Dynamic Modeling of Steam-based Power Plants

Stephen E. Zitney, NETL
Elijah Hedrick, WVU
Katherine Reynolds, WVU
Parikshit Sarda, WVU
Debangsu Bhattacharyya, WVU

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NATIONAL ENERGY TECHNOLOGY LABORATORY

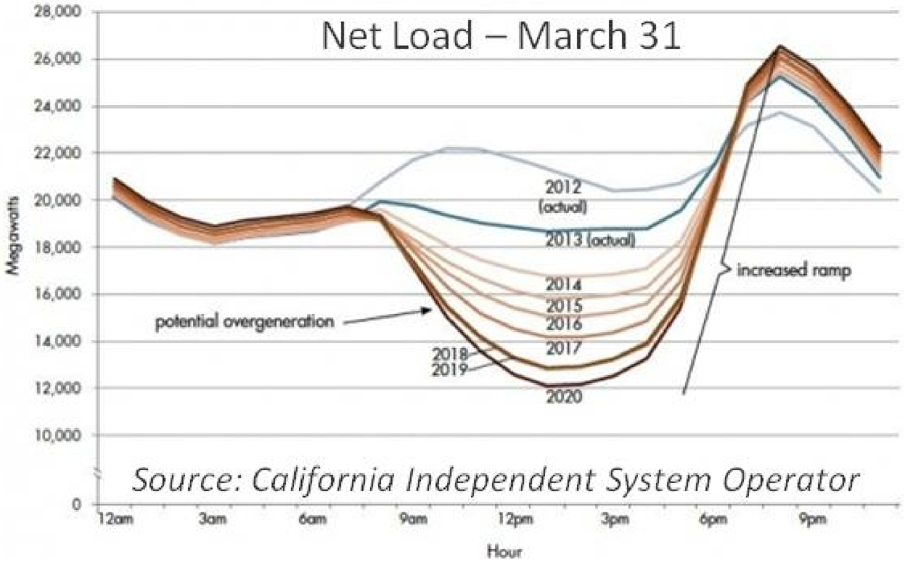
U.S. DEPARTMENT OF ENERGY

Presentation Overview

- **Key Challenges and Research Objectives**
  - Flexible Power Plant Operations
- **Dynamic Performance Baseline**
  - Supercritical Pulverized Coal (SCPC) Power Plant
- **Results and Accomplishments**
  - Dynamic Model Development and Control Design
  - Load-Following and Sliding-Pressure Operation
  - Publications and Presentations
- **Ongoing and Future Work**

Key Challenges Facing the Energy Industry
Rapid Transformation of Power Systems

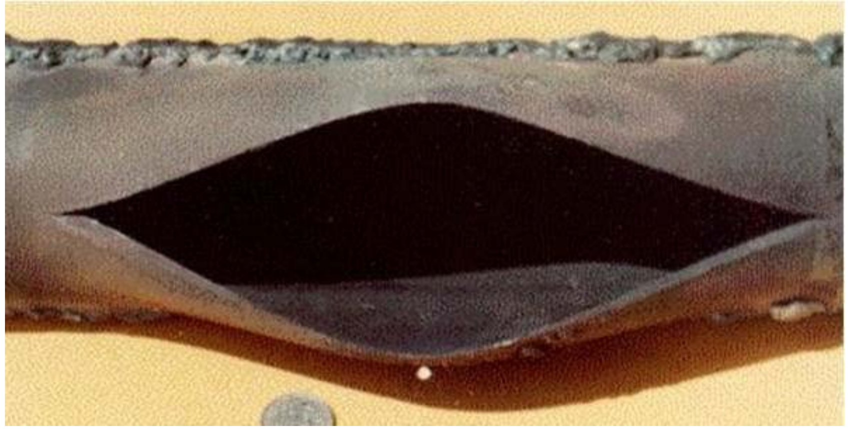
- **Driving Factors**
  - Increasing variable renewable energy resources
  - Growing share of decentralized energy resources
  - Emerging demand side management
- **Key Priority**
  - Enhancing power systems flexibility, while reducing costs and strengthening resilience
- **Changing Role of Fossil Power Plants**
  - Increased cycling operation
  - Faster startup and ramp rates
  - Lower minimum loads



Key Challenges Facing the Energy Industry
Negative Impacts of Power Plant Cycling

- ⬇ Plant performance, efficiency, and profitability
- ⬇ Equipment health and life expectancy
- ⬆ Plant downtime and operations & maintenance (O&M) costs
- ⬆ Environmental emissions

Cracked Economizer Header*



Failed Boiler Tube**

* Hesler, S., "Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants," Power Magazine, August 1 (2011).
** Sakthivel, P., S. Kalaimani, and R. Sasikumar, "Analysis of Tube Failure in Water Tube boiler," International Journal of Innovative Research in Science, Engineering and Technology, Vol. 6, Issue 8, May (2017).

R&D Objectives
Improving Flexible Power Plant Operations

- Develop *dynamic* performance baselines for existing coal-fired electricity generating units (EGUs)*
  - High-fidelity, plant-wide dynamic process and control model
  - Health models for key equipment items
- Quantitatively assess plant operation and control approaches for improving EGU flexibility
- Minimize negative impacts on EGU performance and reliability due to increasing flexible operations

* 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.

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SCPC Plant Configuration

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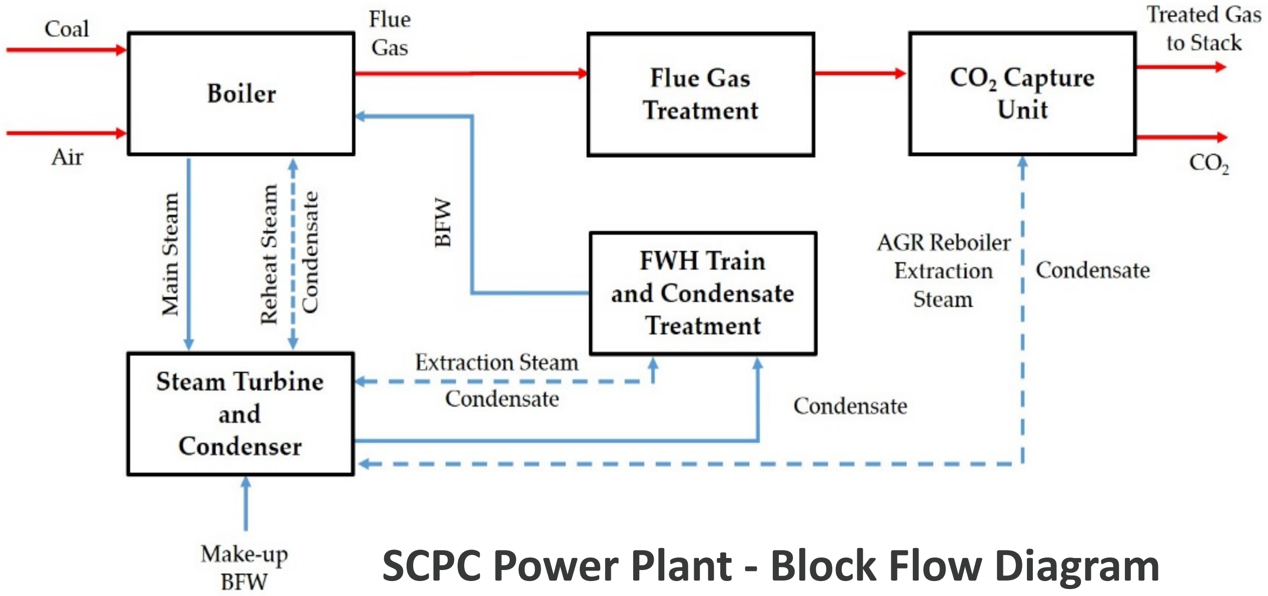
- **Fossil energy cost and performance baseline, Vol. 1a, Rev. 3, DOE/NETL-2015/1723***
  - Case B12B: SCPC with CO_2 Capture
  - Nominal output of 550 MWe (net)
  - Illinois #6 coal



