Modeling and Optimization of Existing Fleet: Boiler HX Network

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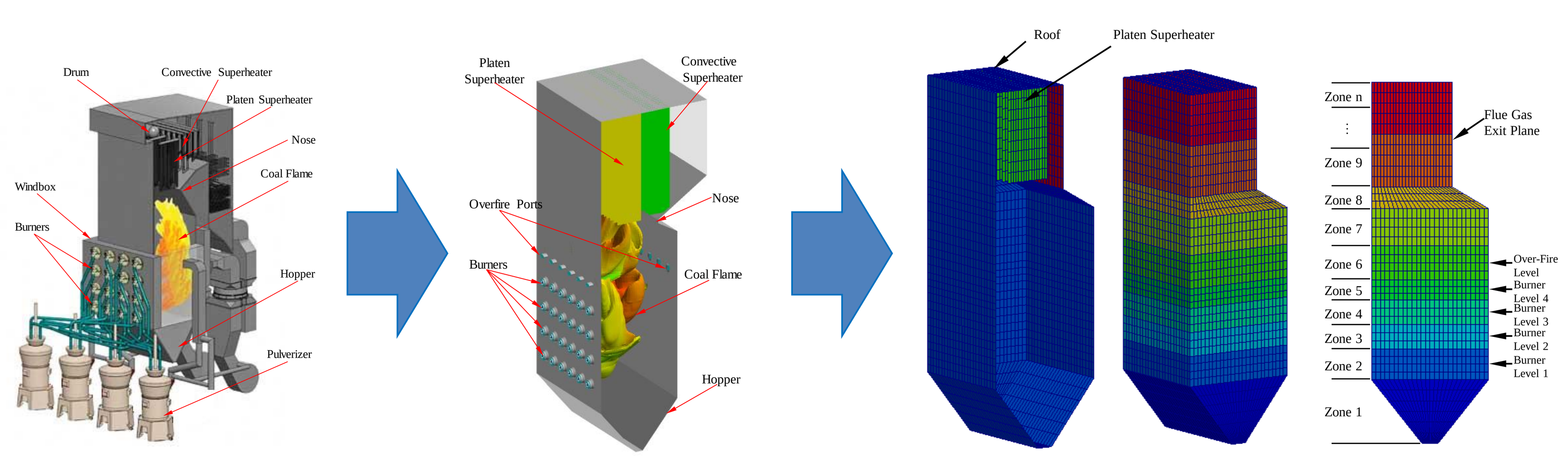
IDAES Institute for the Design of Advanced Energy Systems

IDAES is developing capabilities to **improve the efficiency and reliability** of the existing fleet of **coal-fired power plants** while accelerating the development of a broad range of advanced fossil energy systems

IDAES tools address several important challenges:

- Enabling **flexible long-term operation** to accommodate highly variable renewable energy resources
- Determining the best **options for retirement or refurbishment** of aging fossil energy assets

Overview of Fire-side Boiler Model



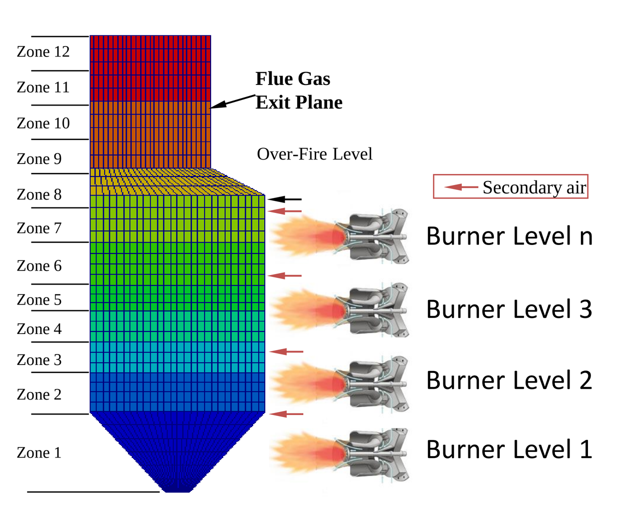
Typical CFD Model   Fire-side Boiler Model

- 1-D discretization along furnace height
  - Uniform flow properties in each zone
- 3-D discretization for rigorous radiation
- Gas phase chemical equilibrium
- Solid phase char reaction kinetics
- NOx reaction kinetics
  - Thermal, fuel, reburning NOx
- Predicts FEGT, flue gas composition, burnout, NOx, and heat flux profile
- CPU time around 30 sec
  - 3 orders of magnitude faster than CFD

