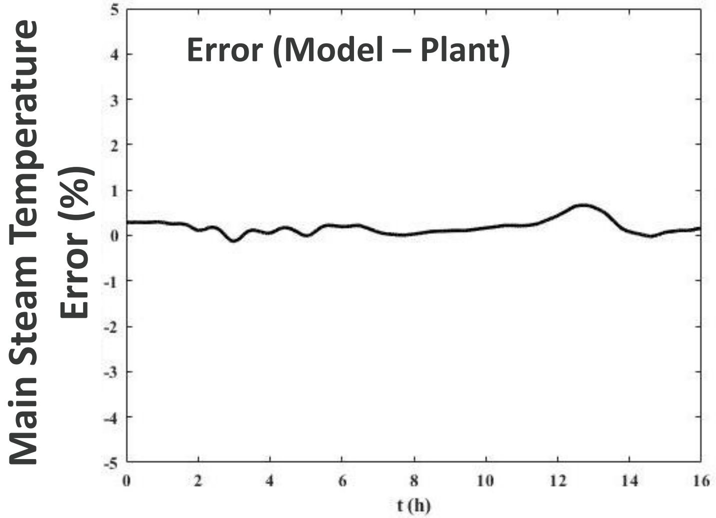
Dynamic Model Validation using Plant Data

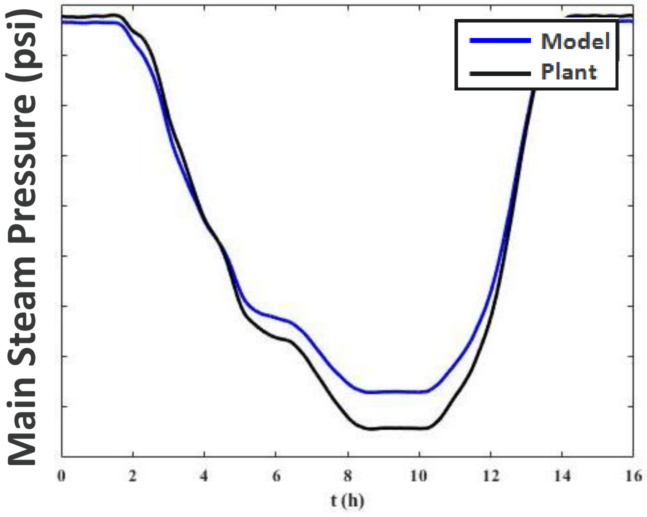
- Load-following operation
  - Ramp down from full load to part load (~70%) over 6 hours at ramp rate of ~0.5 MWe/min
  - Hold for 2 hrs
  - Ramp back up to full load over 4 hrs at ramp of ~0.75 MWe/min
- Data available from the plant is noisy and contains fluctuations
  - High frequency noise filtered out using low-pass Butterworth filter
  - 30-minute smoothing average filter applied
- Dynamic model simulated with mapped inputs from plant load-following data
  - Boiler feedwater flow
  - Coal flow
  - Feedwater heater outlet temperatures
  - Boundary temperatures and pressures
- Control of air feed via ratio with coal flow
- Regulatory control layer for maintaining boiler main steam temperature

Dynamic Model Validation using Plant Data

Load-Following Operation







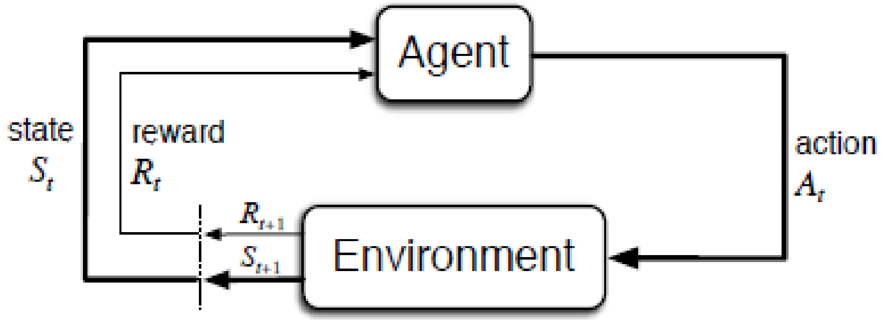
- Model parameters estimated using full-load data remained unchanged for load-following case.
- Inlet coal conditions (moisture, HHV, composition) were not changed.
- Plant-model match for gross power and main steam temperature show good agreement throughout the entire load range.
- Model has a slightly higher pressure at part-load condition mainly because of mismatch in pressure drop profile across throttle valve. Going forward, throttle valve parameters will be estimated considering dynamic data.

