Impact of CFD Enhancements for Modeling Coal-fired Boiler Oxy-Combustion Retrofits

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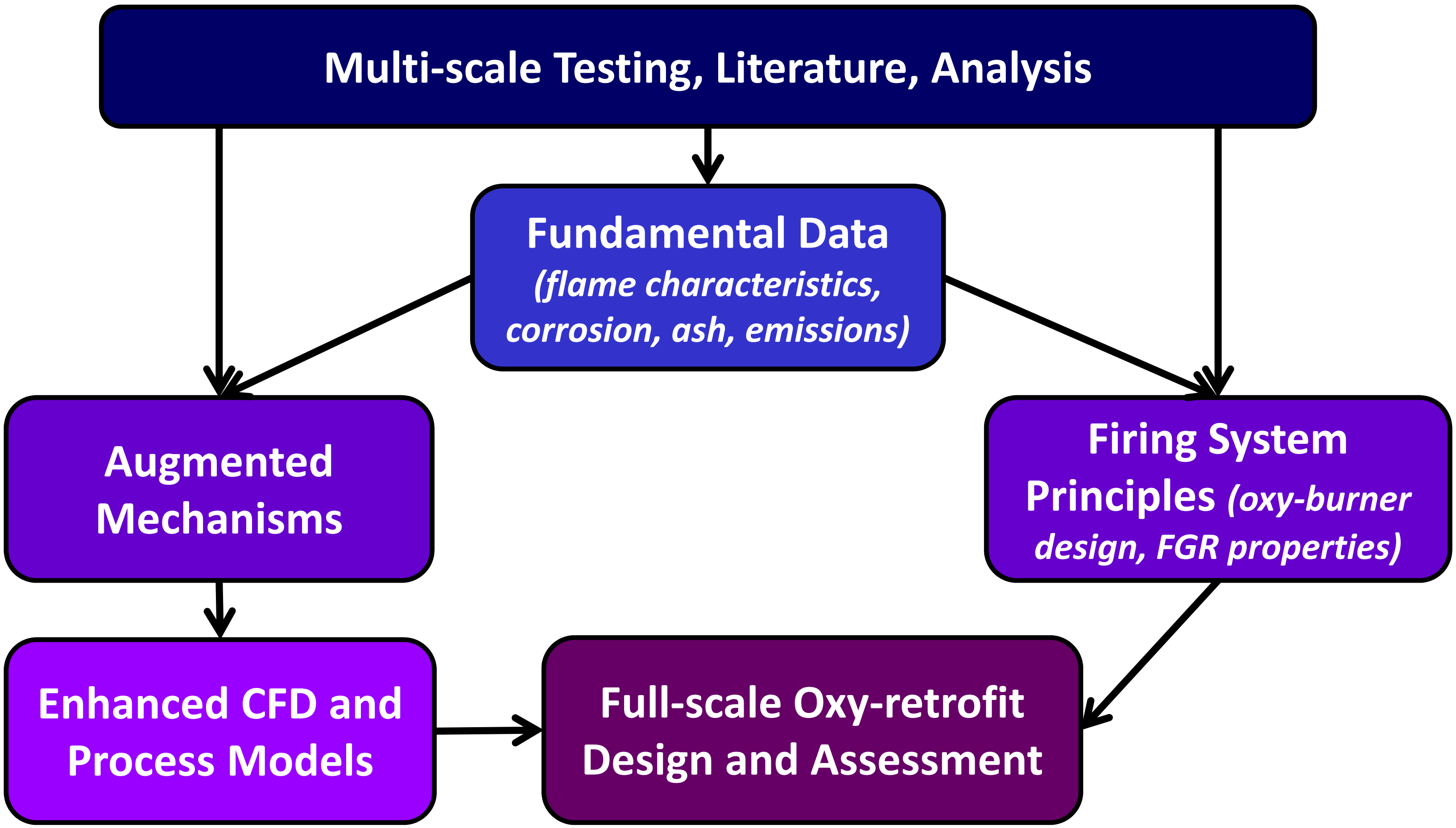
For Energy and Environmental Solutions

REACTION ENGINEERING INTERNATIONAL

Overview

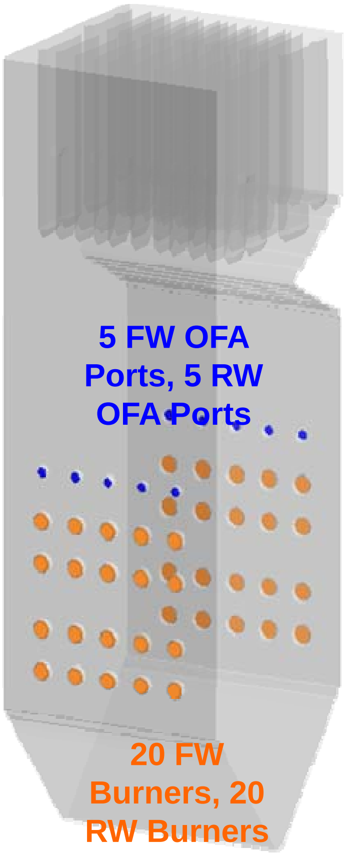
- Retrofit Assessment Approach
- Boiler Retrofit Design
- *Glacier* CFD Software
- CFD Enhancements and Results
- Conclusions