Fire Side: Highly Accurate Algebraic Surrogate Models

Inputs, Latin hypercube sampling

- Wall temperature (each zone)
  - 400 – 1100 K
- Fuel flow rate
  - 10 – 45 kg/s
- Stoichiometric ratio
  - 1.1-1.2 calc O_2/real O_2
  - Air splits calculated
    - Primary Air
    - Secondary Air
    - Over-Fire Air
- Secondary air temperature
  - 550 – 650 K
- Burners operation
  - Full load (i.e. n burners)
  - Mid load (i.e. 3 burners)
  - Low load (i.e. 2 burners)

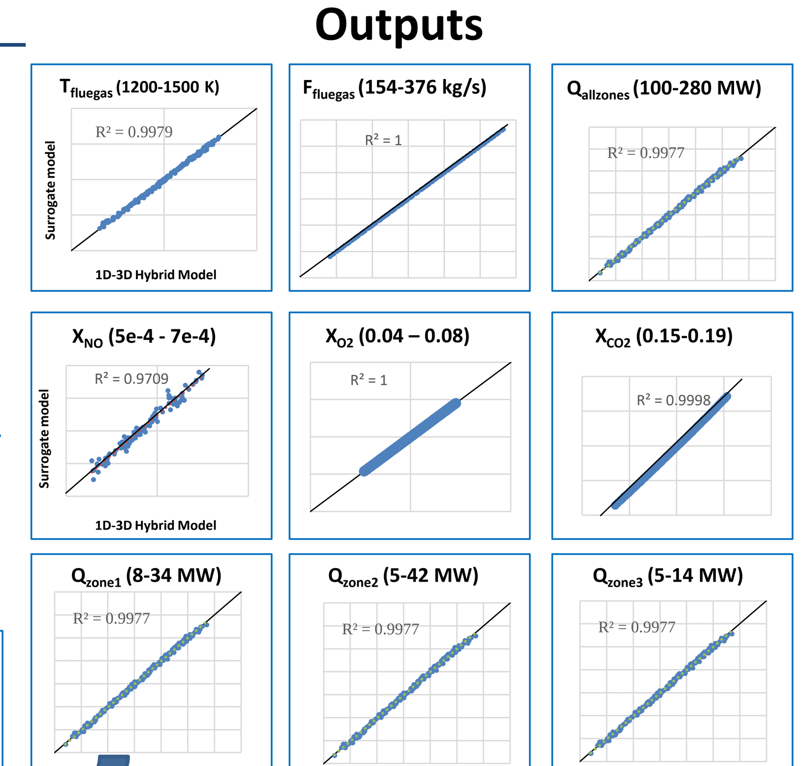


3D/1D Mesh

Outputs

- Heat transfer rate (each zone)
- Flue gas composition
  - x_{CO2}
  - x_{H2O}
  - x_{O2}
  - x_{NOx}
  - x_{SOx}
- Flue gas exit temperature
- Unburned carbon

Outputs



Surrogate model example:

$$q_1 = \alpha_1 F_F + \alpha_2 2ndAirT - \alpha_3 T_{w1} + \alpha_4 T_{w2} + \alpha_5 T_{w7} + \alpha_5 T_{w7} + \log(2ndAirT) - \log(F_F)$$

Boiler Model: Integration Fire Side and Water Wall

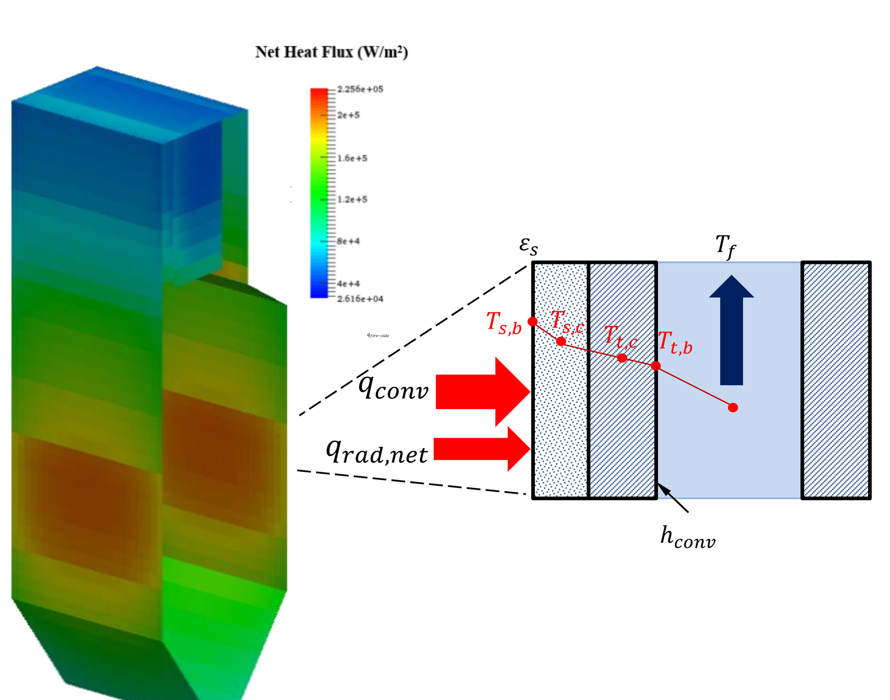
Fire Side:

