Fuel-Nitrogen Chemistry in Coal, Biomass, and Cofired Flames

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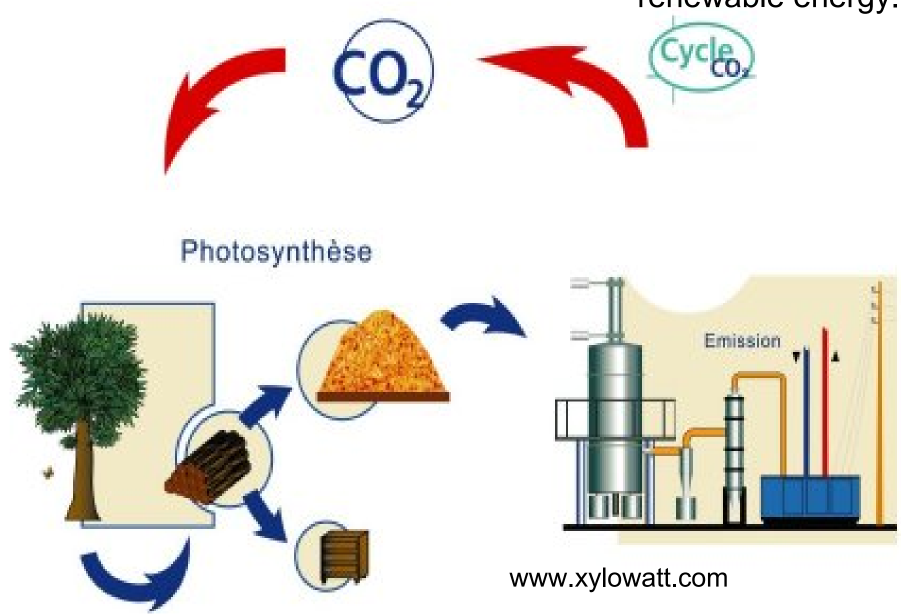
Introduction

- Concerns about climate change have led to more research in renewable energy
  - Cofiring is the among the most efficient, most economic and least risky renewable energy source available

Baxter, L. (2005). "Biomass-coal co-combustion: opportunity for affordable renewable energy." Fuel **84**(10): 1295-1302.



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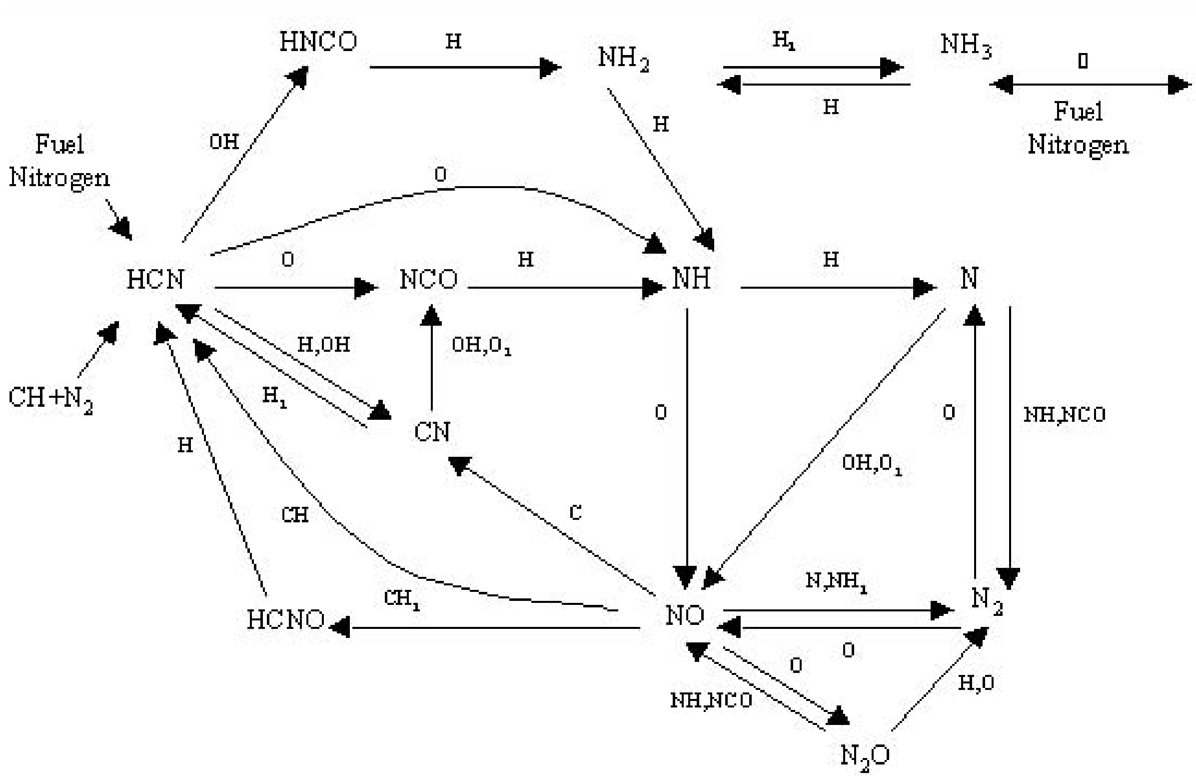
Background

- Low-NO_x burners are prevalent in pulverized coal-fired boilers
  – Complex airflows / fuel interactions produce a reducing zone where fuel-N is converted to N_2 rather than NO
- Biomass fuels are very different than coal
- Cofiring: Replace a portion of coal with a biomass fuel
  – Reduces net CO_2 emissions

Background – Fuel-N

- Fuel-N accounts for 80% of NO_x generated in pf flames
- Coal fuel-N exists in aromatic ring structures
- Biomass fuel-N exists in linear proteins



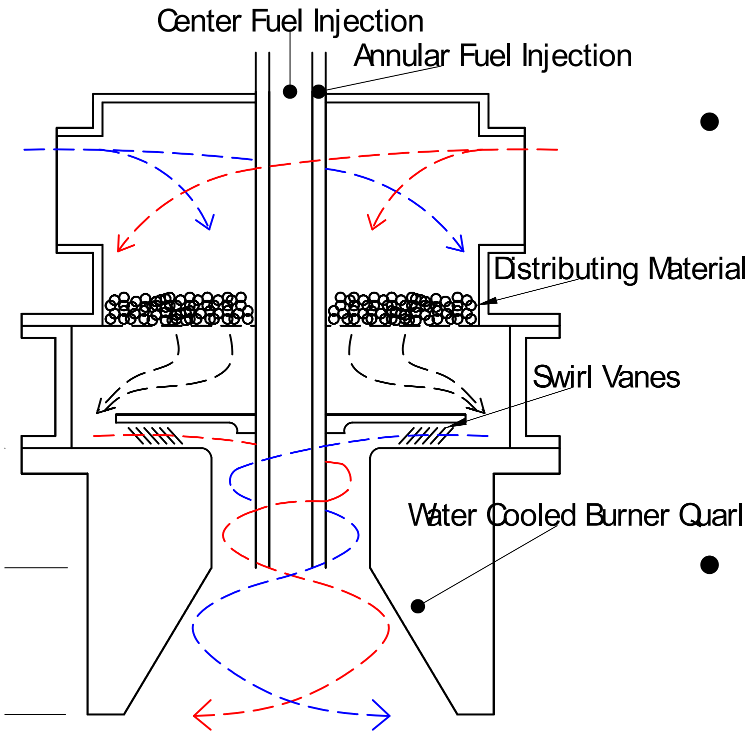
The Issue

- Using a biomass fuel in a low-NO_x burner designed for coal will disrupt optimization
- Different fuel-N behavior may influence nitrogen chemistry
- The objectives of this work are to:
  - (1) Investigate flame structure differences between coal, biomass and cofired flames in a pilot-scale low-NO_x burner facility
  - (2) Investigate fuel-nitrogen evolution in these flames