Retrofit Assessment Approach



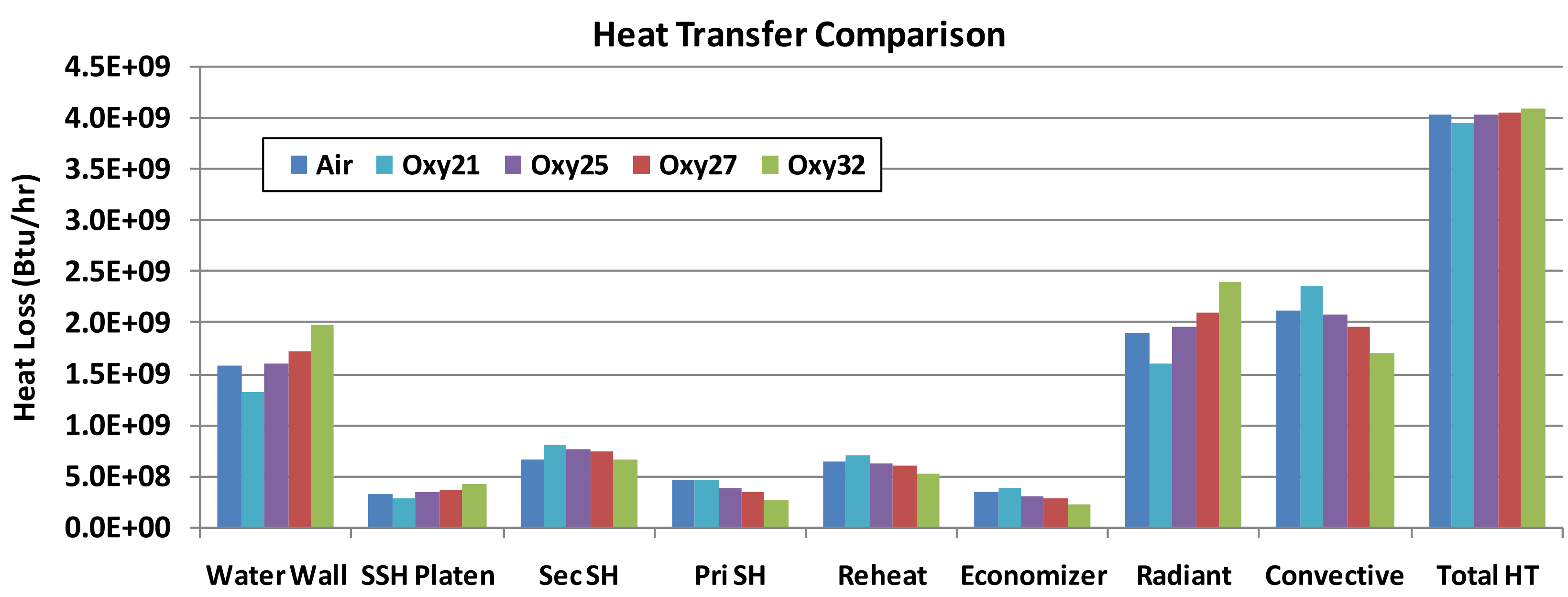
PacifiCorp Hunter Unit 3 Retrofit

- 480 MW opposed-wall, staged firing, Utah bituminous coal
  - Focus on radiant furnace results
- Main retrofit tasks:
  - Determine firing conditions (REI)
  - Design oxy-burner (Siemens)
  - Match air-fired heat transfer
- Oxy-coal firing potential impacts:
  - Char oxidation / LOI
  - Sooting
  - Radiative heat transfer
  - Slagging
  - Corrosion
  - Emissions



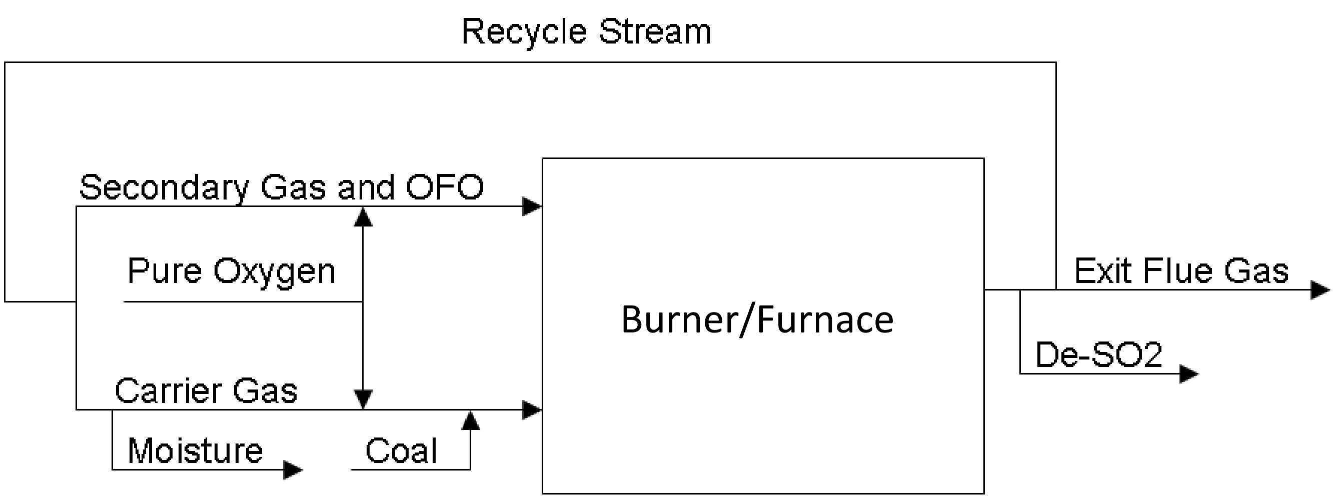
Retrofit – Firing Conditions

- Retrofit Task 1 – determine firing conditions (REI):
  - Based on SteamGen Expert process model (combustion + steam circuit)
  - Suggests 25-27% O_2 in O_2/FGR mixture would best match air-fired heat transfer (O_2 and FGR mixed at burner)