Presentation Overview

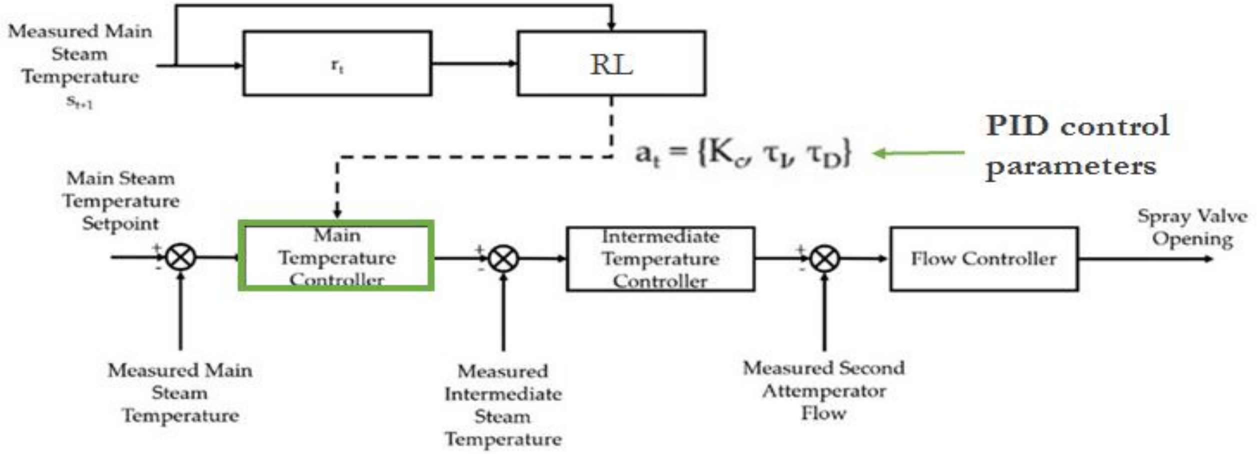
- **Dynamic Power Plant Modeling**
  - Process, Control, and Health
- **Model Validation under Load-Following Operation**
- **Reinforcement Learning-Augmented Control Results**
  - Main steam temperature control
  - NOx control in SCR unit
- **Boiler Health Modeling Results**
- **Concluding Remarks and Future Work**