Specific Objectives

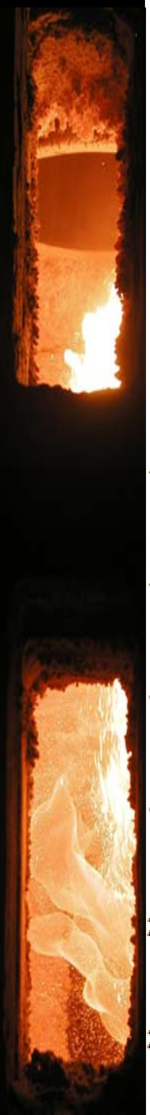
- Design, fabricate and characterize a low-NO_x burner capable of independently feeding 2 non-blended fuels
- Produce detailed gas species maps of different pulverized fuel flames, including coal, biomass, and cofiring flames
- Perform rigorous data analysis to compare flame structure and nitrogen behavior between the flames
- Also, characterize system well enough to be able to use the data for CFD validation

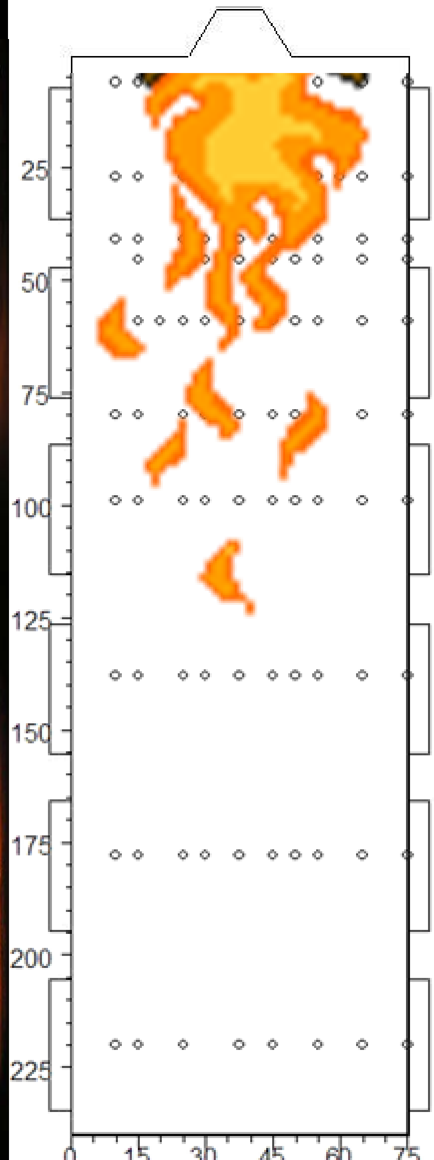
Facilities – Burner



- Two independently operated fuel streams
  - Center and annular tubes with equal cross sectional area
- Swirl generator theoretically capable of S from 0-3.5
- Axisymmetric secondary air outlet