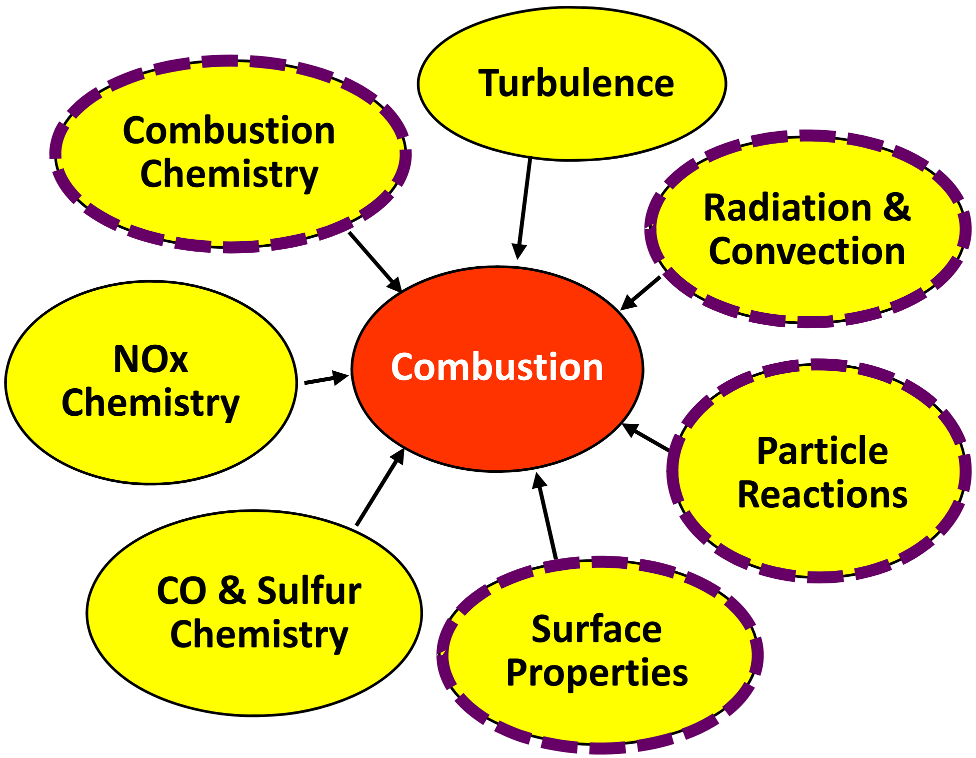
Retrofit – Oxy-Burner Design

- Retrofit Task 2 – oxy-burner design (Siemens):
  1) Estimate O_2 and flue gas flows (SR, excess O_2)
  2) Determine scaling factors to produce aerodynamic similitude
  3) Account for heterogeneous O_2/FGR mixtures
  4) Allocate flows to burner sections and overfire gas ports
  5) Size burner sections and OFG ports (fit in existing boiler cut-outs)



REI's *Glacier* CFD Software

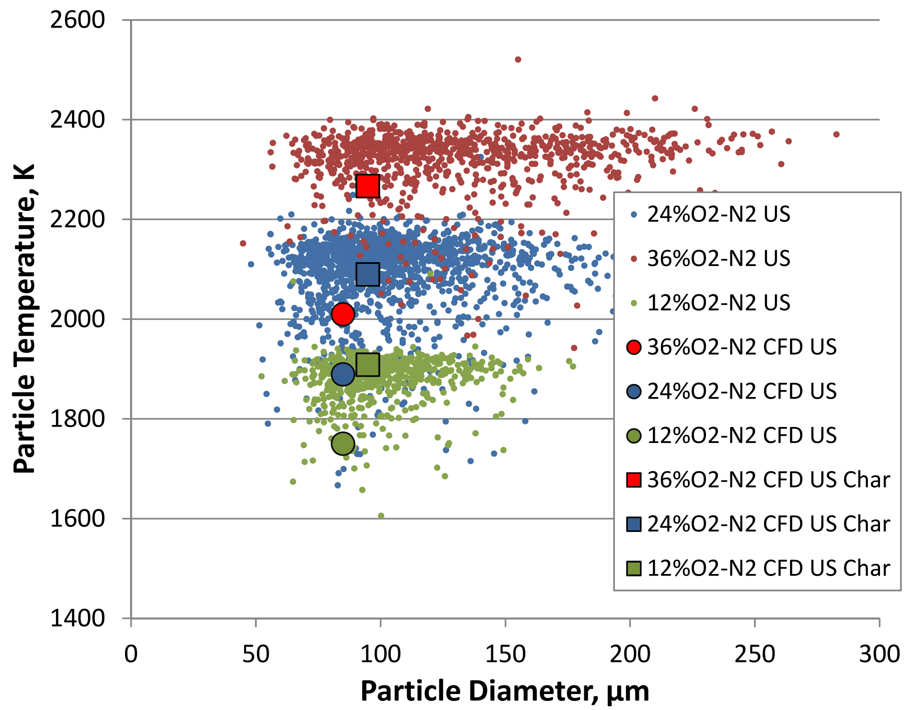
- 20+ years of development and application to coal combustion
- Advanced chemistry (NOx, CO, sulfur, soot, ash)
- Two-phase flow
  - Heterogeneous reactions (volatiles, char, soot)
  - Burnout / LOI
  - Deposition, slagging, sintering
  - Multiple fuels
- Radiative heat transfer
- Corrosion (H_2S, pyrite, sulfur)
- Erosion
- Variable surface conditions, coupling to steam circuit



Compare air-fired and oxy-fired results, with and without upgraded sub-models

Extended Char Oxidation Sub-Model

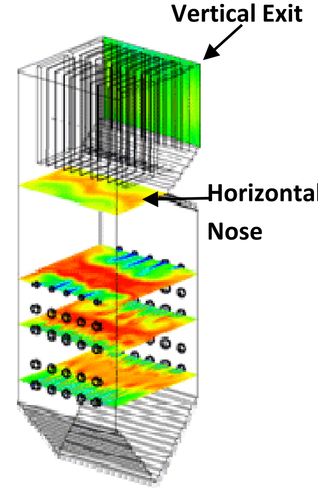
- Based on work by Shaddix and Geier[1] at Sandia using measurements in Sandia's Entrained Flow Reactor and SKIPPY modeling
- Started with heterogeneous surface reactions
- Added Extended Single Film model including:
  - Steam gasification
  - CO_2 gasification