SCPC Power Plant - Block Flow Diagram

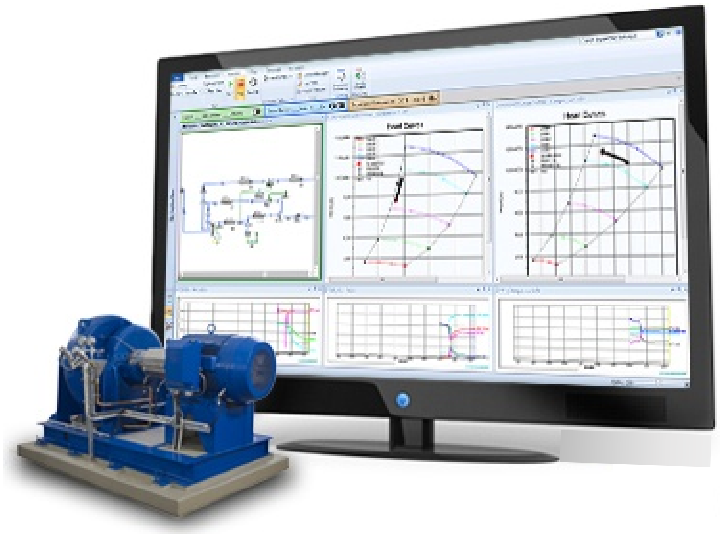
Four Major Sections

- **Boiler**
  - Supercritical, once-through boiler with single-reheat
  - 24.1 MPa/593°C/593°C
  - Air fans and air preheater
- **Steam Turbine**
  - Condenser
- **Feedwater Treatment and Heating**
- **Flue Gas Treatment**
  - Selective catalytic reduction
  - Flue gas desulfurization
  - CO_2 Capture

* Case B12B, 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.

SCPC Plant-wide Dynamic Modeling and Control
Software and Physical Properties

- **Software Tools**
  - Steady-State: Aspen Plus
    - Sequential-modular, tear streams
  - Transient: Aspen Plus Dynamics
    - Equation-oriented, pressure-driven
    - Regulatory control
    - Coordinated control system
  - Equipment:
    - Aspen Exchanger Design & Rating (EDR)
    - Aspen Custom Modeler (ACM)



- **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.
** Wanger , 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.

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SCPC Plant-wide Dynamic Modeling
Boiler Section

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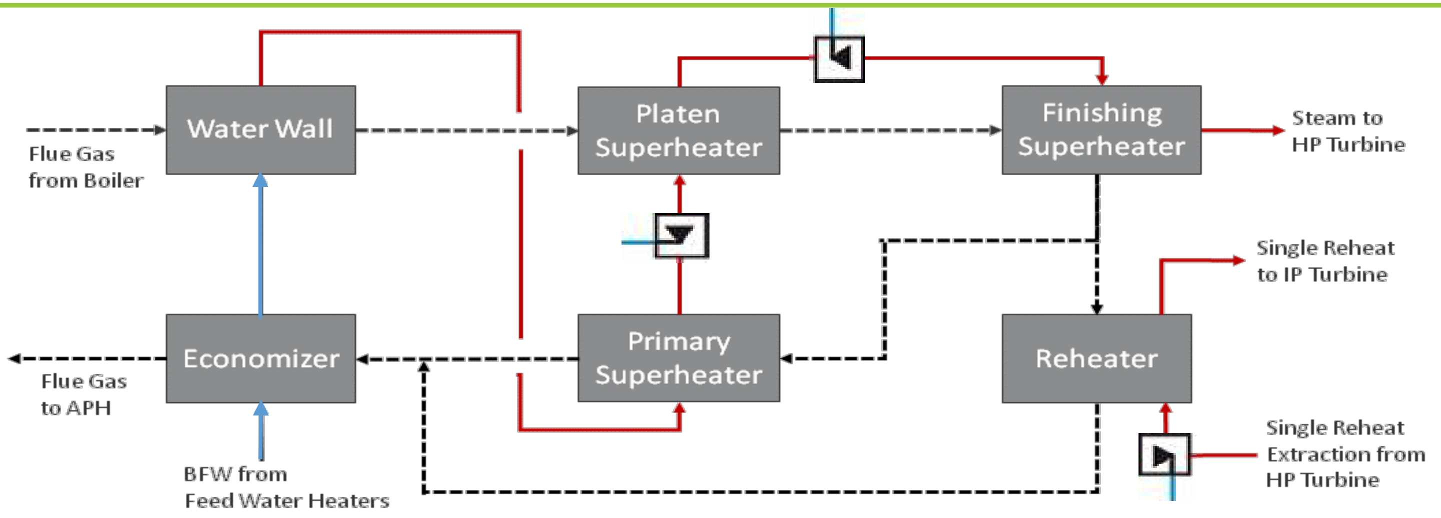
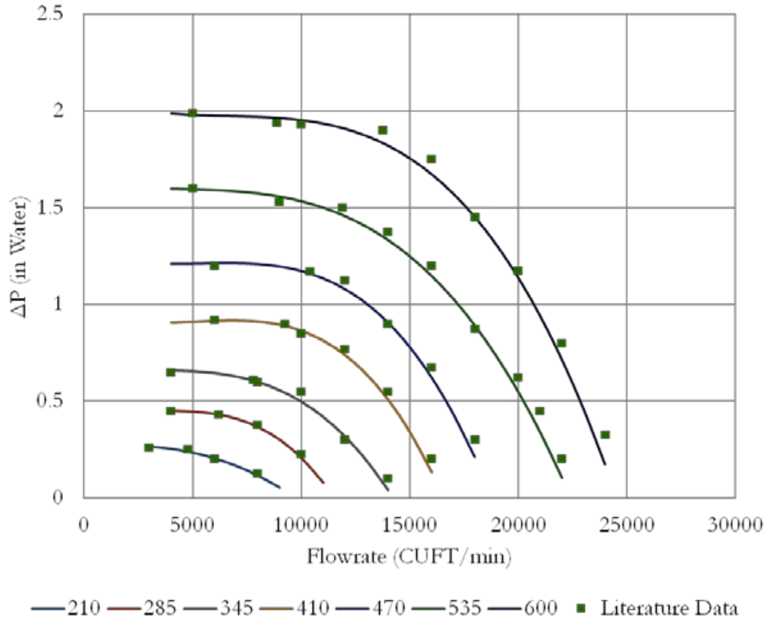


Boiler Section - Block Flow Diagram

- **Heat Exchangers**
  - Shell-and-tube exchangers
  - Thermal and volumetric holdups included
  - Heat transfer coefficients calculated using flow-dependent correlations
  - Gas-side dynamics assumed to be very fast in comparison to water/steam side