Inputs:

- Furnace geometry
- Fuel properties, PSD
- Fuel/Air flow rates
- Wall Temperatures

Outputs:

- Heat transfer rates
- Flue Gas:
  - Flow rate
  - Temperature
  - Mole fractions (NOx)
  - Unburned carbon



Schematic representation of the integration of the fire side 1D/3D model and Water side model

Water Side:

Inputs:

- Tube Geometry (i.e. tube diameter)
- Inlet water/steam
  - Flow rate
  - P, h (or T, x)

Outputs:

- Slag wall temperature
- Outlet water/steam
  - Flow rate
  - P, h (or, T, x)

Tube Side Model:

$$Q + Fh_{in} = Fh_{out}$$

$$Q = \frac{A(T_{s,b} - T_f)}{\frac{1}{h_{conv}} + \frac{1}{h_{tube}} + \frac{1}{h_{slag}}}$$

$h_{conv} = Eh_l + Sh_{pool}$ (two phase flow)

h_l Liquid only heat transfer coef.

h_{pool}: Pool boiler heat transfer coef.

$$h_{tube} = \frac{C_{shape,tube} k_{tube}}{\delta_{tube}}$$

$$h_{slag} = \frac{C_{shape,slag} k_{slag}}{\delta_{slag}}$$

Steam quality in boiler zones at various operations:

	Vapor Fraction				
Zone	Low Load....		Medium		...High Load
12	0.056	0.058	0.065	0.077	0.080
11	0.052	0.053	0.060	0.072	0.074
10	0.045	0.047	0.053	0.063	0.065
9	0.034	0.035	0.040	0.048	0.050
8	0.019	0.020	0.023	0.028	0.029
7	0.016	0.016	0.019	0.024	0.025
6	0.012	0.012	0.014	0.018	0.019
5	0.007	0.007	0.009	0.012	0.013
4	0.002	0.002	0.004	0.006	0.006
3	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000

Modeling and Optimization of the Existing Fleet

General Power Plant Modeling Library:

- Hybrid Boiler Model (integration of fire and water side)
  - Customizable (coal type, furnace geometry, and materials)
  - Reliable predictions of unburned carbon, Sox, NOX, excess O2
- Customized heat exchanger model
  - Co-current, counter-current, cross-flow
  - Rigorous heat transfer correlations:
    - Convective heat transfer (single phase or two phase)
    - Ash layer and tube thickness (wall conduction model)
- Rigorous turbine model
  - Customizable (turbine type, materials, # stages, extraction points)
  - Efficiency penalties for off-design conditions