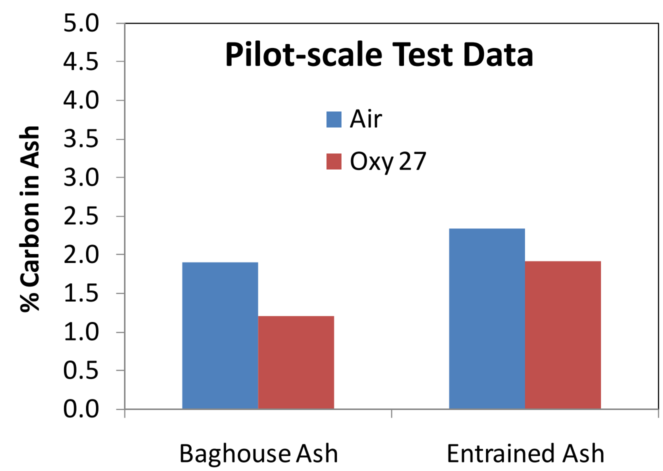
[1] M. Geier, C. Shaddix, K. Davis, H. Shim, "On the Use of Single-Film Models to Describe the Oxy-fuel Combustion of Pulverized Coal Char", 2011 Clearwater Clean Coal Conference

Char Oxidation Results

	Air	Air w/ Char	Oxy27	Oxy27 w/ Char
Horizontal Nose Plane				
Temperature (˚F)	2418	2417	2461	2473
CO Concentration, wet (ppm)	4,414	6,168	9,886	15,123
Vertical Exit Plane				
Temperature (˚F)	1649	1644	1622	1641
CO Concentration, wet (ppm)	1,032	1,436	2,429	3,815
Unburned Carbon in Fly Ash	7.4%	3.8%	8.6%	2.2%



- Original char oxidation model predicts:
  - Very high unburned carbon in ash
  - Increased UBC for oxy-combustion
- New char oxidation model predicts:
  - Reasonable UBC concentrations (2 - 3% UBC observed at the plant)
  - Decreased UBC for oxy-combustion
  - Increased CO concentrations

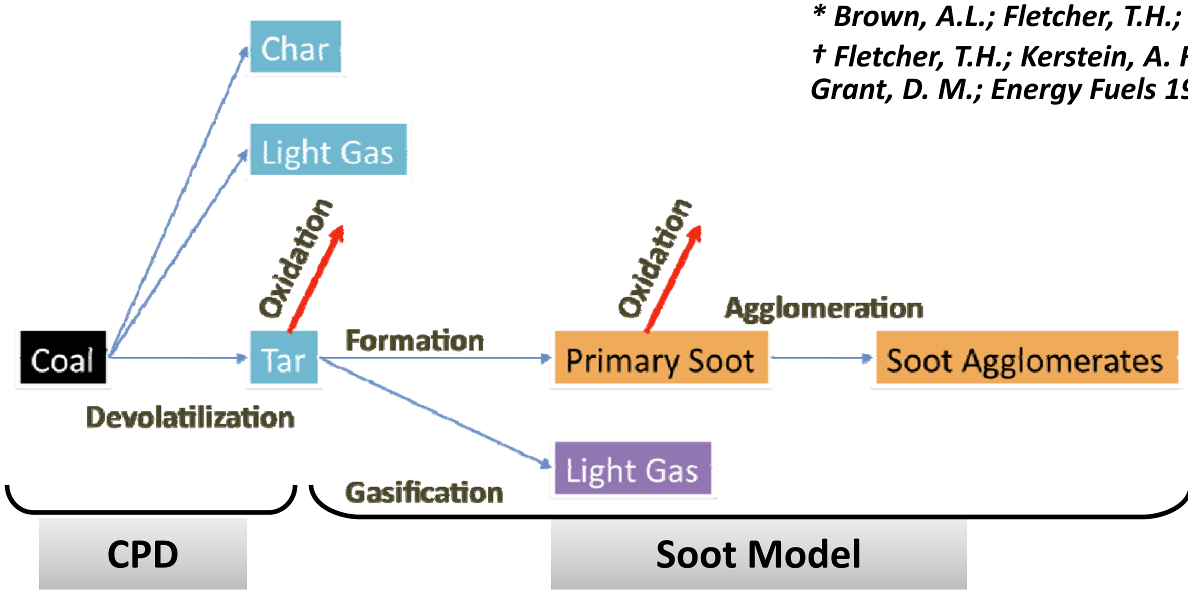


Soot Sub-Model

- Coal-derived soot is assumed to form from only tar*
  - Relatively constant mass of soot plus tar after devolatilization
  - Acetylene and benzene are not found in significant quantities
- Tar yields calculated by CPD model† based on measured coal properties
- CFD code tracks three equations for conservation of mass of soot, tar, and number of soot particles

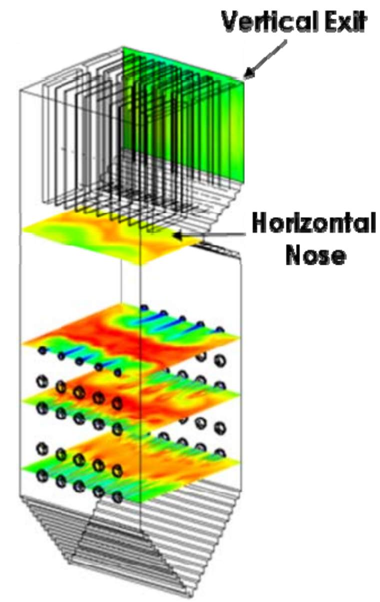
** Brown, A.L.; Fletcher, T.H.; Energy Fuels 1998, 12, 745-757.*

† Fletcher, T.H.; Kerstein, A. R.; Pugmire, R. J.; Solum, M. S.; Grant, D. M.; Energy Fuels 1992, 6, 414-431.