Facilities – Reactor

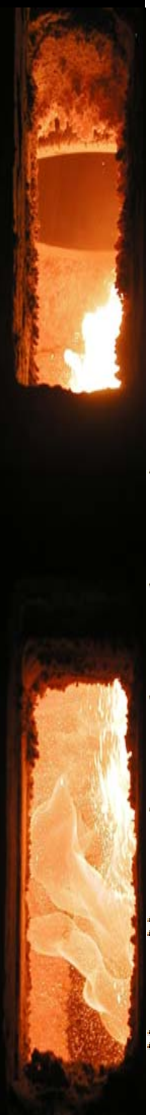


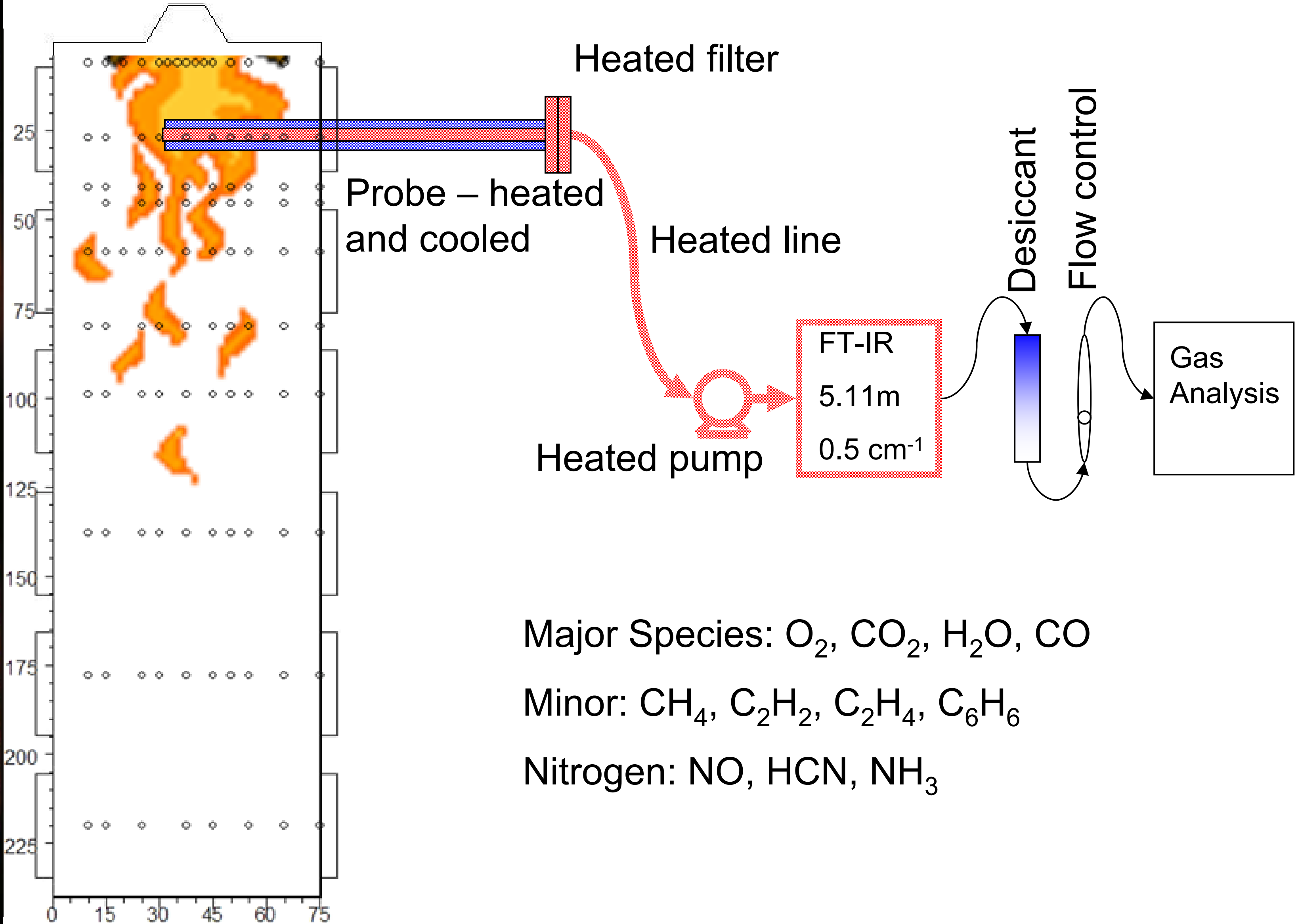


- **B**urner **F**low **R**eactor
- Large enough to minimize flame confinement
- Exceptional access to the flame
- Cylindrical shape promotes axisymmetric flames
- Typically firing rate = 150kW

  ≈ 0.5 MMBTU/hr

Facilities – Sampling





Major Species: O_2, CO_2, H_2O, CO

Minor: CH_4, C_2H_2, C_2H_4, C_6H_6

Nitrogen: NO, HCN, NH_3

Test Matrix

Test ID	Center Fuel (kg/hr)	Annular Fuel (kg/hr)	φ	S	Central Pri Air (kg/hr)	Priority
Coal	Coal (15.3)	none	0.8	1.0	11	*Reqd*
Straw	Straw (26.5)	none	0.76	1.0	8.5	*Reqd*
Wood	Wood (28)	None	0.95	1.0	9.5	Bonus
Cofiring 1.0	Straw (15.1)	Coal (7.5)	0.81	1.0	9	*Reqd*
Cofiring 2.0	Straw (13.5)	Coal (8.7)	0.83	2.0	9	*Reqd*
Fine Straw	Fine Straw (28)	none	0.79	1.0	9	Bonus
Large Straw	Large Straw (28)	None	0.80	1.0 2.0	4	Bonus
Cofiring Long	Straw (13.5)	Coal (8.5)	0.72	1.0	16.5	Bonus
Cofiring Short	Straw (13.5)	Coal (8.5)	0.75	1.0	6.5	Bonus

Blue: Comparing different fuels

Purple: Comparing biomass particle size

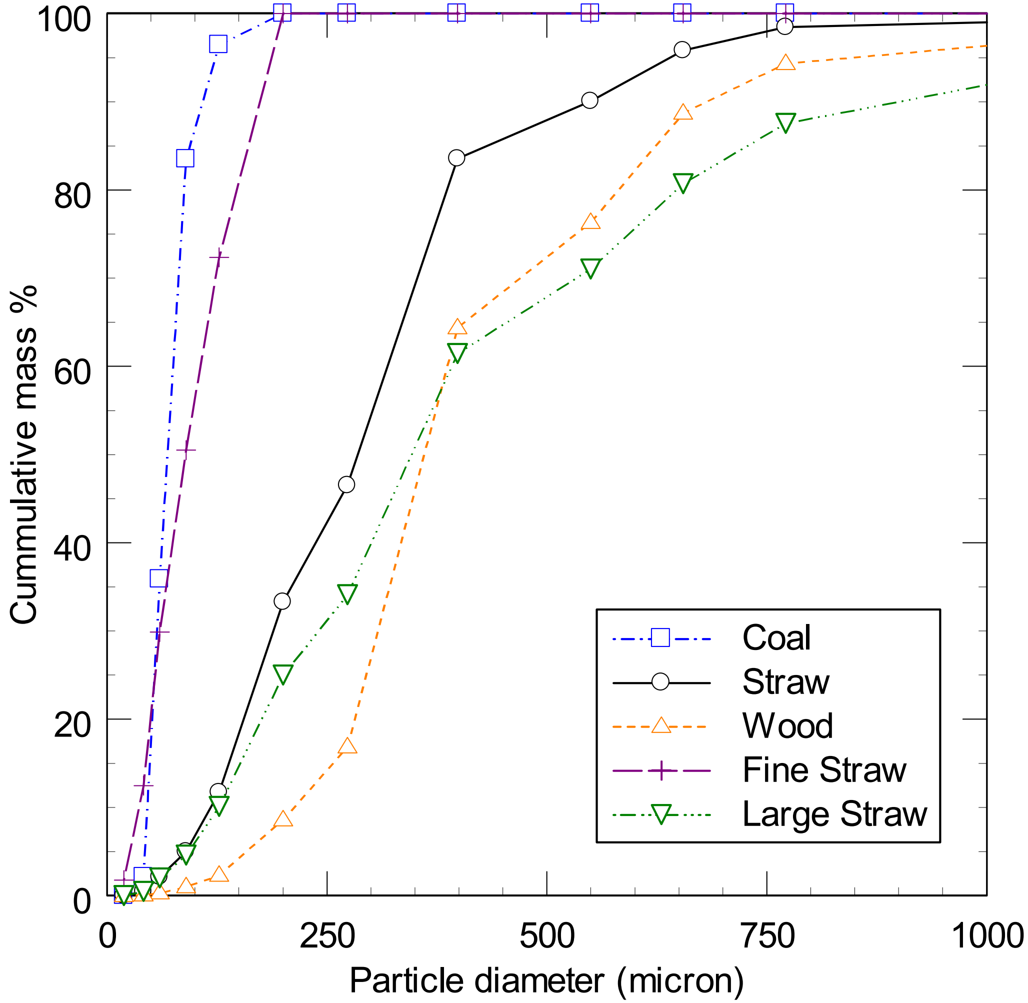
Red: Comparing Swirl numbers

Green: Comparing biomass injection speed

Fuels

Analysis	Coal	Straw	Wood	
Proximate (dry)				
Fixed Carbon	51.5	15.6	15.4	
Volatile	40.6	79.5	84.1	
Ash	7.89	4.91	0.52	
Moisture	2.1	7.7	7.8	
HHV	13213	7951	8490	
Ultimate (dry)				
C	74.8	47.3	51	
H	5.08	5.68	5.7	
O	10.1	41.6	42.6	
N	1.53	0.54	0.14	
S	0.58	<0.01	<0.01	