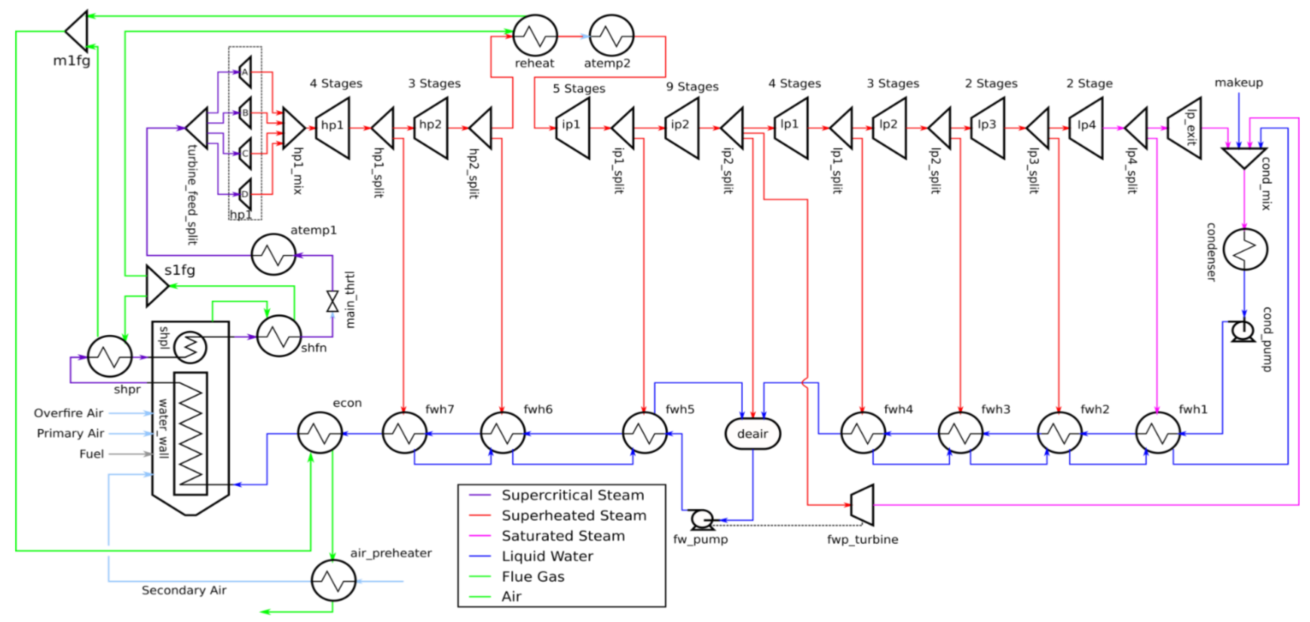
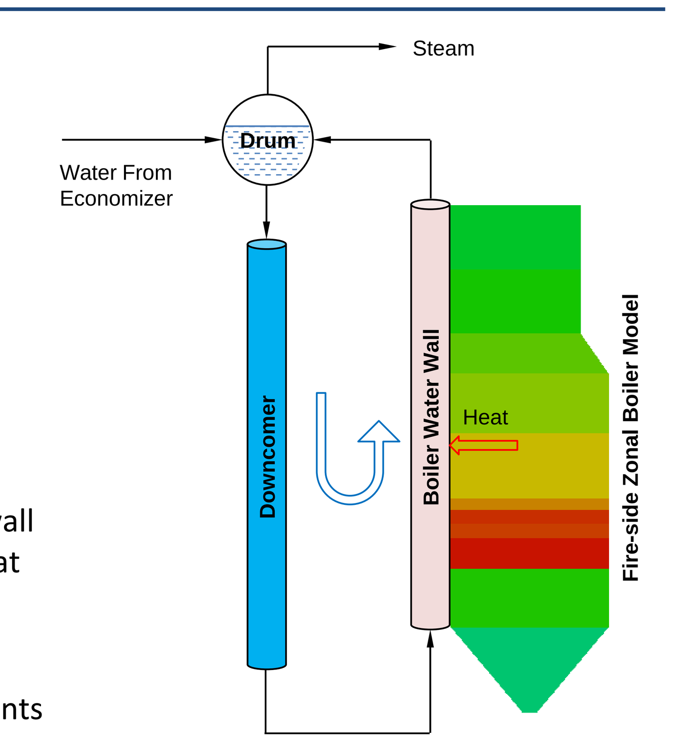
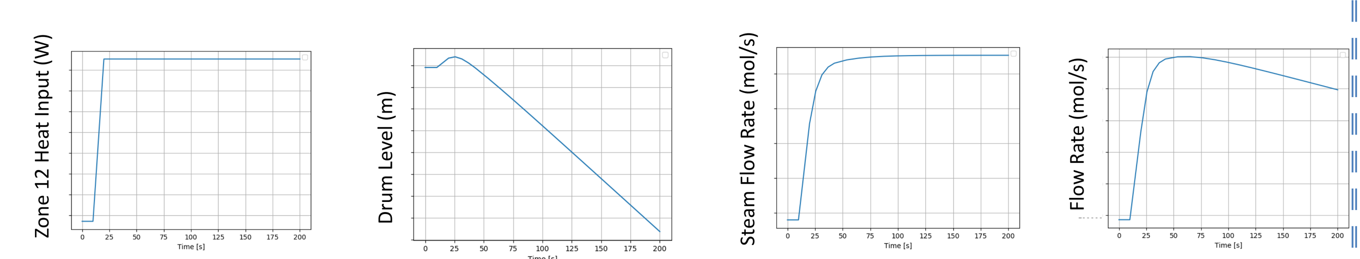