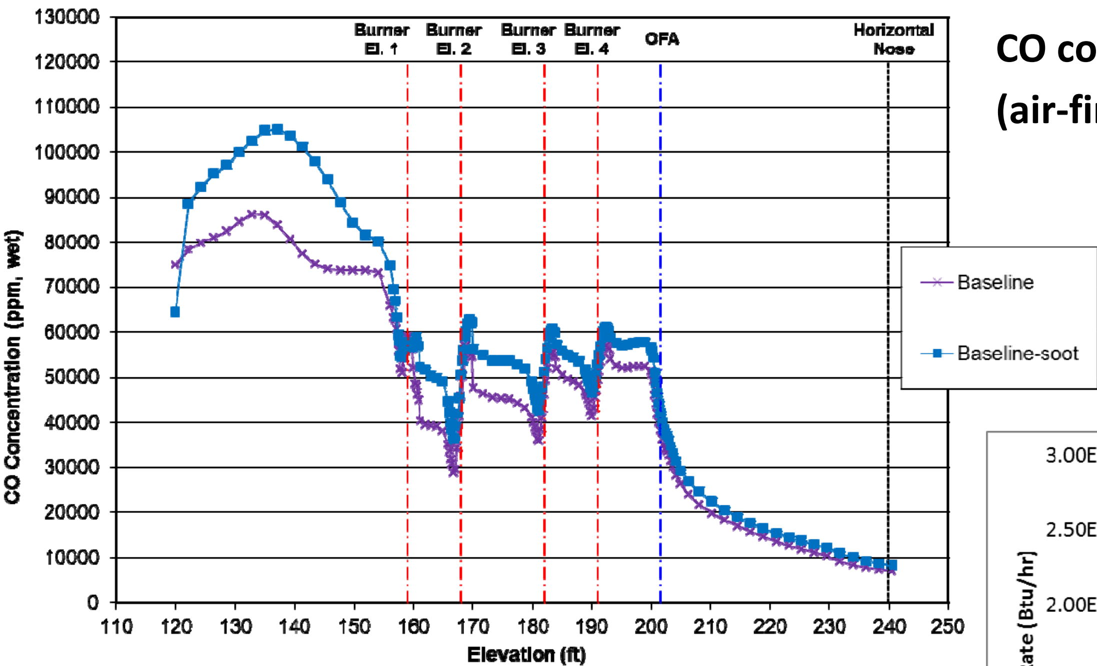
Soot Results

	Skyline Bituminous Coal		
	Baseline	Baseline w/ soot	Oxy26 w/ soot
Horizontal Nose Plane			
Temperature (°F)	2502	2518	2582
CO Concentration, wet (ppm)	7,038	8,454	16,451
Vertical Exit Plane			
Temperature (°F)	1785	1787	1765
CO Concentration, wet (ppm)	1,745	3,060	5,663
O_2 Concentration, wet (%)	3.2%	3.3%	2.9%
Unburned Carbon in Fly Ash	3.3%	3.6%	2.1%

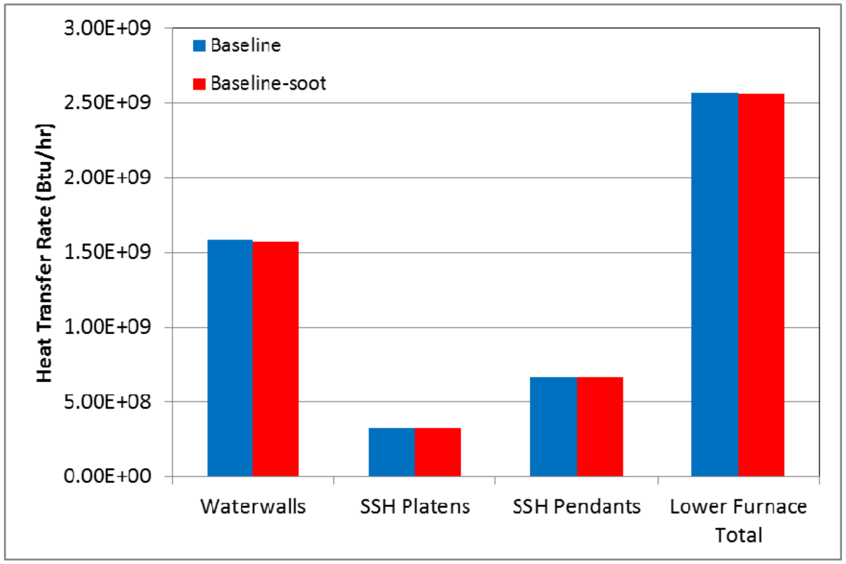


- **Including soot sub-model had only minor impact on results, largest impact was on CO concentration**
- **Soot formation/destruction depends on oxidant availability and the fuel-oxidizer mixing under given operating conditions**

Soot Results



CO concentration vs boiler elevation (air-firing)

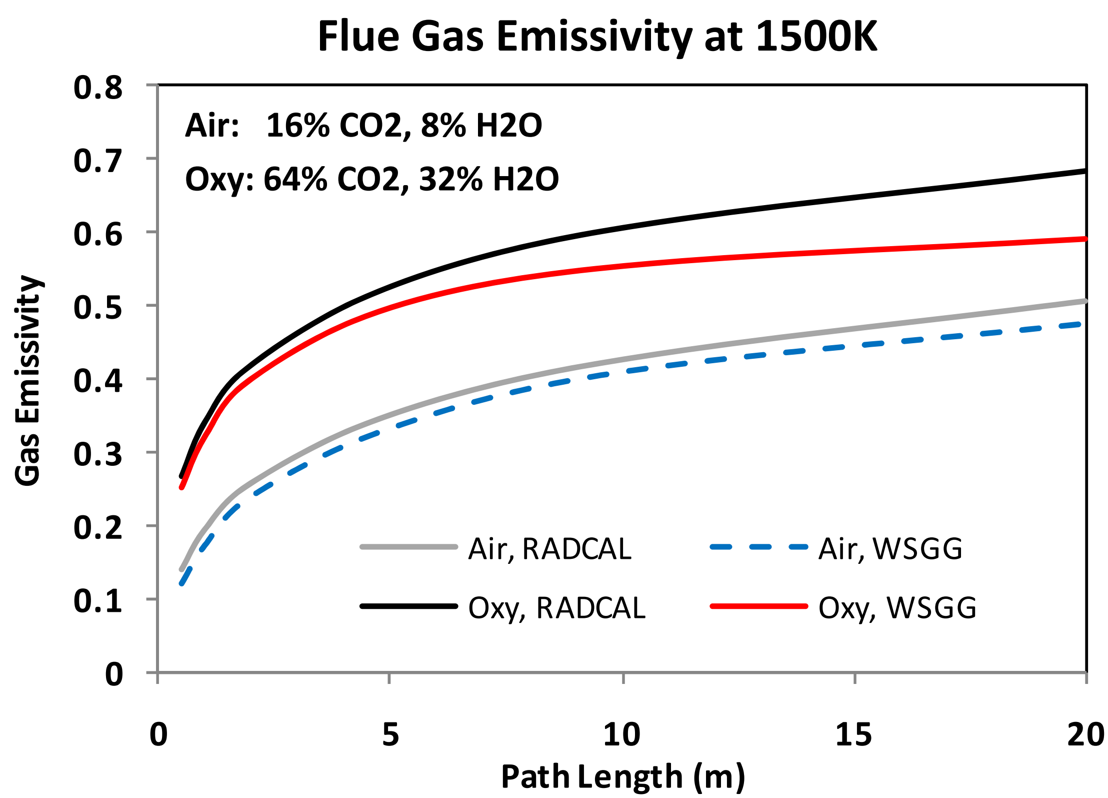


Lower furnace heat transfer (air-firing)