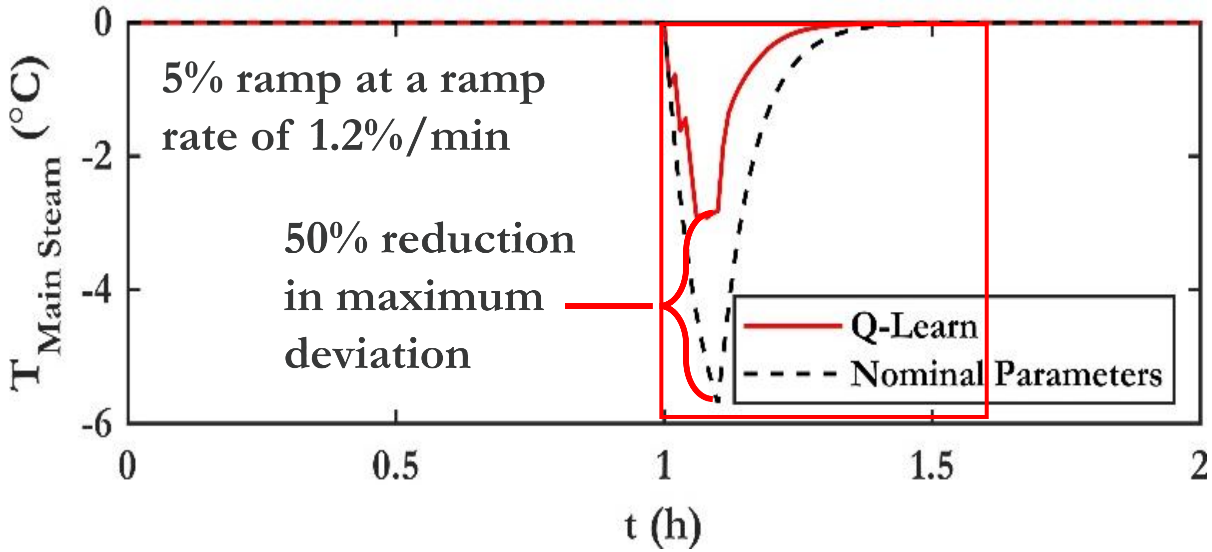
Main Steam Temperature Control
Reinforcement Learning(*RL*)-*Augmented PID Control*

- Adaptive and retentive learning



- Q-learning for PID control parameters
- Episodic learning
  - Disturbance: Random ramped load changes
  - Input: BFW flow to Attemperator before FSH
  - Output: Main Steam Temperature
- State-action clustering
  - Retentive learning
  - Reduces computation time



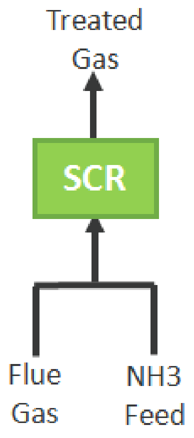


Hedrick, E., K. Reynolds, P. Sarda, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Development of a Reinforcement Learning-Based Control Strategy for Load Following in Supercritical Pulverized Coal (SCPC) Power Plants," *Clearwater Clean Energy Conf.*, Clearwater, FL, June 16-21 (2019).

Selective Catalytic Reduction (SCR) Control
RL-Augmented Model Predictive Control

NATIONAL ENERGY TECHNOLOGY LABORATORY

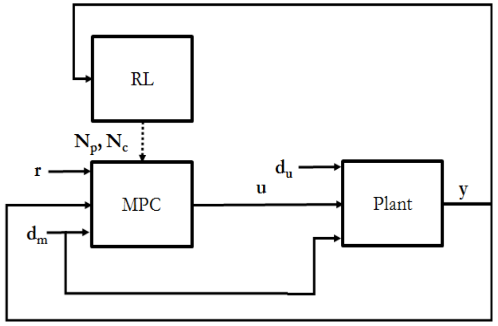
- SCR for NOx control is highly nonlinear time-varying system with time-delay
- SCR dynamic model is 1D heterogeneous plug flow reactor with detailed kinetics
- Reduced model is identified from dynamic SCR model of the form:



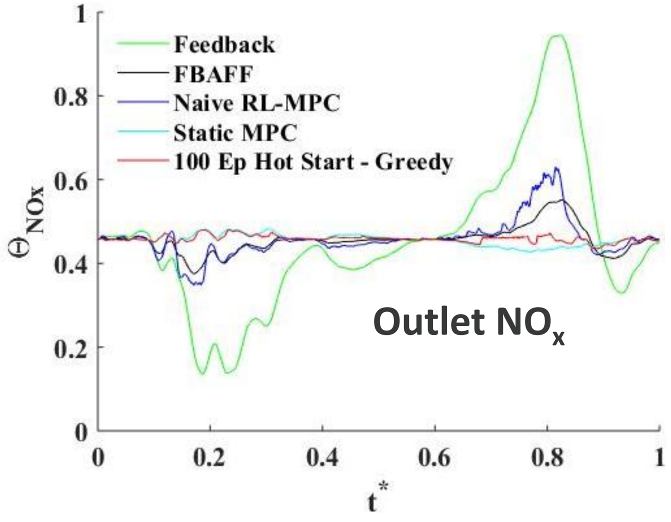
MPC Model Variable	System Variable
u_1	NH_3 Flow (kmol/h)
d_1	Flue Gas Flow (kmol/h)
d_2	Flue Gas NO_x Flow (kmol/h)
d_3	Flue Gas Temperature (°C)
y	Outlet NO_x (ppm)