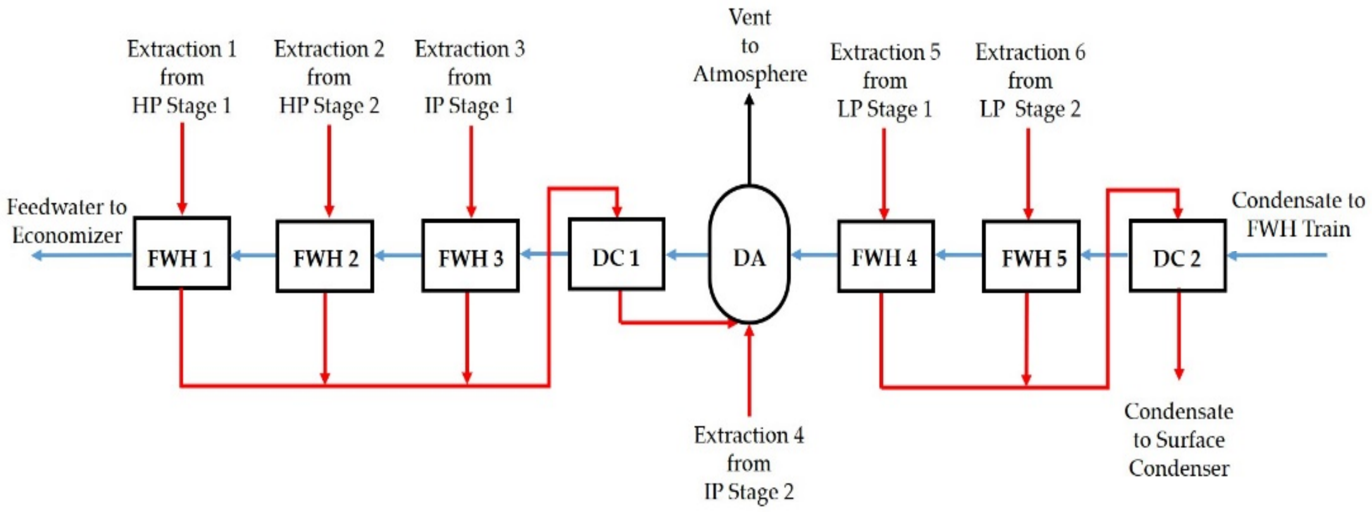
- **Attemperation**
  - Two-stage for main steam
  - Single-stage for reheat steam

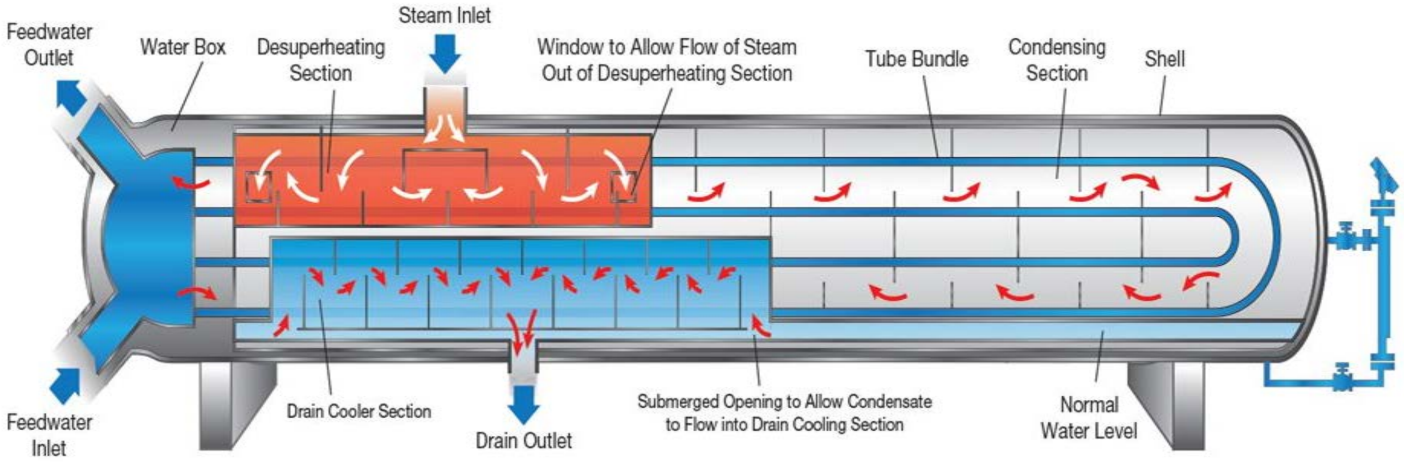
- **Air Fans**
  - Air-side dynamics impact water/steam-side dynamics, especially during load-following
  - Performance curves* to capture dynamics of air flow into boiler
  - Vary fan speeds to control air flow during load following operations



* The Basics of Fan Performance Tables, Fan Curves, System Resistance Curves and Fan Laws (FA/100-99) Available online: http://www.greenheck.com/library/articles/10 (accessed on Jan 1, 2017).

SCPC Plant-wide Dynamic Modeling
Feedwater Treatment and Heating Section



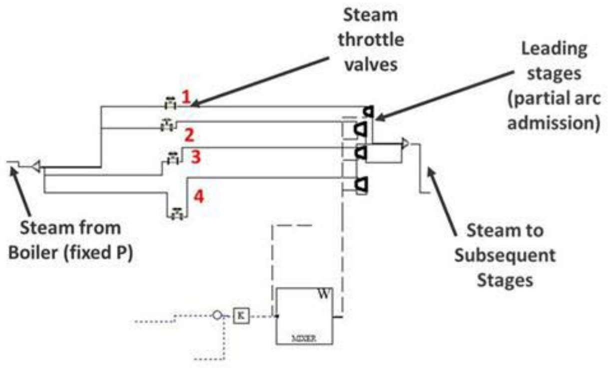


- **Feedwater Heater (FWH) Model**
  - ACM dynamic model with 1D cross-flow in water/steam directions
  - <u>Tube-side</u>
    - Pre-heated feedwater
    - Gnielinski correlation for heat transfer
  - <u>Shell-side</u>
    - Superheated extraction steam
    - ε-NTU method with heat transfer correlations
      - Gnielinski correlation for sub-cooling and de-superheating
      - Pepukhov & Papov correlation for condensation
    - Setpoint for condensate level
      - Regulates amount of heat transfer
      - Level controlled using steam flow to FWH

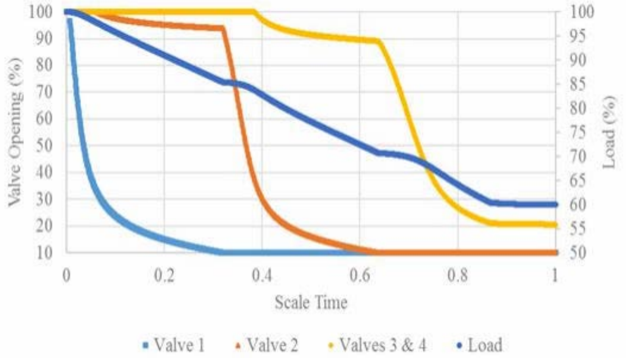
DC – Drain Cooler
DA - Deaerator

SCPC Plant-wide Dynamic Modeling
Steam Turbine Section

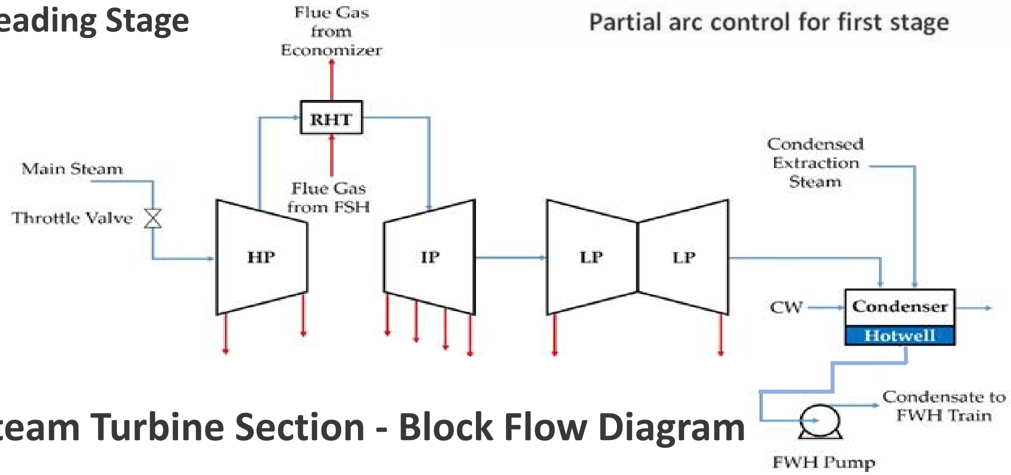
- **Steam Turbine**
  - **Leading (governing) stage**
    - Full- and partial-arc admission
    - Fixed- and sliding-pressure operation
  - **Intermediate HP/IP/LP stages**
    - Isentropic enthalpy calculations
    - Moisture detection for load-following operation, especially under low-load conditions where reheat temperature may not be maintained
    - Efficiency change for non-condensing stages needed for sliding-pressure operation and inlet temperature variations under load-following
  - **Final stage before condenser**
    - Choked flow condition with Stodola equation for mass flow in presence of condensation
    - Exit pressure constrained to condenser pressure