Radiation Property Sub-Model

- Flame emission = $f(\varepsilon, T_g^4, k_p, T_p^4)$
- Gas emissivity = $f(T_g$, CO_2 & H_2O conc., path length)
- Compare impact of two gas emissivity sub-models:
  - Modified weighted-sum-of-gray-gas model (WSGG)
    - Based on curve-fits of measured data (Hottel charts) and high temperature correlations
    - Potentially limited in oxy-combustion because original measurements done at shorter path lengths and lower CO_2, H_2O concentrations (typical of air-fired combustion)
  - Statistical Narrow Band model (RADCAL)
    - Based on statistical representation of full radiation spectrum
    - Extends emissivity calculations beyond original data range
    - More accurate but more computationally expensive

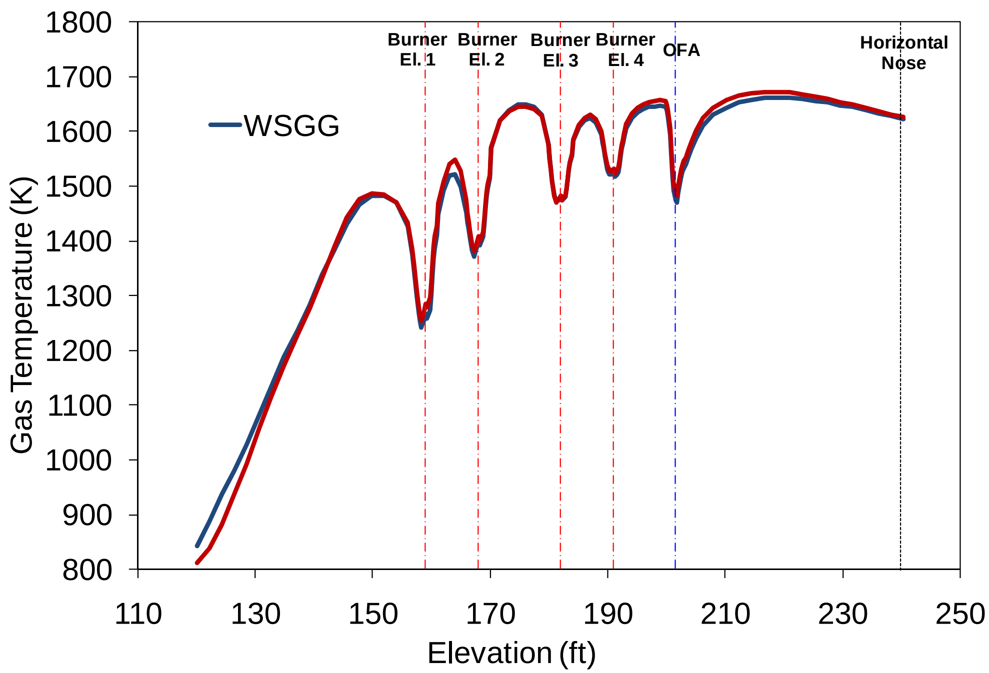
Emissivity Sub-model Comparison

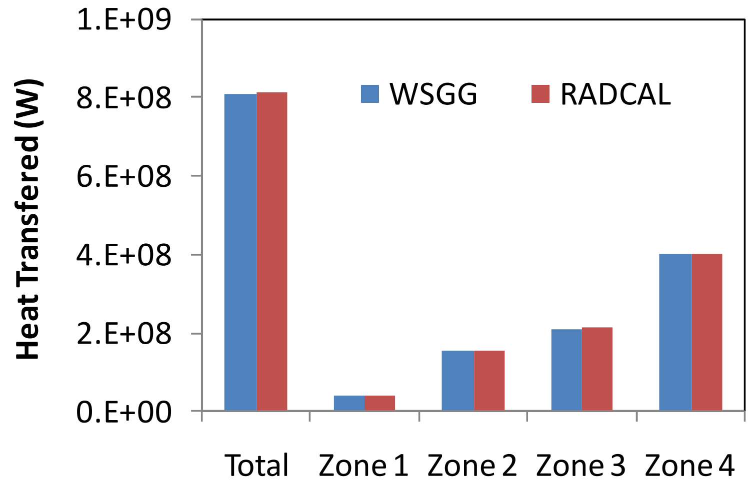


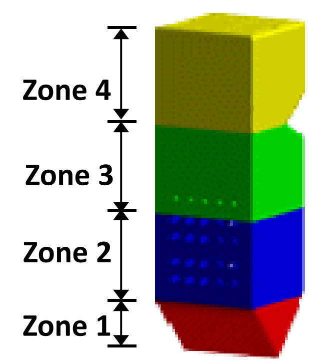
- H_2O has greater impact on emissivity than CO_2

Radiation Comparison

Oxy-coal Firing	WSGG	RADCAL
Horizontal Nose Temp. (°F)	2461	2476
Vertical Exit Temp. (°F)	1621	1626