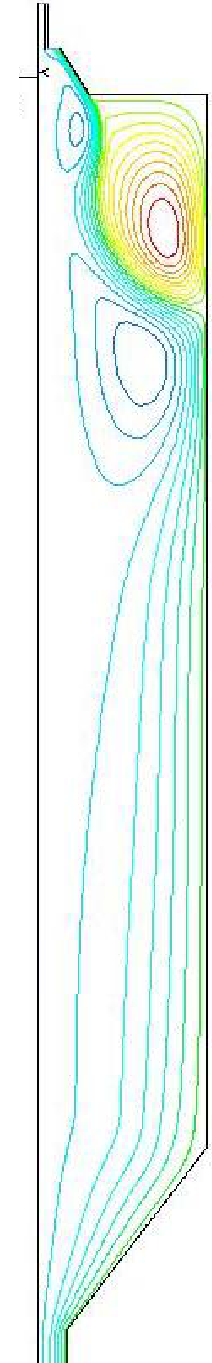
Fuels



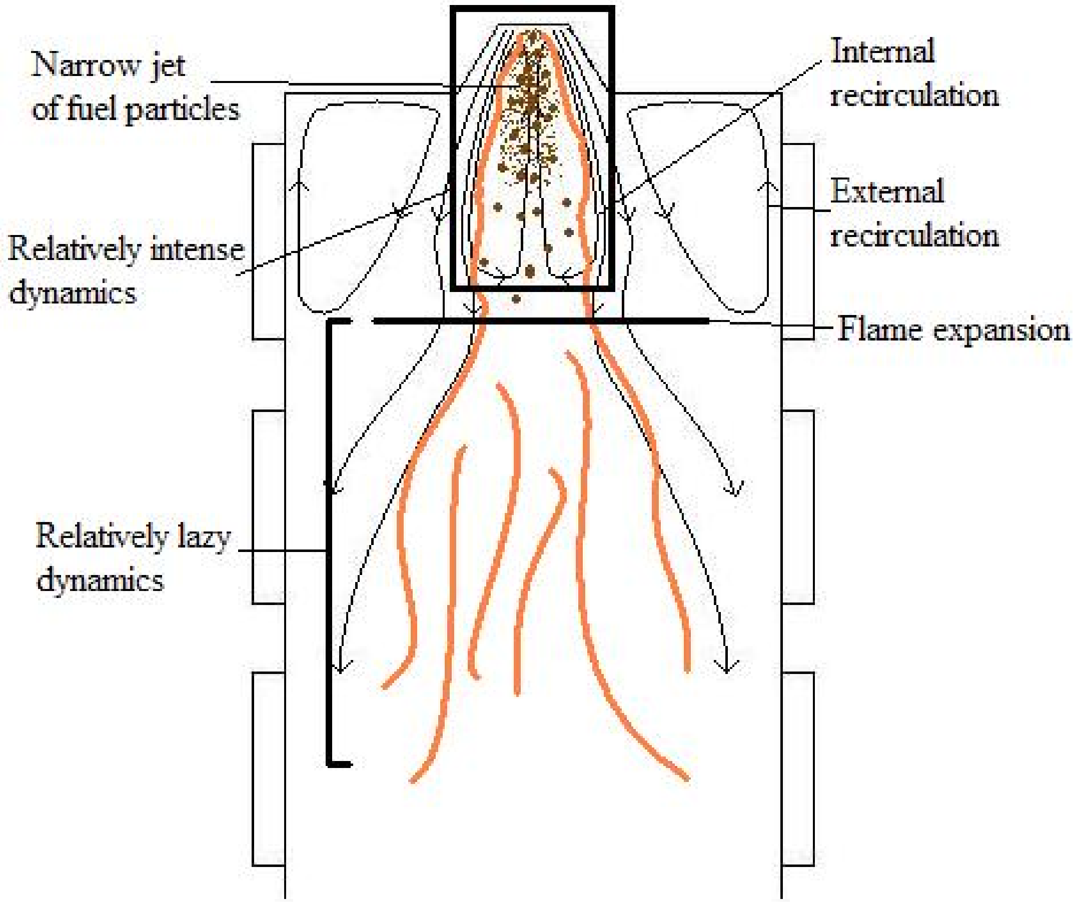
Fuel	d_{ave} (μm)	n
Coal	110.4	4.40
Straw	451	2.31
Fine Straw	160	1.98
Large Straw	589	1.87
Wood	580	3.47

Application to CFD

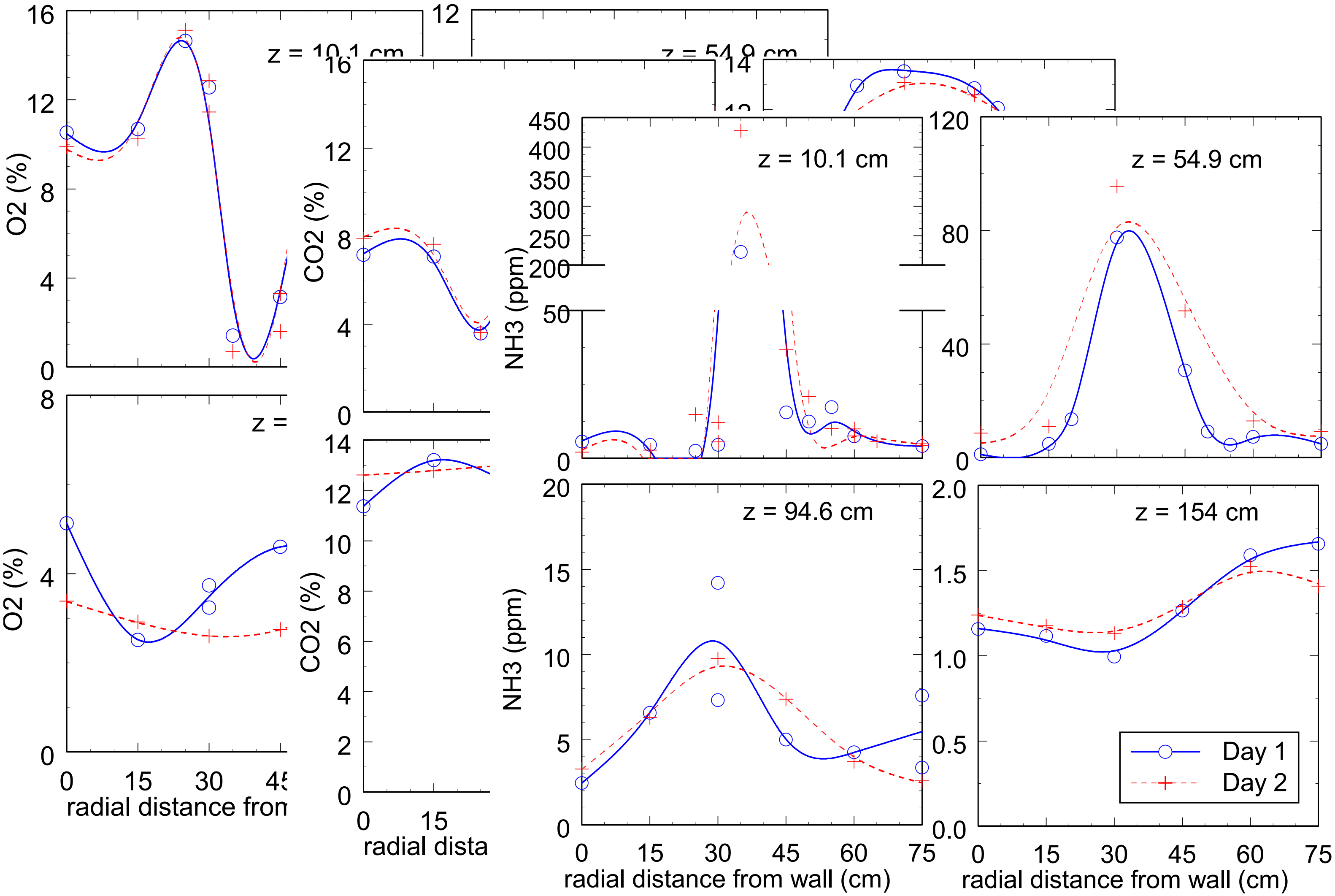
- Geometry of both burner and BFR available
- Air flows calibrated with a mass flow meter accurate to within 1%
- Mass flows monitored using weight cells
- All boundary information available (feedrates, wall temperatures, velocity profiles, fuel characteristics)
- No CFD modeling was performed during this study; collaborators at DONG and Aalborg University were tasked with this