- Identified model is used in a static linear Model Predictive Control (MPC)

- **RL-augmented MPC**
  - Temporal-difference learning
  - Learned parameters are MPC prediction (N_p) and control (N_c) horizons



- **NO_x control under load-following**



Controller	ISE	Ratio to FBAFF
Feedback	2529	32
Naïve RL-MPC	166	2.1
FBAFF	79	1.0
Static MPC	13	0.16
RL-MPC Greedy	5	0.063

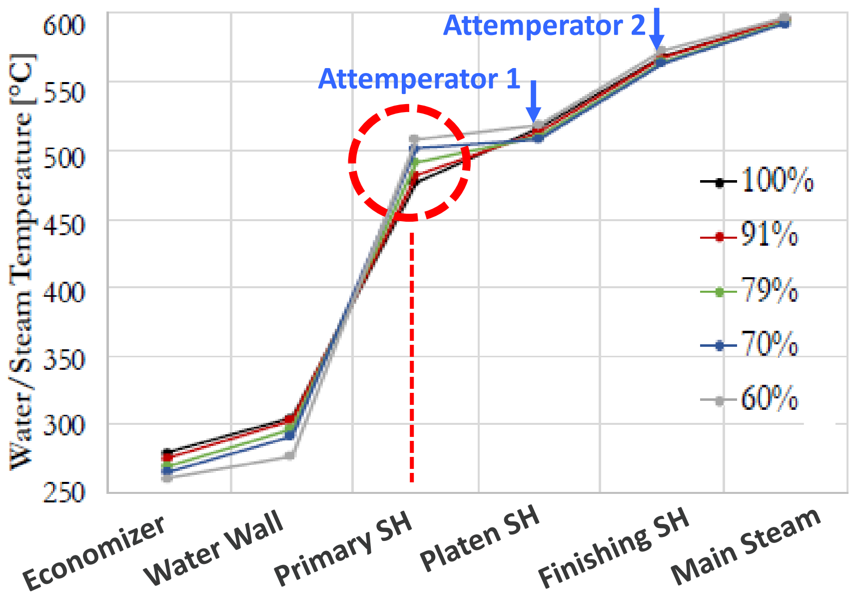
ISE: Integral Square Error
FBAFF: FeedBack-Augmented FeedForward (Industry Standard)

Presentation Overview

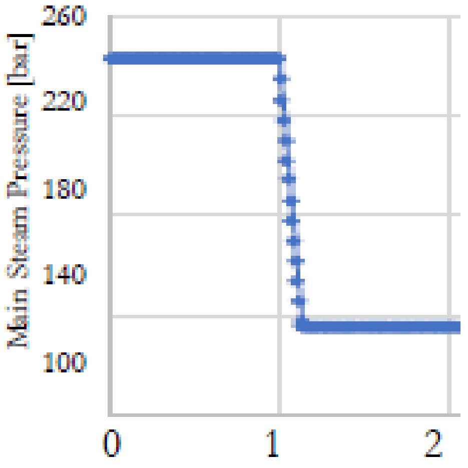
- **Dynamic Power Plant Modeling**
  - Process, Control, and Health
- **Model Validation under Load-Following Operation**
- **Reinforcement Learning-Augmented Control Results**
  - Main steam temperature control
  - NOx control in SCR unit
- **Boiler Health Modeling Results**
- **Concluding Remarks and Future Work**