ST Leading Stage



Partial arc control for first stage



Steam Turbine Section - Block Flow Diagram

- **Condenser**
  - Crossflow model with ε-NTU heat transfer method

E. Liese, "Modeling of a Steam Turbine Including Partial Arc Admission for Use in a Process Simulation Software Environment.", *Journal of Engineering for Gas Turbines and Power, vol. 136, no. 11, pp. 112 605-1 - 112605-7, 2014. doi: 10.1115/1.4027255.*

SCPC Plant-wide Dynamic Modeling

Validation at Full-Load

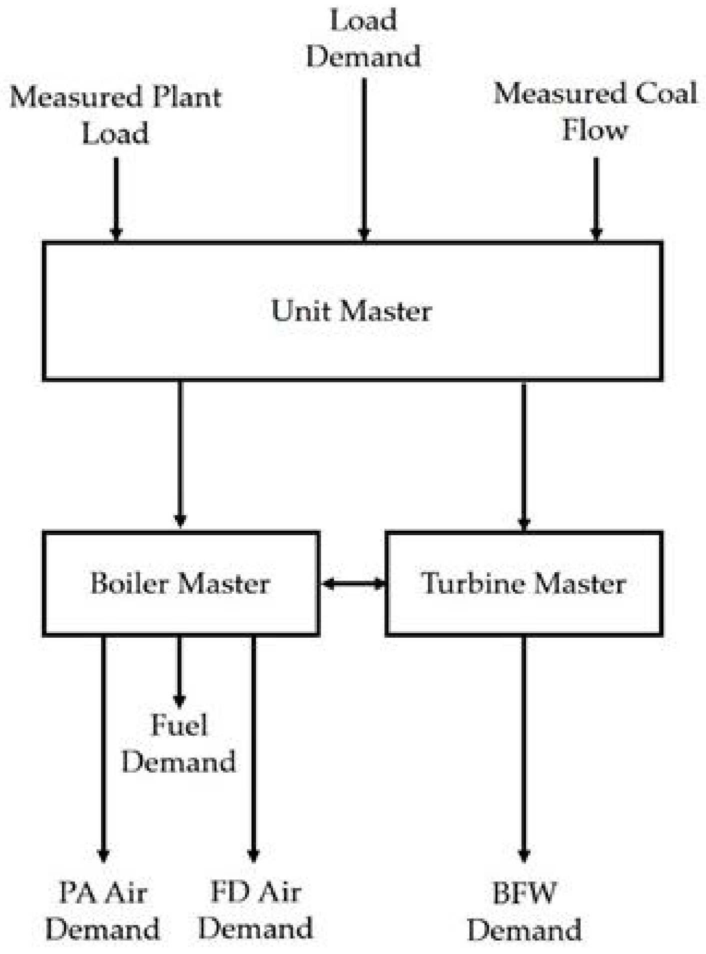
Parameter	Unit	NETL Baseline Study*	SCPC Dynamic Model	Error
Coal Flow Rate	tonne/h	225	228	1.53%
Gross Power	MW	641	620	-3.28%
Net Power	MW	550	532	-3.21%
Heat Rate	kJ/kWh	11,086	11,629	4.90%
Main Steam Pressure	MPa	24.2	24.1	-0.37%
Main Steam Temperature	°C	593	593	0.00%
Main Steam Flow Rate	tonne/h	2,003	2,027	1.19%

- **Dynamic SCPC model operating at base load was shown to be in good agreement with the steady-state results from the NETL baseline study***

* Case B12B, 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.

SCPC Control System Design
Regulatory and Supervisory Control Layers

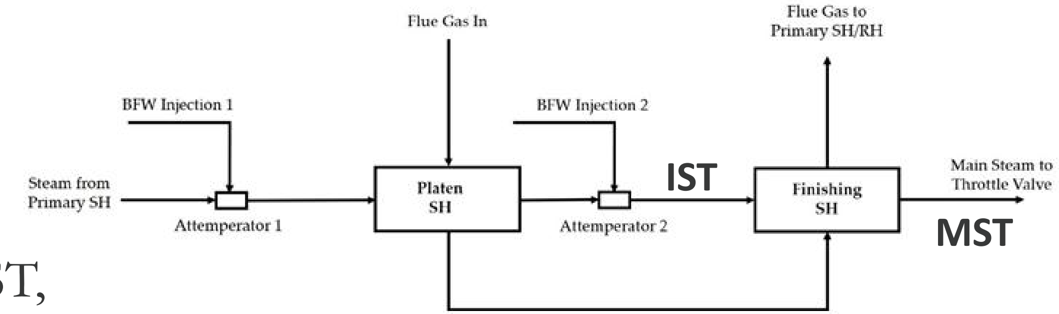
- **Challenges**
  - Water/steam-side is a time-delay system
  - Steam properties and heat transfer characteristics are highly nonlinear phase transitions (super/subcritical)
  - Complex configuration of FWHs, coupled with sliding-P operation that changes pressure of steam extractions
- **Regulatory Control Layer**
  - 16 single-loop feedback control loops and 13 cascade control loops, where PID controllers are used
  - Key Controllers
    - Speed control for forced draft (FD) and primary air (PA) fans
    - Flow control for boiler feedwater (BFW)
    - Level control for inventory in deaerator and condenser hotwell
    - Temperature control for main steam and reheat steam



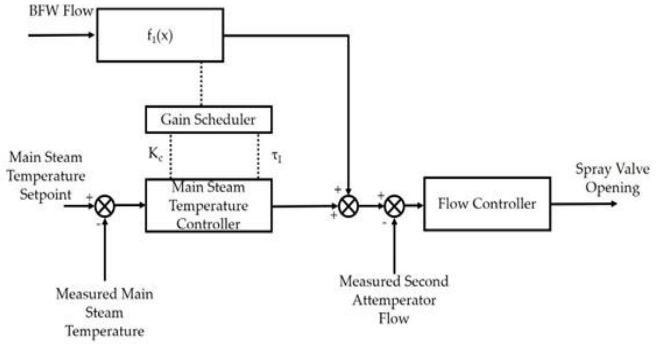
Coordinated Control System (CCS)

Main Steam Temperature (MST) Control
Spray Attemperation

- Tight MST control desired under load-following conditions
  - Lower MST leads to losses in efficiency
  - Higher MST can lead to damage in SH tubes and steam turbine
- Manipulated variable is injection flow rate into Attemperator 2
- Note that IST responds faster to spray changes compared to MST, which lags due to thermal and volumetric holdup of Finishing SH