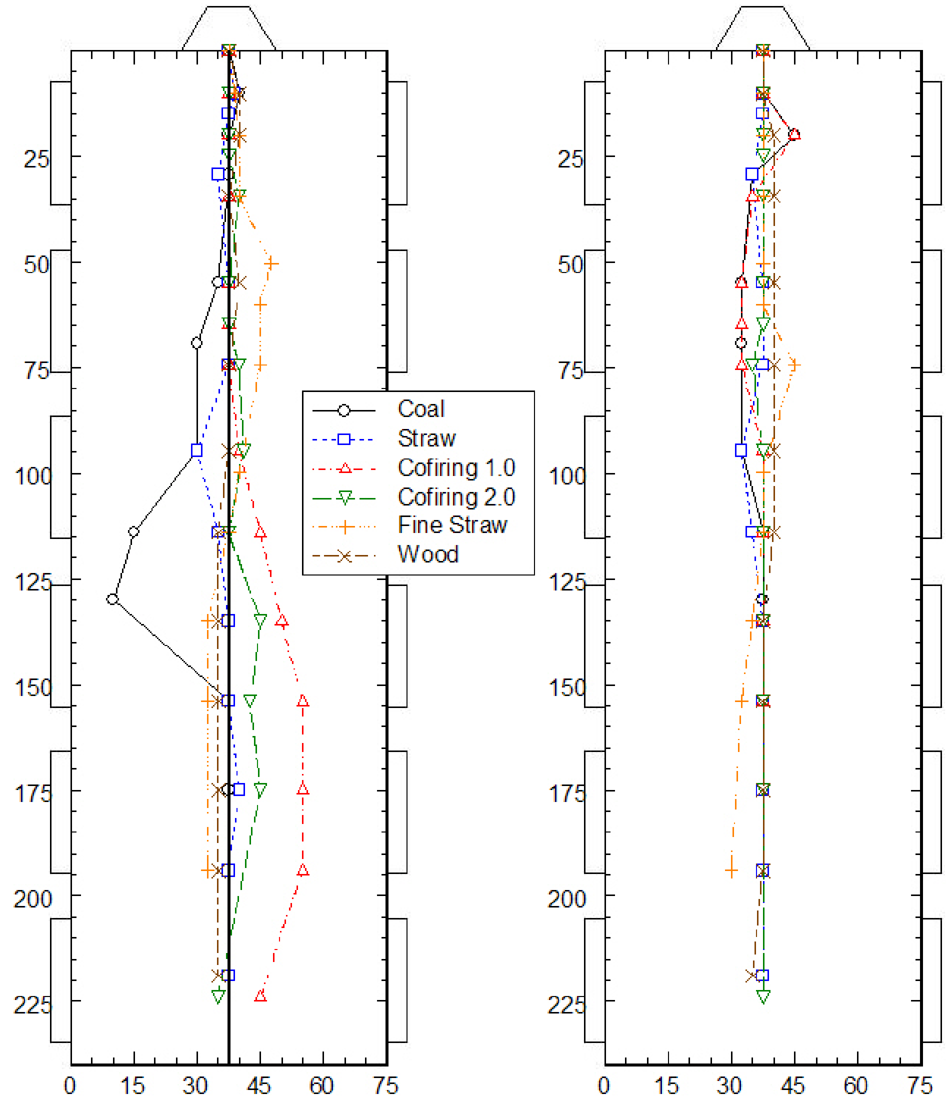
General Results



Results – Data Quality

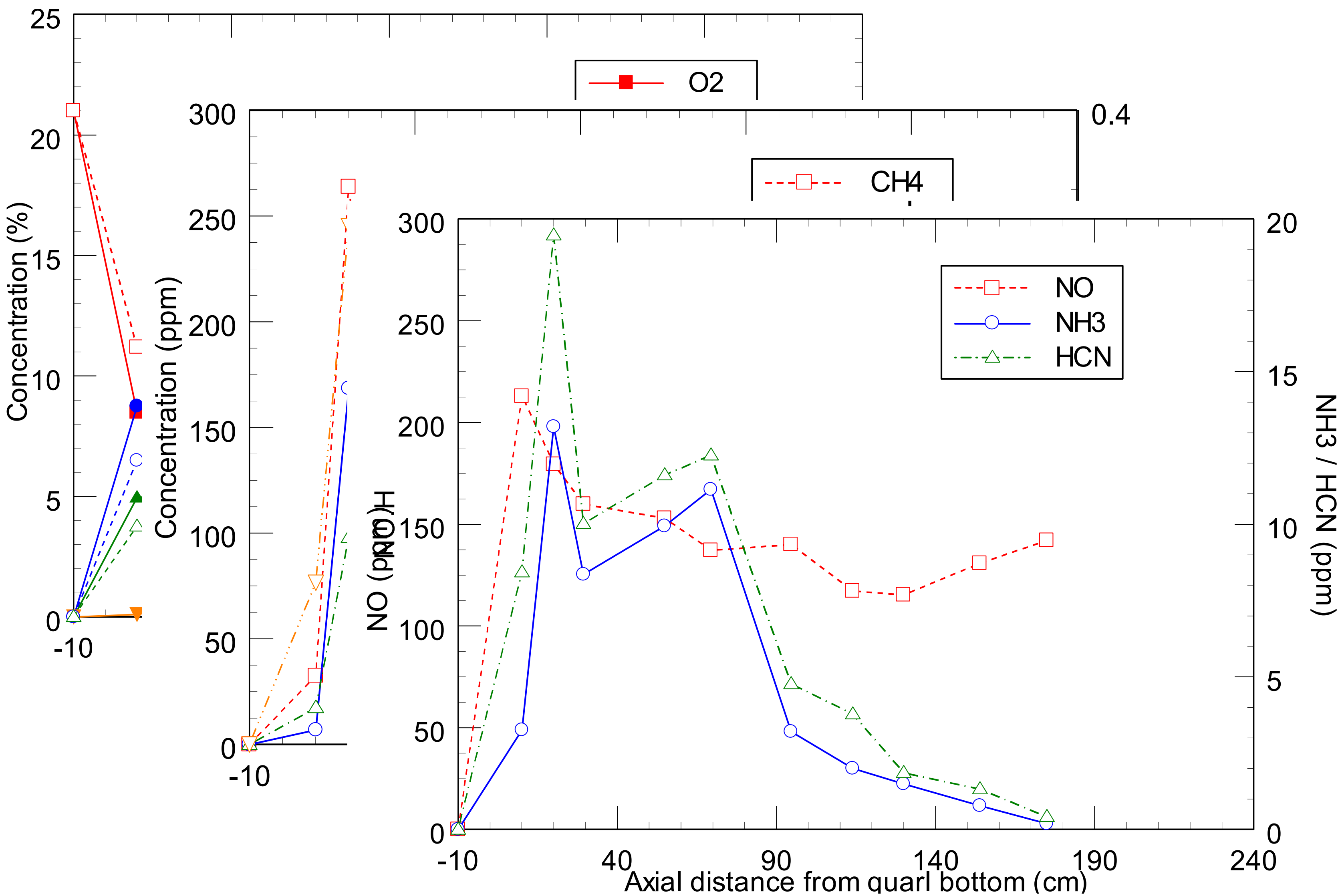


Results – Data Quality

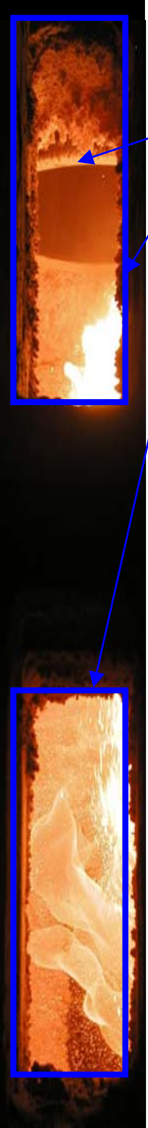


Symmetry based on: O_2 CO

Results – Data Quality



Results – How to read a Map



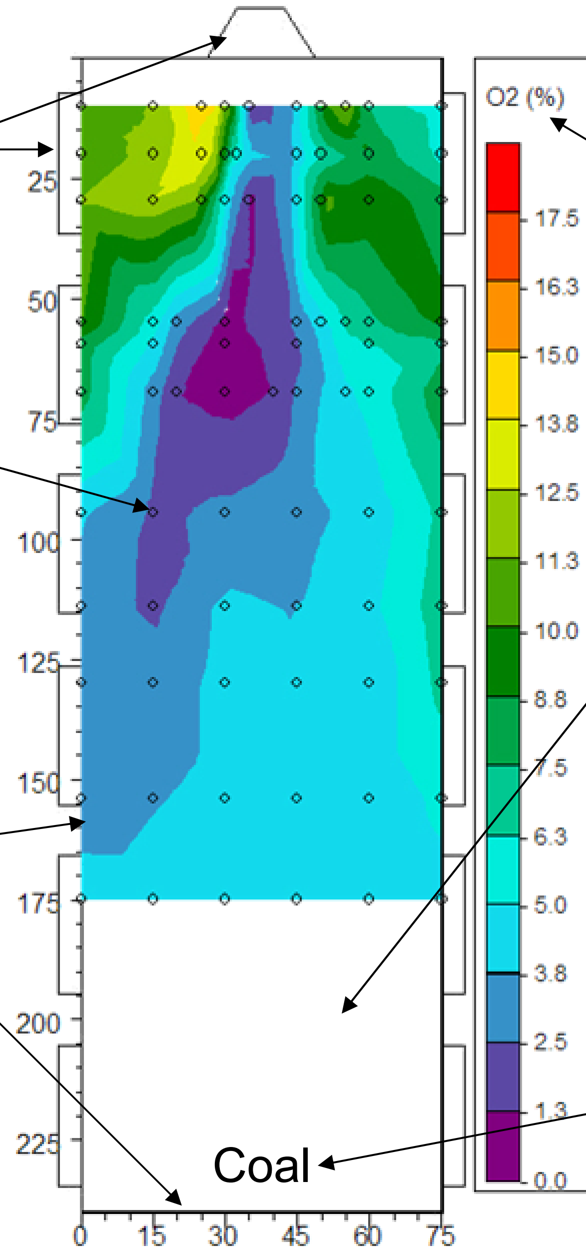
BFR outline, with burner quarl and access windows

Sampling location

2 scales in cm

Axial distance from quarl bottom (z)

Radial distance from sampling wall (r)



Species being plotted, with concentration index

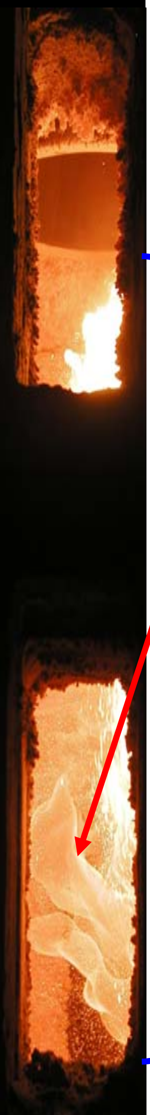
Empty space, either no sampling, or the reading was slightly less than zero and should be regarded as zero