Impact of Load-Following on Boiler Health
Primary Superheater - Tubes

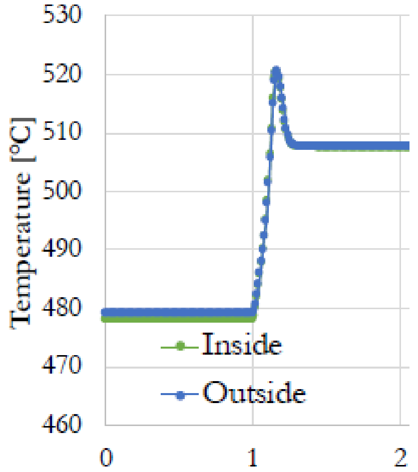
- Load ramped from 100% to 60% (5%/min)
- Boiler thermal profile depends on plant design and controls
- Temperature at inlet of Primary SH rises with reduction in load — possible location for damage



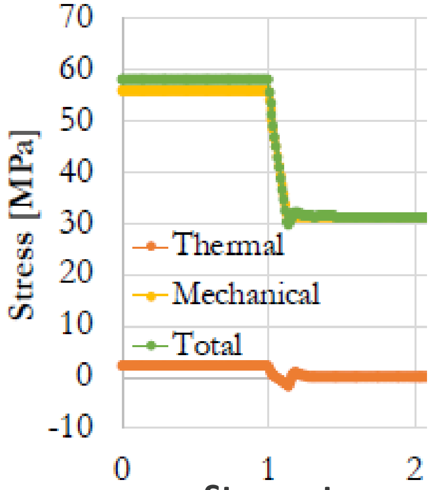
Boiler Thermal Profile



Sliding Pressure Operation



Tube Temperature at Primary SH Inlet



Stress at Primary SH Inlet

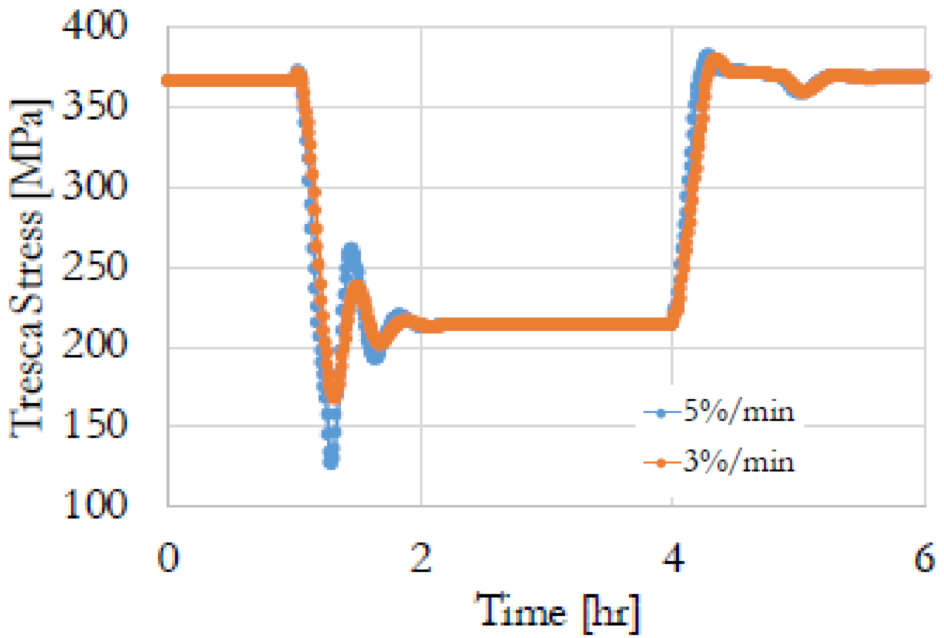
- ΔT between inner and outer tube wall is small
- Thermal stress does not add significantly to total stress (fatigue)
- However, higher temperature (+40°C) at 60% load increases **creep damage**
- **Relative rupture time** at 60% load reduced by 6X compared to full load

	PSH	
Load	100%	60%
Wall Surface Temperature [°C]	477.92	507.41
Equivalent Stress [MPa]	71.72	39.18
Relevant Rupture Time	1.00	0.16

* - "Water-tube boilers and auxiliary installations - Part 3: Design and calculation of pressure parts," British Standards Institution, London, UK, BS EN 12952-3:2001, May 2002.