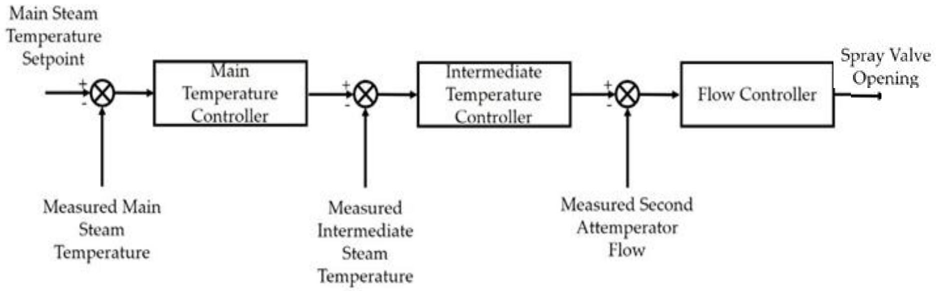


High-Pressure Steam Attemperation



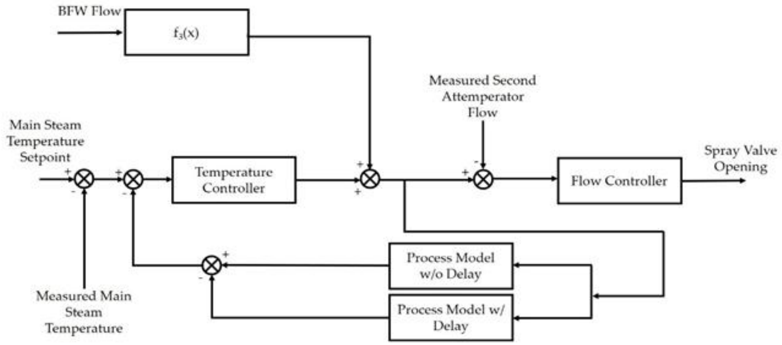
Configuration 1*

- Feedback loop for MST control with feedforward gain-scheduled correction based on BFW flow
- No consideration of IST after Attemperator 2



Configuration 2*

- IST controller before Finishing SH manipulates the injection flow rate to Attemperator 2
- MST controller generates setpoint for IST controller
- No feedforward correction based on BFW flow



Configuration 3

- Feedback loop for MST control
- Smith predictor** used with Finishing SH represented as 1st-order process with time delay
- Feedforward correction based on BFW flow

* Chen, C.; Zhou, Z.; Bollas, G.M. Dynamic modeling, simulation and optimization of a subcritical steam power plant. Part I: Plant model and regulatory control. *Energy Convers. Manag.* 2017, *145*, 324–334, doi:10.1016/j.enconman.2017.04.078.
** Ogunnaike, B.A.; Ray, H.W. *Process Dynamics, Modeling and Control*; Oxford University Press: Oxford, United Kingdom, 1994.

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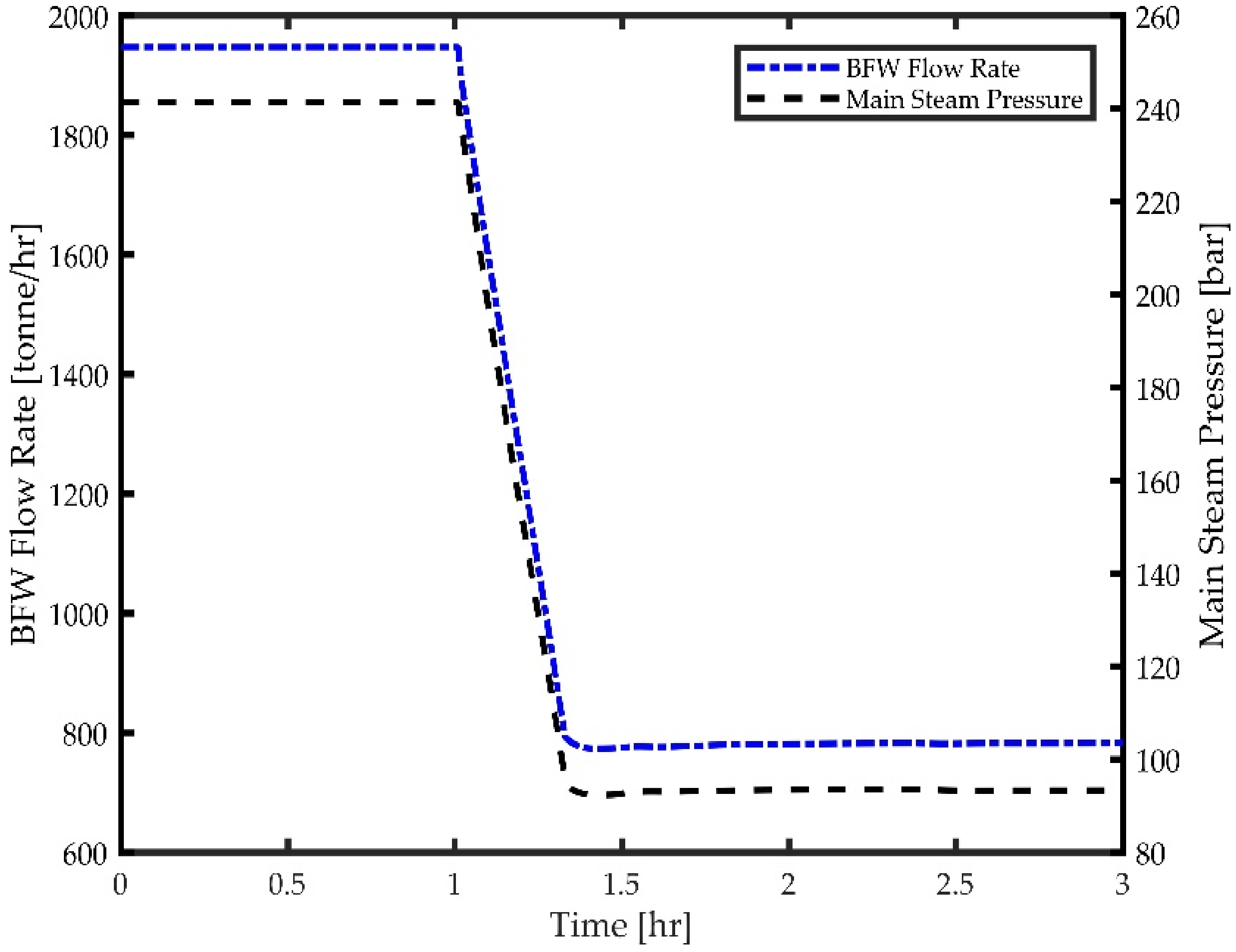
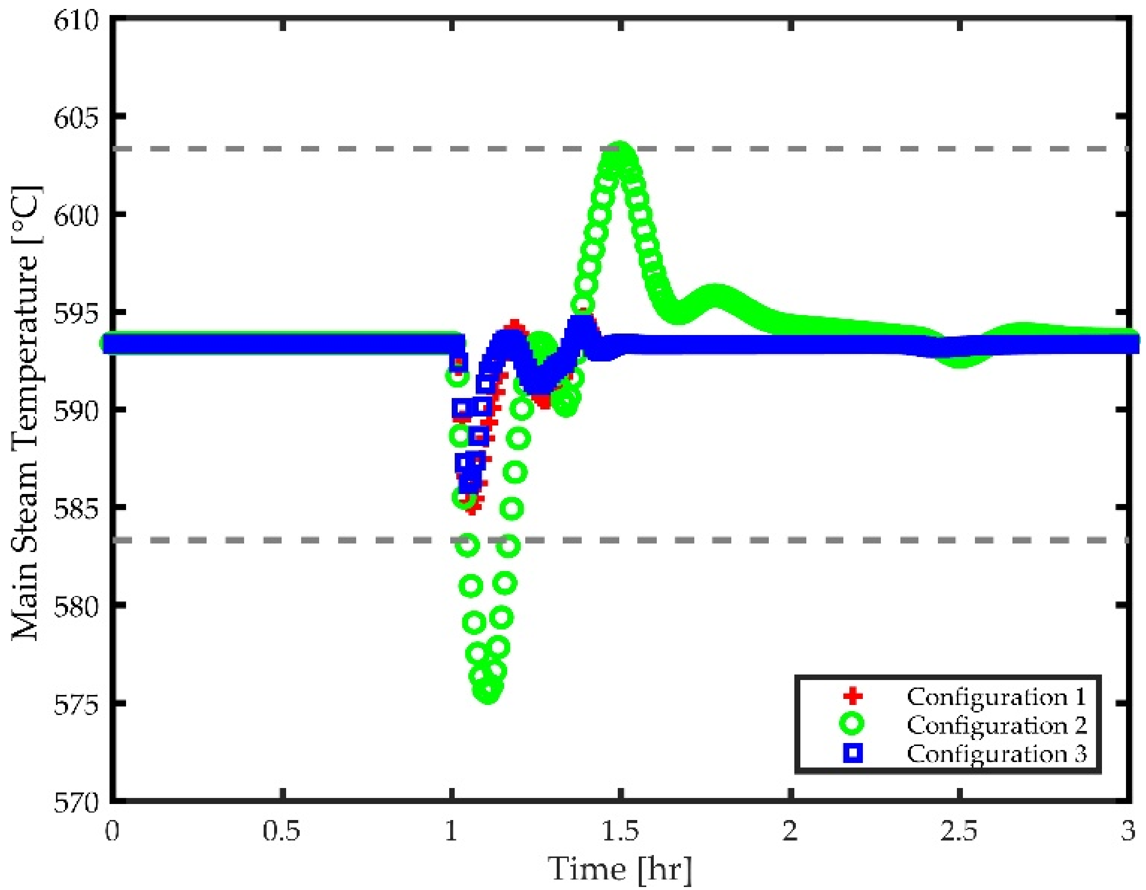
Results
Ramp Down in Power Demand (Load)