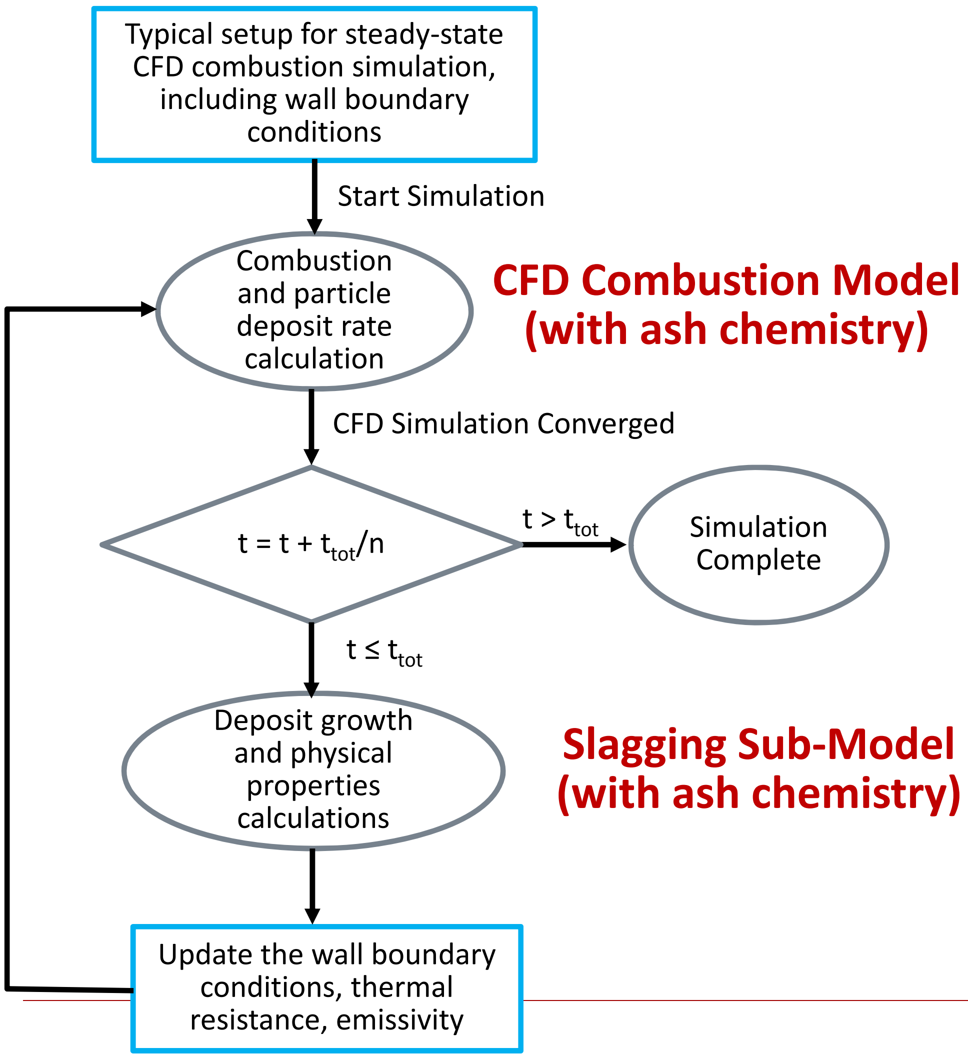






- Flue gas conditions have greater impact than property model calculation

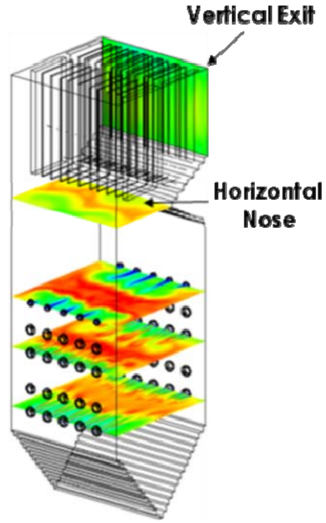
Ash Chemistry and Slagging Sub-model



- **Mineral matter transformation model used to predict ash size distribution and composition**
- **Viscosity predicted as a function of ash temperature and composition**
- **Fraction of particles deposited based on viscosity of impacting particle and surface**
- **Extent of slagging and sintering calculated as the deposit accumulates**

Slagging Results

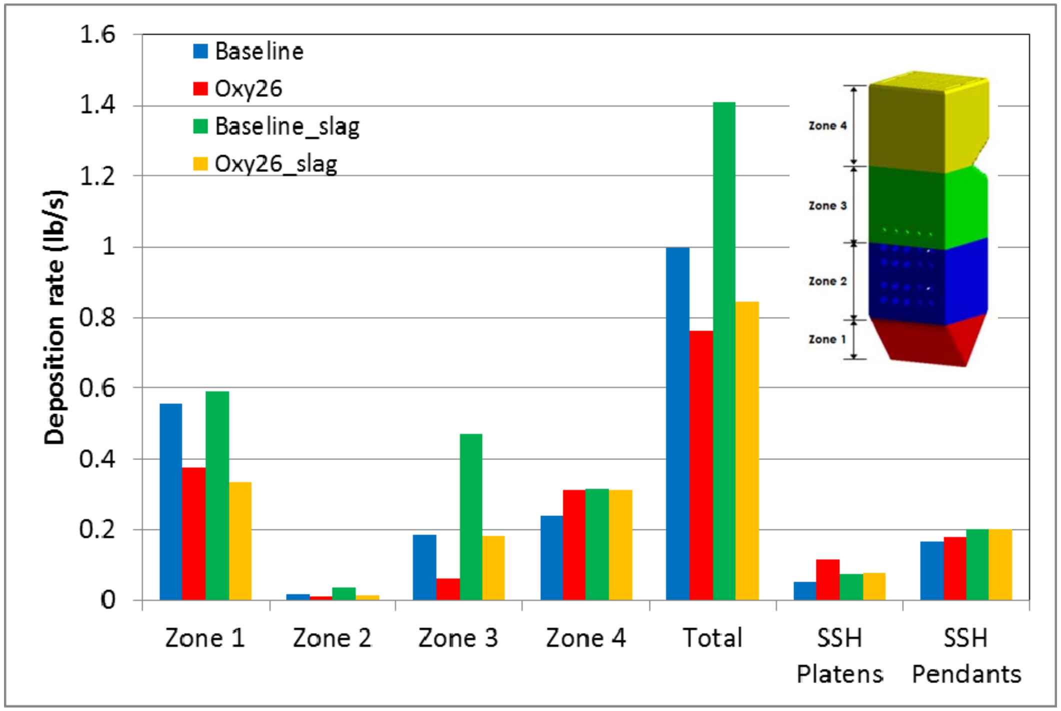
	Baseline	Baseline slag	Oxy26	Oxy26 slag
Horizontal Nose Plane				
Temperature (ºF)	2518	2554	2582	2566
CO Concentration, wet (ppm)	8,454	9,415	16,451	15,765
Vertical Exit Plane				
Temperature (ºF)	1787	1808	1765	1781
CO Concentration, wet (ppm)	3,060	3,404	5,663	5,685
O_2 Concentration, wet (%)	3.3%	3.3%	2.9%	2.7%
Unburned Carbon in Fly Ash	3.6%	1.7%	2.1%	1.1%