Figure: Supercritical Power Plant Flowsheet (NETL Baseline Report)

Dynamic Modeling and Optimization

- Fixed Inputs:
  - Drum pressure
  - Feed water flow
  - Feed water state (p, T, h)
- Initial Condition:
  - Steady-state
  - Drum level at 0.89 m from bottom
- Step Change:
  - Heat from fireside to waterwall increased by 5% in all zones at 20 sec
- Duration:
  - 200 sec, 20 discretization points





5% step increase of heat to waterwall (WW)

Level increased initially due to increased vapor fraction in waterwall tubes

Steam flow increases due to the increase of heat input

Recirculation water rate increases due to the decrease of density in WW tubes

Data Reconciliation Framework

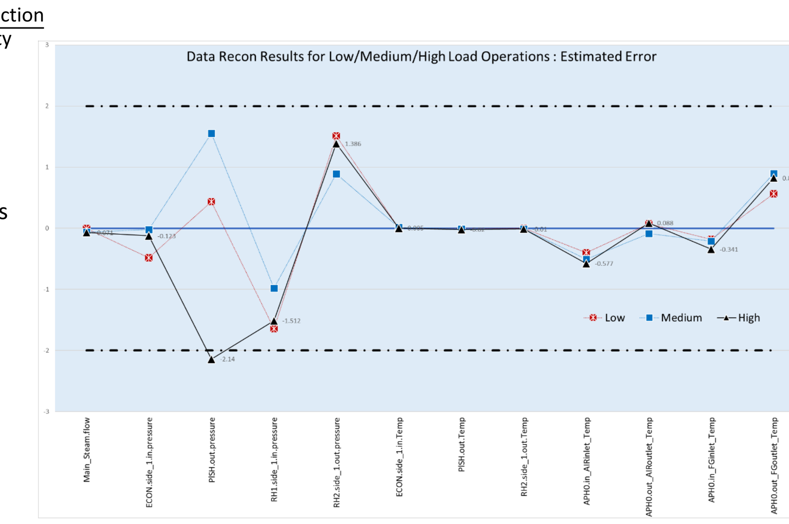
"Ensure data is reliable"

$$\underset{\{temps, pressures, flows\}}{\textbf{Minimize}} \sum_{data} (error_{meas})^2$$

$$error_{meas} = \frac{\text{measurement} - \text{model prediction}}{\text{measurement uncertainty}}$$

subject to

- Flowsheet connectivity
- Mass and energy balances
- Physical property calculations



Sensitivity Study: Slag Layer Thickness

The models were used to simulate different cases (slag thickness from 1 to 4 mm) to quantify the changes in:

- Heat transfer coefficients
- Wall temperature
- Slag temperature
- Heat transfer
- Flue gas outlet temperature

Remarks: the slag layer can reach very high temperatures; need to:

- Prevent liquid ash formation
- Avoid ash accumulation in the superheater and reheater

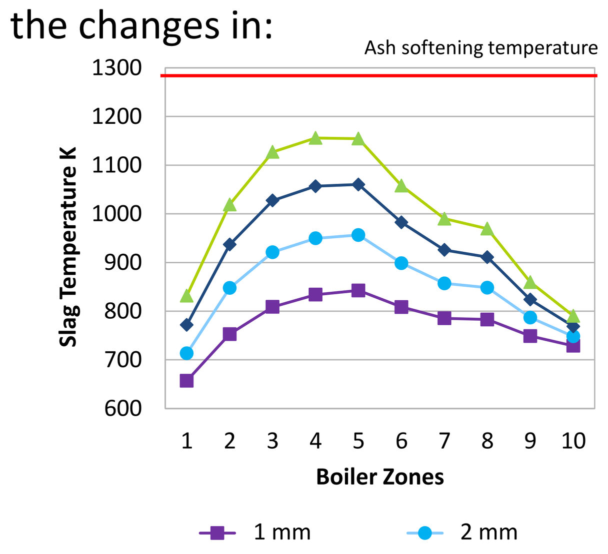


Figure: Slag temperature as a function of slag thickness

IDAES Supports:

- Advanced modeling and machine learning techniques for multi-scale energy systems
- Integration of high fidelity models and surrogate models (i.e. boiler fire side and water wall model)
- Advanced optimization tools for optimal operation of subcritical and supercritical coal-fired power plants.
  - Steady State and Dynamic Optimization
  - Data Reconciliation Framework
  - Parameter Estimation Framework
- Rigorous glass box models can be leveraged to incorporate health models and analyze the impact of cycling in coal-fired power plant operations.

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