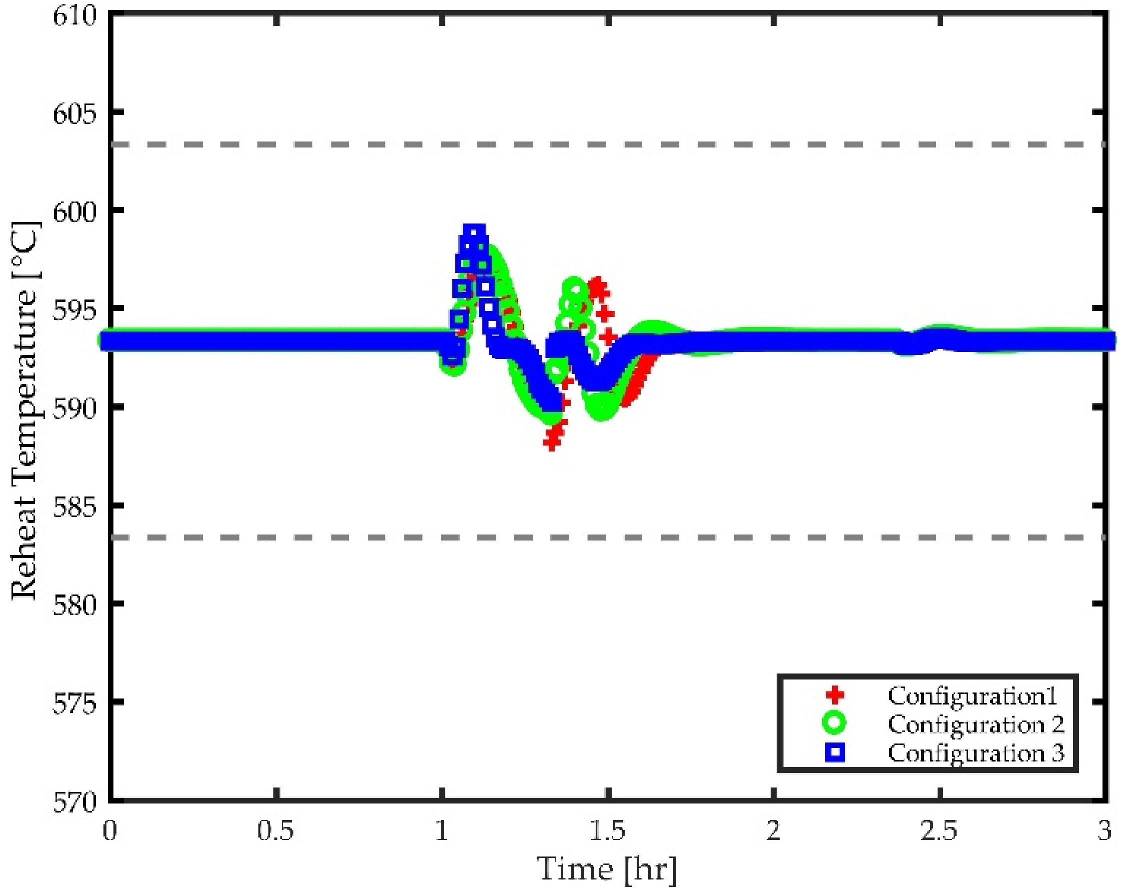
- Load decrease from 100% to 40% over 20 min
- Ramp rate of 3% load per min (Current industry practice 3-8% load change per min for SCPC*)
- Near-perfect tracking of the load
- BFW flowrate and main steam pressure decrease slightly more than 60%
- Main steam pressure slides from 242 bar to 93 bar (7.5 bar per min)



* Lindsay, J.; Dragoon, K. *Summary Report on Coal Plant Dynamic Performance Capability*; Renewable Northwest Project, pp. 4–7, 2010.

Main and Reheat Steam Temperatures
Responses for Control Configurations 1-3





Results
Disturbance in Coal Feed Composition

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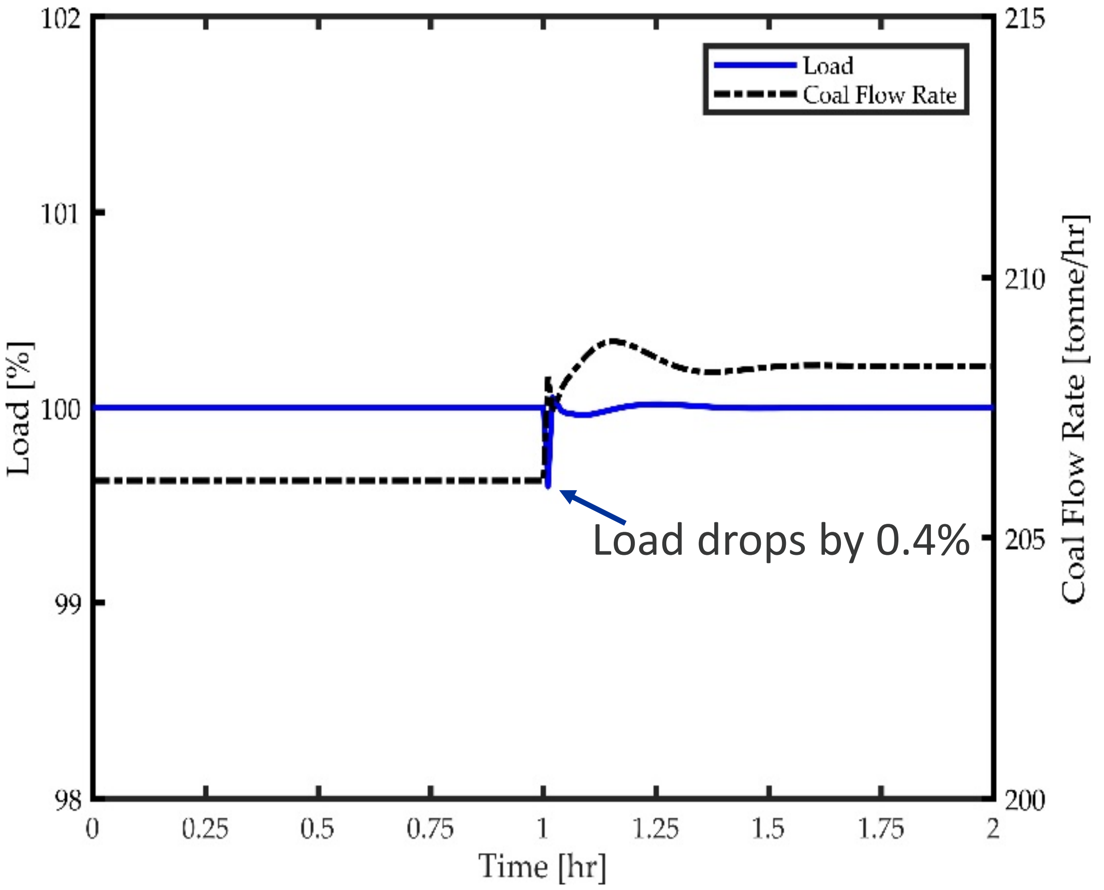
- Base case: Illinois #6 coal*
- Transient Study
  - 2.6% reduction in calorific value of coal feed