Flame ID

Discussion

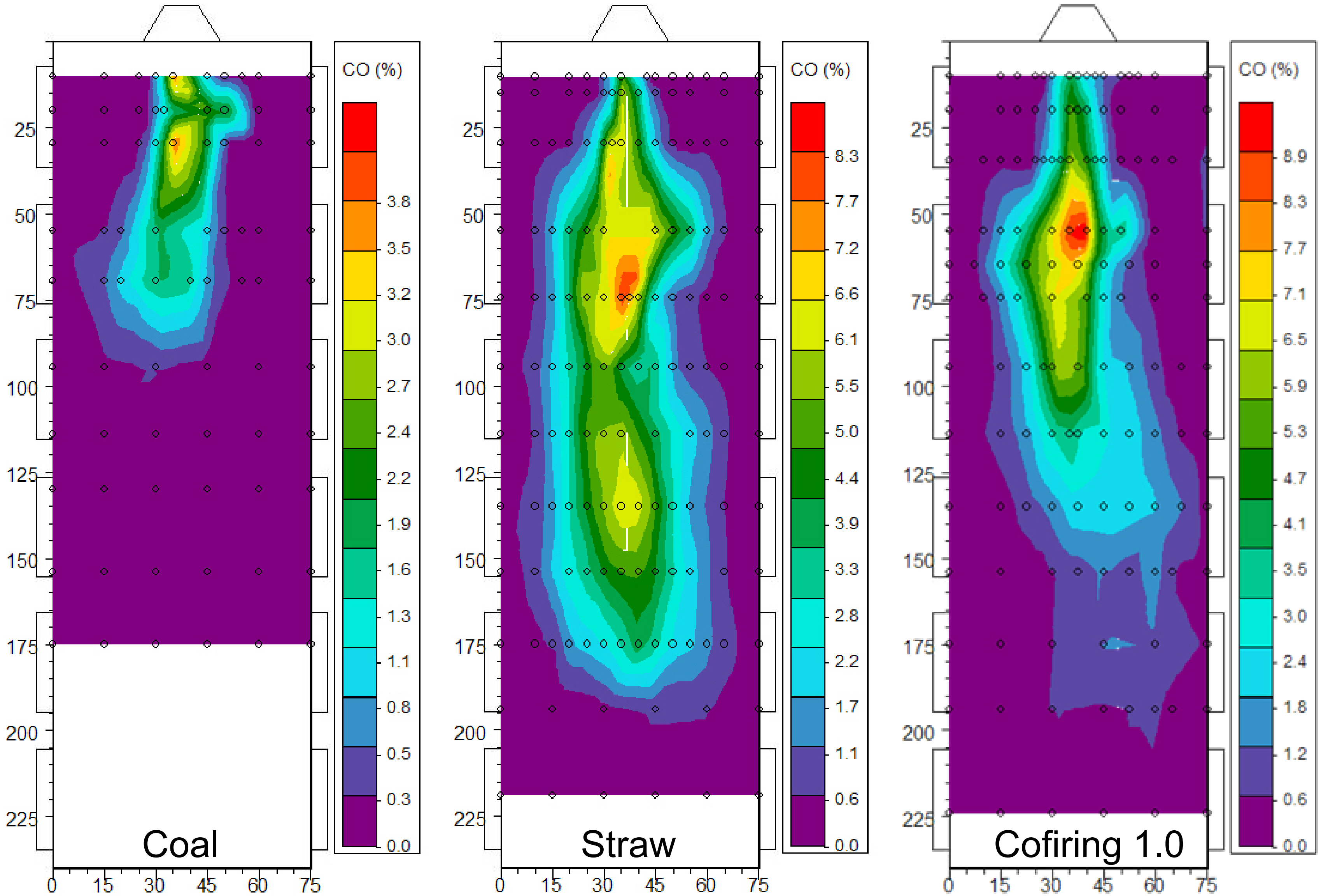
- Flame Structure Story
  - What are the differences between the flames?
- Fuel-Nitrogen Chemistry
  - Are there significant differences in the fuel-nitrogen evolution of coal and biomass?

Flames vs. Flamelets

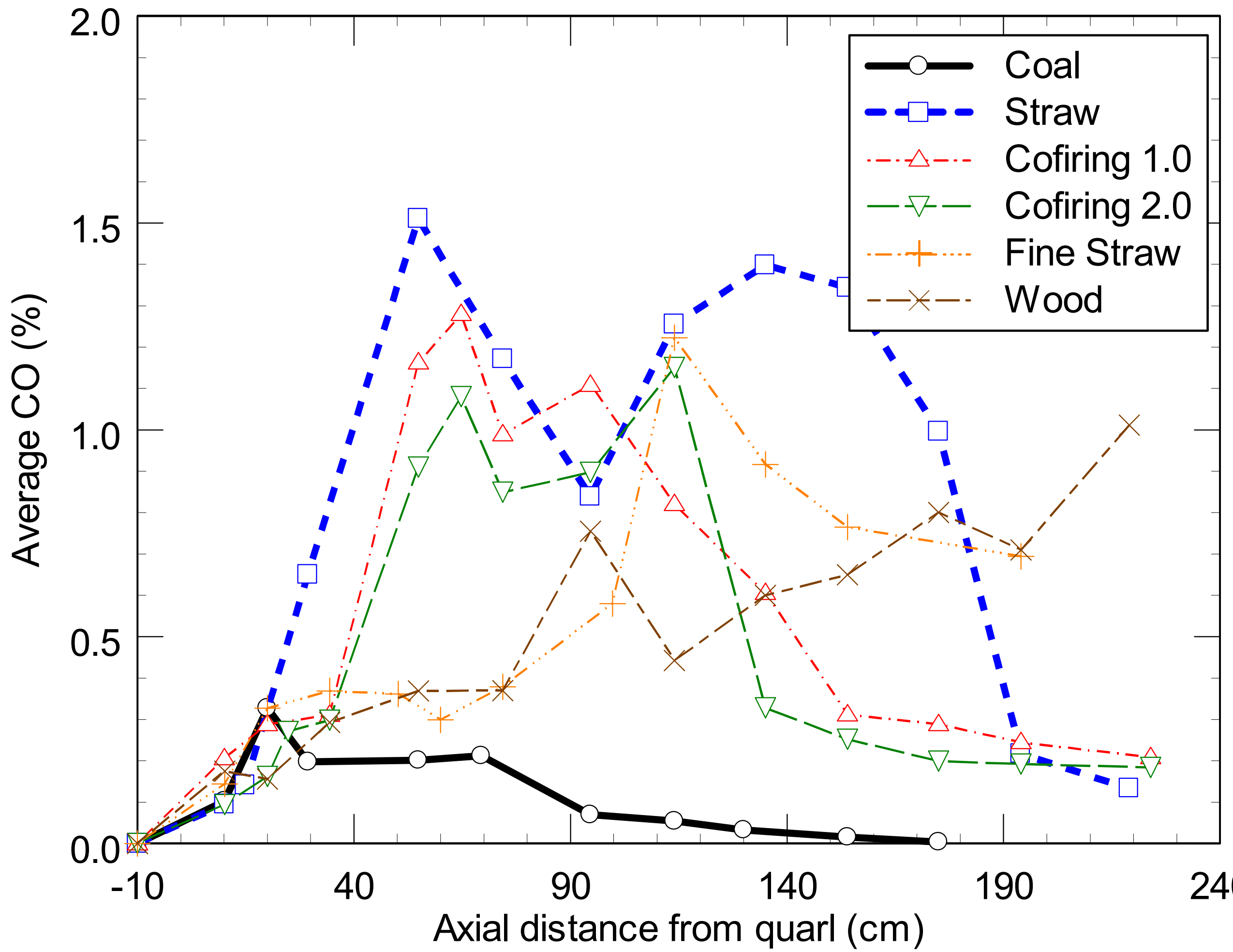


- Flamelet: An individual reacting eddy
  - Fuel particles and volatile gases surrounded by a flame membrane
  - Very transient in time and space
  - Easy to visualize in a Lagrangian view
- Flame: Ensemble of many flamelets
  - The volume of space occupied a significant fraction of time by flamelets
  - Easy to visualize in a Eularian view