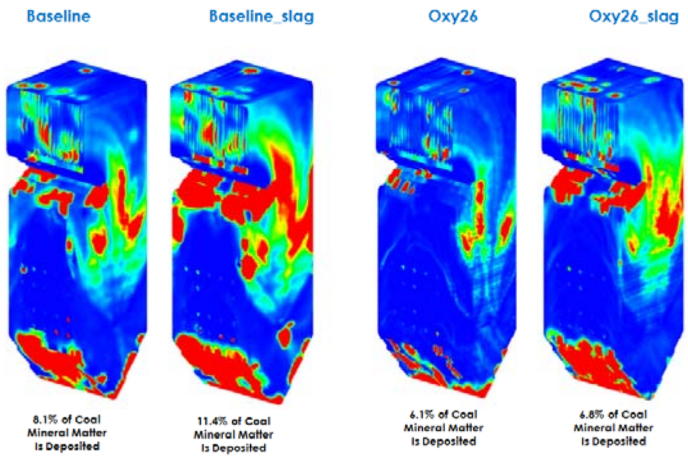
- Minimal overall impacts; air-fired UBC decreased
- Some local differences in heat flux caused by differences in local deposition rates and slag properties

Slagging Impacts

Deposition Rates



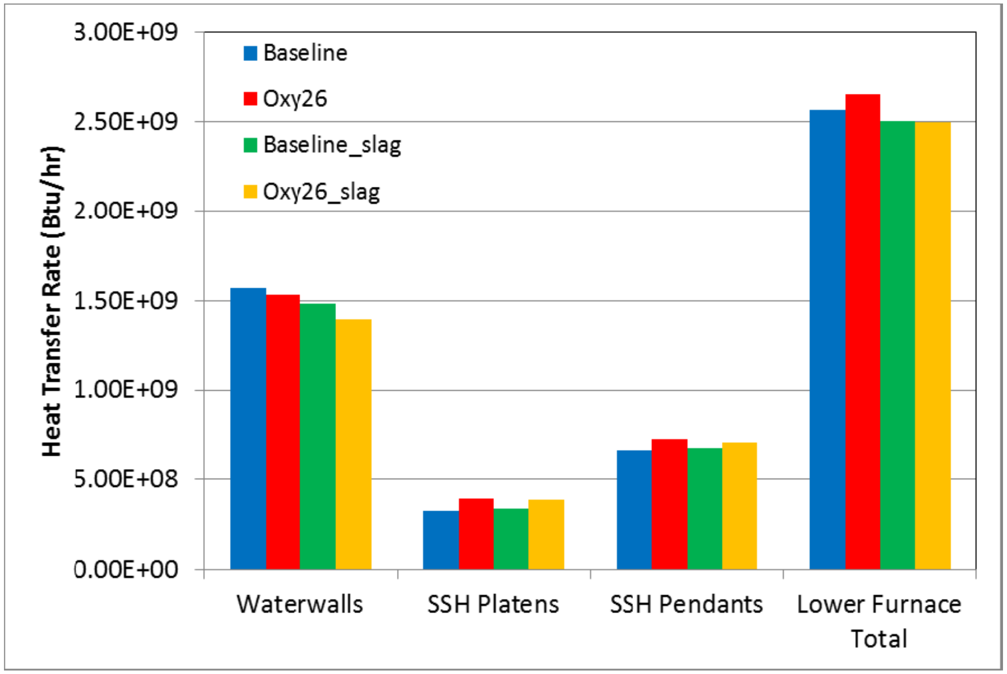
Deposition Flux Profiles



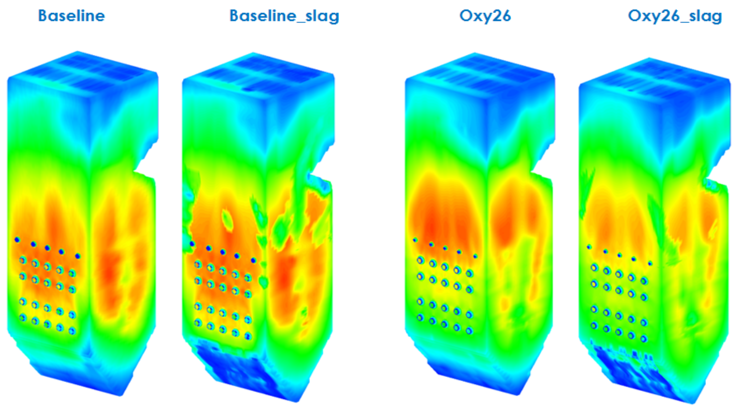
- Slagging model increases deposition rates, particularly for air-firing

Slagging Impacts – Heat Transfer

Heat Transfer Rates



Heat Flux Profiles



- Slagging model slightly decreases net heat flux to waterwalls

Conclusions

- Testing and analysis results used to guide retrofit design and upgrade CFD sub-models
  - Char oxidation was enhanced when steam and CO_2 gasification reactions were included (produced higher CO and lower UBC)
  - Including soot formation had only minor impacts on results, largest impact was increasing CO concentration
  - Improved gas emissivity sub-model had negligible impact
  - Upgraded ash chemistry and slagging sub-model had minimal overall impact; localized changes in deposition rates and surface properties did impact local heat fluxes
- Upgraded CFD sub-models provide improved predictive capability for oxy-combustion retrofits and new designs
  - Combustion, heat transfer, slagging, corrosion, emissions

Acknowledgements

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