	Ultimate Coal Analysis	
	Base Case	Changed
H_2O	11.12	13.18
C	63.75	59.36
H_2	4.5	5.18
N_2	1.25	1.49
Cl	0.29	0.29
S	2.51	2.88
O_2	6.88	7.92
Ash	9.7	9.7



Disturbance rejection results for load and coal flow using Configuration 3 to control main and reheat steam temperatures

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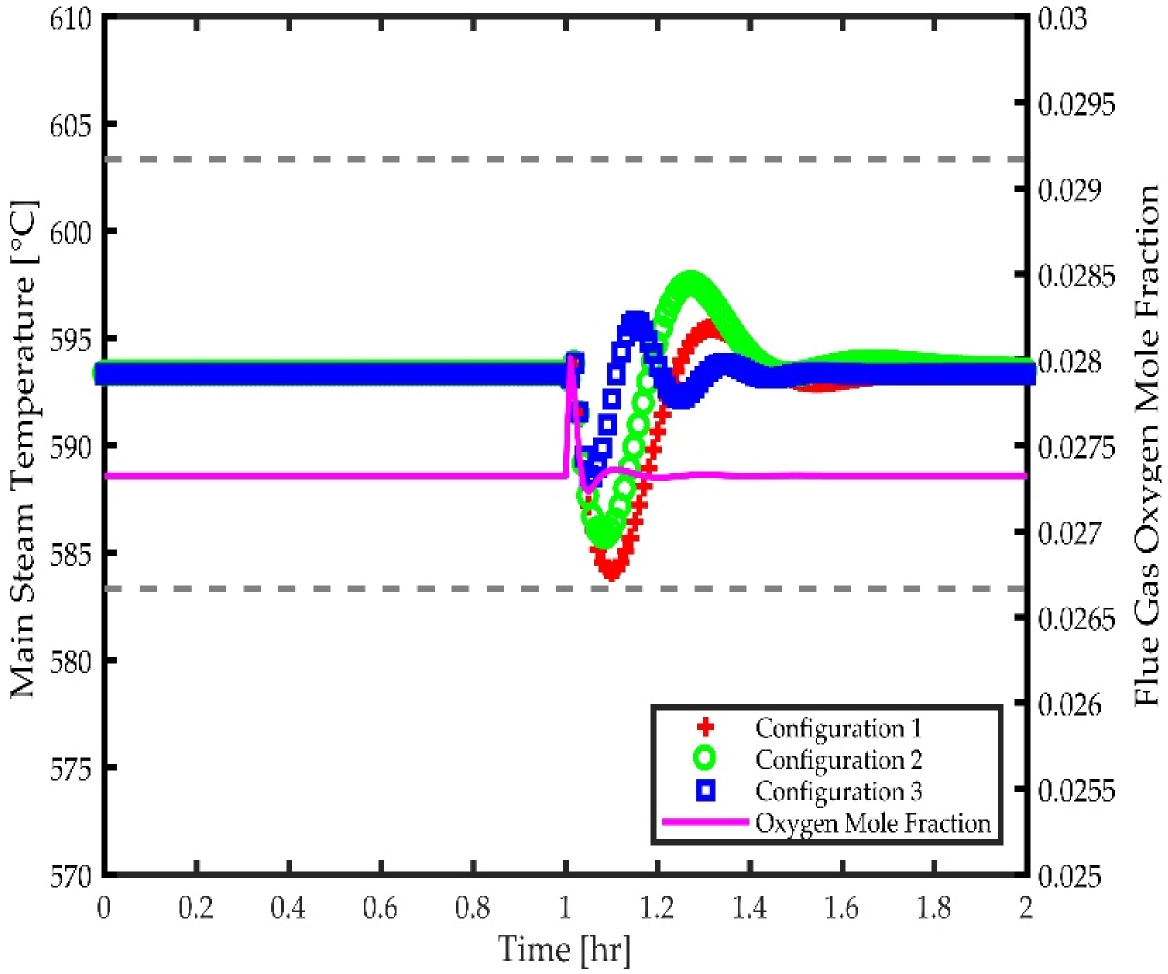
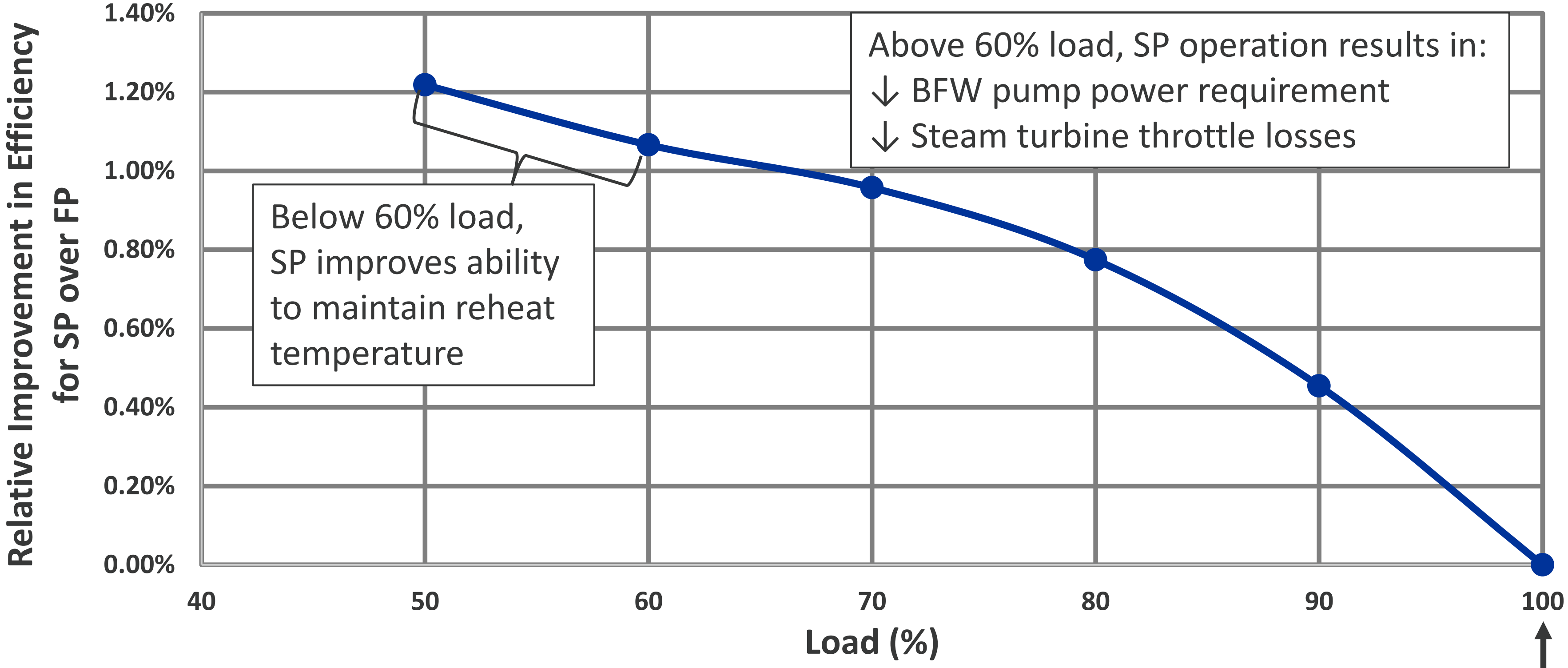
* Case B12B, Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3, National Energy Technology Laboratory, www.netl.doe.gov, DOE/NETL-2015/1723, July 6, 2015.