Impact of Load-Following on Boiler Health
Primary Superheater - Header

- Stresses in **superheater headers** are higher than in tubes due to thicker walls and larger through-wall temperature differences, so **fatigue damage** is of more concern
- Stress used in a fatigue cycle calculation **(rainflow counting using ASTM E1049)***
- **Ramp rate affects number of allowable cycles**



- Load ramped from 100% to 60% at Time=1 hr and then back up to 100% at Time = 3 hr
- Two different ramp rates: 3%/min, 5%/min

Ramp Rate [%/min]	3	5
$\Delta\sigma_{Tresca}$ [MPa]	212	256
Relative # of Cycles	1	0.14

Concluding Remarks and Future Work

- **Developed first-principles dynamic power plant model with controls and health models**
- **Validated dynamic power plant model using industrial load-following data**
- **Demonstrated reinforcement learning-augmented control**
  - RL-augmented PID control improved main steam temperature control by reducing maximum temperature deviation by 50% during load ramp
  - RL-augmented MPC improved NOx control for highly nonlinear SCR process with time-delay
- **Studied impact of load-following on boiler health with focus on primary SH**
  - Tube rupture times due to creep damage are impacted by low load operation
  - Fatigue damage and number of allowable cycles for thick-walled headers are greatly affected by ramp rate
- **Future work**
  - Adaptive NMPC strategies to maximize efficiency with health/damage constraints during load-following

Upcoming Presentations and Publications

NATIONAL ENERGY TECHNOLOGY LABORATORY

Presentations

- Hedrick, E., K. Reynolds, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Development of Algorithms for Reinforcement Learning Augmented Model Predictive Control," *AIChE 2021 Annual Meeting*, Boston, MA, November 7-12 (2021).
- Hedrick, E., K. Reynolds, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Nonlinear Predictive Control of an Industrial Selective Catalytic Reduction Unit with Time-Varying Time Delay," *AIChE 2021 Annual Meeting*, Boston, MA, November 7-12 (2021).
- Hedrick, E., K. Reynolds, S. Hong, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Advanced Model Predictive Control for Reducing Equipment Damage in a Supercritical Pulverized Coal Fired Power Plant during Load-Following Operation," *AIChE 2021 Annual Meeting*, Boston, MA, November 7-12 (2021).
- Reynolds, K., E. Hedrick, B. Omell, S.E. Zitney, D. Bhattacharyya, "Dynamic Optimization of the Operational Trajectory of a Supercritical Pulverized Coal-Fired Boiler under Load-Following with Consideration of Boiler Health," *AIChE 2021 Annual Meeting*, Boston, MA, November 7-12 (2021).
- Reynolds, K., E. Hedrick, B. Omell, S.E. Zitney, D. Bhattacharyya, "Health Monitoring of an Industrial Supercritical Pulverized Coal Boiler," *AIChE 2021 Annual Meeting*, Boston, MA, November 7-12 (2021).

Publications

- Hedrick, E., K. Reynolds, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Reinforcement Learning for Online Adaptation of Model Predictive Controllers: Application to a Selective Catalytic Reduction Unit," In Preparation.
- Reynolds, K., E. Hedrick, B. Omell, S.E. Zitney, D. Bhattacharyya, "Dynamic Data Reconciliation, Parameter Estimation, and Health Analysis of a Supercritical Pulverized Coal Boiler Under Load-Following Operation," In Preparation.

Contact Information

Stephen E. Zitney, Ph.D.

U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
(304) 285-1379
Stephen.Zitney@netl.doe.gov