Results
Disturbance in Coal Feed Composition

- **Configuration 3 with Smith predictor provides best performance**
  - Lower under/overshoot (< 5 °C)
  - Faster settling time for control of main steam temperature
    - Faster by more than 20 min
- **Oxygen concentration in flue gas remains relatively constant at its setpoint**
  - Irrespective of the configuration for steam temperature control



Results
Sliding- vs. Fixed-Pressure for 100% to 50% Load



- Improved efficiency for sliding-pressure (SP) over fixed-pressure (FP) at part-load operation
- Full-load results
  - Efficiency: 40.69%
  - Heat rate: 8846.69 kJ/kWh

Paper for Special Issue of Open-Access Journal *Processes*: Modeling and Simulation of Energy Systems

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processes

MDPI

Article

Development of a Dynamic Model and Control System for Load-Following Studies of Supercritical Pulverized Coal Power Plants

Parikshit Sarda [1], Elijah Hedrick [1], Katherine Reynolds[1], Debangsu Bhattacharyya [1,*], Stephen E. Zitney[2], and Benjamin Omell[3]

[1] Department of Chemical and Biomedical Engineering, West Virginia University, 395 Evansdale Drive, Morgantown, West Virginia 26506-6070 USA
[2] National Energy Technology Laboratory, 3610 Collins Ferry Road, Morgantown, WV 26507, USA
[3] National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA
* Correspondence: debangsu.bhattacharyya@mail.wvu.edu; Tel.: 304-293-9335

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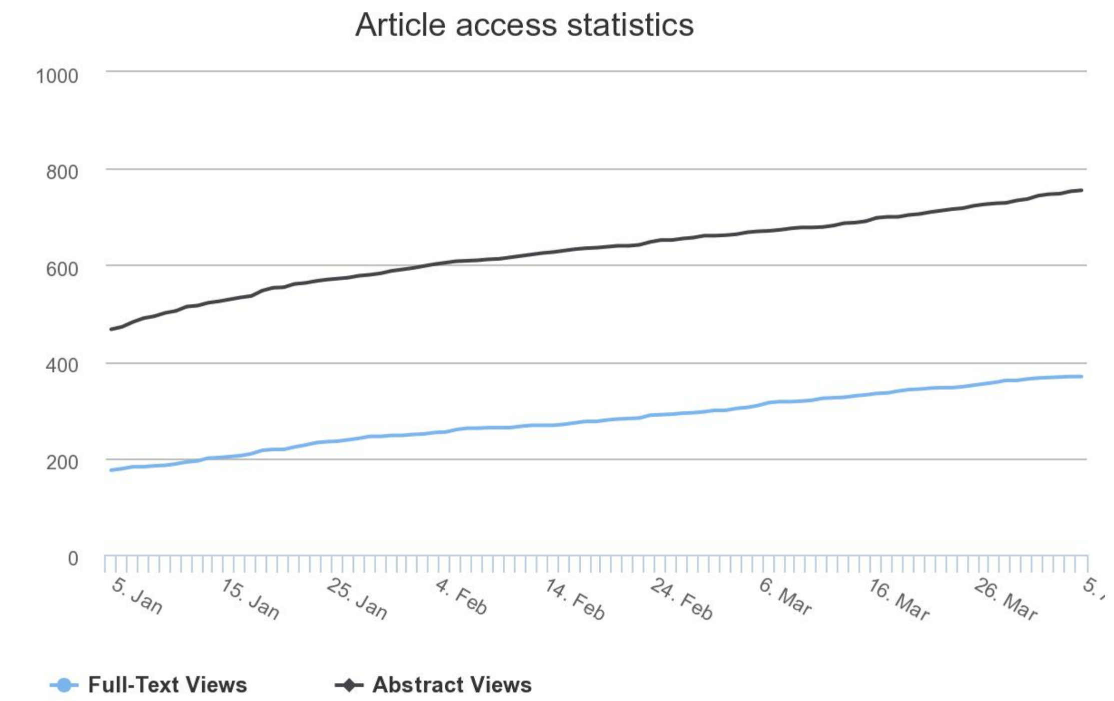
Abstract: Traditional energy production plants are increasingly forced to cycle their load and operate under low-load conditions in response to growth in intermittent renewable generation. A plant-wide dynamic model of a supercritical pulverized coal (SCPC) power plant has been developed in the Aspen Plus Dynamics® (APD) software environment and the impact of advanced control strategies on the transient response of the key variables to load-following operation and disturbances can be studied. Models of various key unit operations such as the steam turbine are developed in Aspen Custom Modeler® (ACM) and integrated in the APD environment. Various coordinated control strategies (CCS) are developed above the regulatory control layer. Three control configurations are evaluated for the control of the main steam; the reheat steam temperature is also controlled. For studying servo control performance of the CCS, the load is decreased from 100% to 40% at a ramp rate of 3% load per min. Impact of a disturbance due to change in the coal feed composition is also studied. The CCS is found to yield satisfactory performance for both servo control and disturbance rejection.

Keywords: Dynamic Modeling; Process Control; Load-Following; Supercritical Pulverized Coal (SCPC); Cycling; Time-Delay; Smith Predictor

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; https://doi.org/10.3390/pr6110226, Nov. 2018.



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Presentations

- Sarda P., E. Hedrick, K. Reynolds, E. Tomer, A.P. Burgard, A. Lee, J.C. Eslick, D.C. Miller, B. Omell, S.E. Zitney*, and D. Bhattacharyya, "Optimal Load-Following Operation of Supercritical Pulverized Coal Power Plants," *EPRI Flexible Operations Conference: Conventional and Combined Cycle Power Plant Cycling Damage and Management*, Tulsa, OK, June 6-8 (2018).
- Zitney*, S.E., "Fossil Energy Dynamic Performance Baselines for Improving Flexible Operations," *NETL-EPRI Coal Plant Flexibility Workshop*, Pittsburgh, PA, August 14-15 (2018).
- Sarda*, P., E. Hedrick, K. Reynolds, E. Tomer, B. Omell, S.E. Zitney, and D. Bhattacharyya, "Development of Advanced Model-Based Controllers for Optimal Load-Following Operation of the Supercritical Pulverized Coal Power Plants," *AIChE 2018 Annual Meeting*, Pittsburgh, PA, October 28 - November 2 (2018).
- Reynolds*, K., E. Hedrick, P. Sarda, E. Tomer, B. Omell, S.E. Zitney, and D. Bhattacharyya, "On the Temporal Evolution of the Material Stress Profile in a Supercritical Pulverized Coal Boiler under Load-Following Operation," *AIChE 2018 Annual Meeting*, Pittsburgh, PA, October 28 - November 2 (2018).
- Reynolds, K., E. Hedrick, P. Sarda, , S.E. Zitney, B. Omell, and D. Bhattacharyya*, "Dynamic Modeling and Simulation of a Supercritical Pulverized Coal-Fired Boiler under Load-Following Operation," *EPRI Flexible Operations Conference: Conventional and Combined Cycle Power Plant Cycling Damage and Management*, Pittsburgh, PA, June 5-7 (2019).
- 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 Conference*, Clearwater, FL, June 16-21 (2019).

Ongoing and Future Work

- **Complete development of high-fidelity dynamic boiler model**
- **Complete development of boiler health sub-models**
- **Implement high-fidelity boiler model with health sub-models in the dynamic baseline SCPC plant model**
- **Adapt high-fidelity dynamic SCPC baseline model and controls to match industry partner SCPC plant configuration and controls**
  - Analyze operating scenarios of interest
  - Improve flexible operations and minimize health impacts

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

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