Discussion – Flame Structure



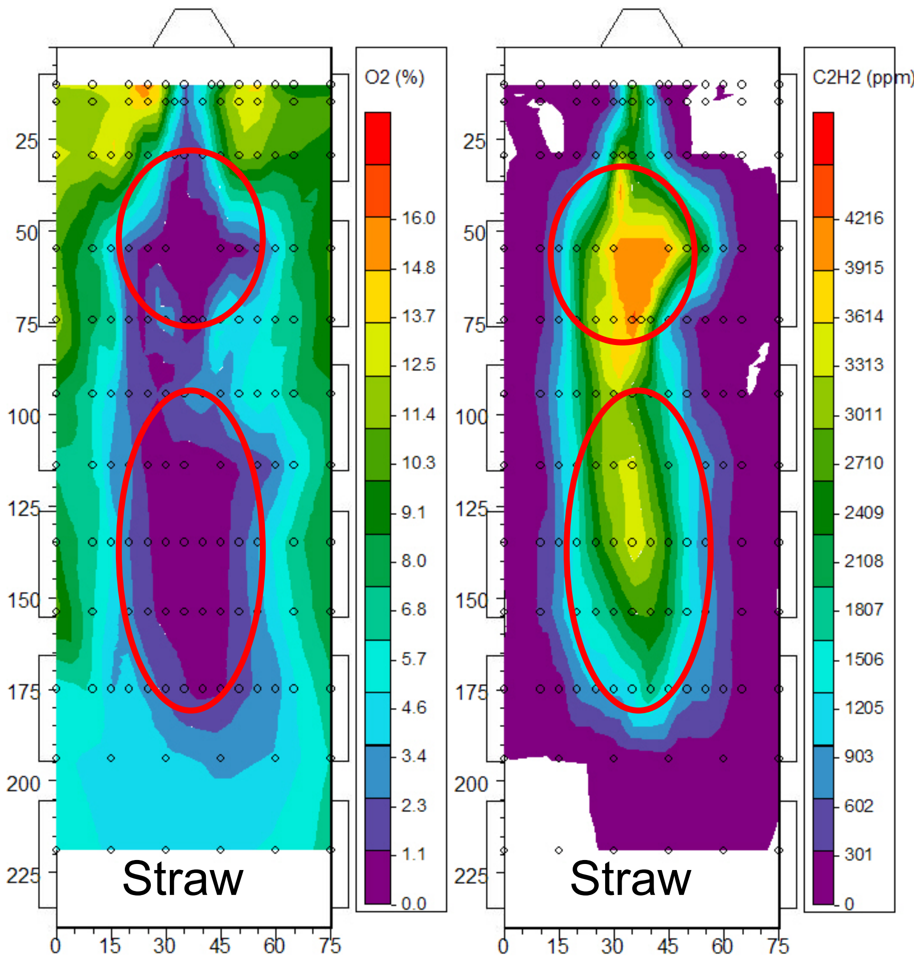
Discussion – Flame Structure



Flame Volume Increase

- Flame volume for biomass and cofiring flames much larger than for coal
  - Increase in primary momentum
  - Biomass particle characteristics
    - Size
    - Shape
  - Volatiles content of biomass fuels higher

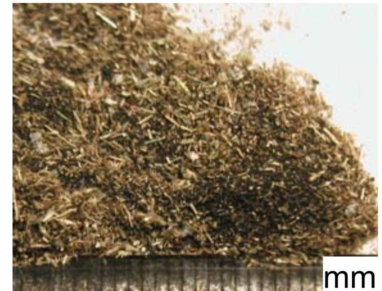
Discussion – Flame Structure



- Secondary flame structures observed in straw flames, physically separated from primary

Secondary Flame Structure

z = 0 cm:
Pure straw, $d_{p,ave}$= 650µm
Pulverized coal



z = 6 cm:
Mixture of coal and all types of straw particles

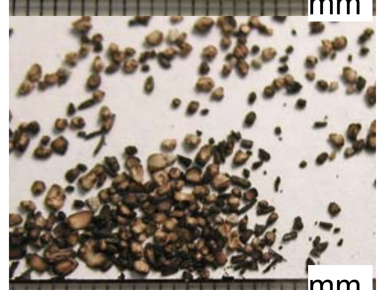
z = 27 cm:
Mostly straw, medium to large, flaky particles; some small char particles

z = 46 cm:
Mostly straw, medium to large, flaky particles; some small char particles

z = 65 cm:
Mostly straw char, straw “knees” becoming more prominent

z = 85 cm:
Mixture of large straw particles and knees, with some straw char

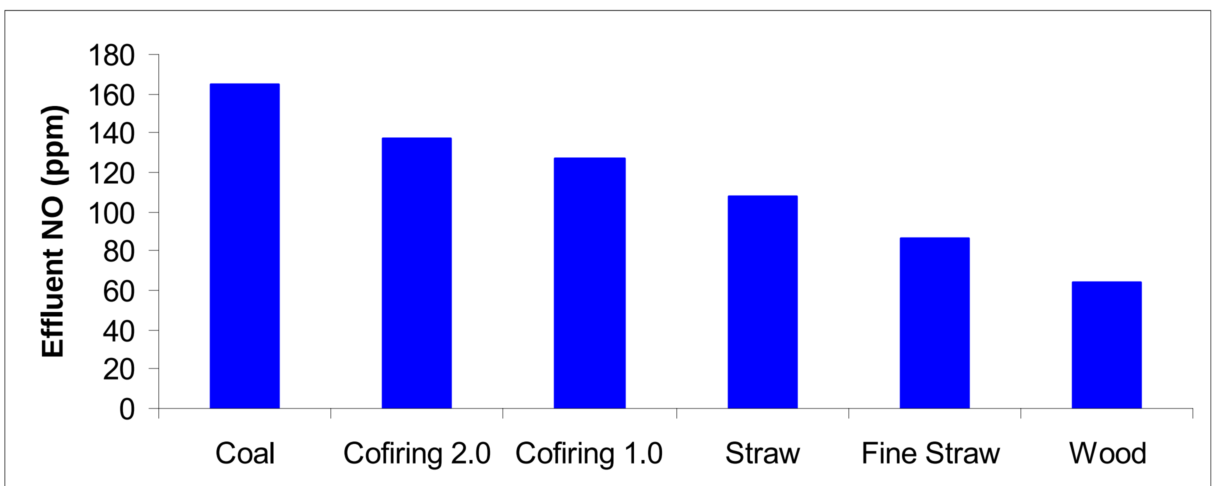
z = 106 cm:
Mostly straw knees with some straw chars, knees slightly charred



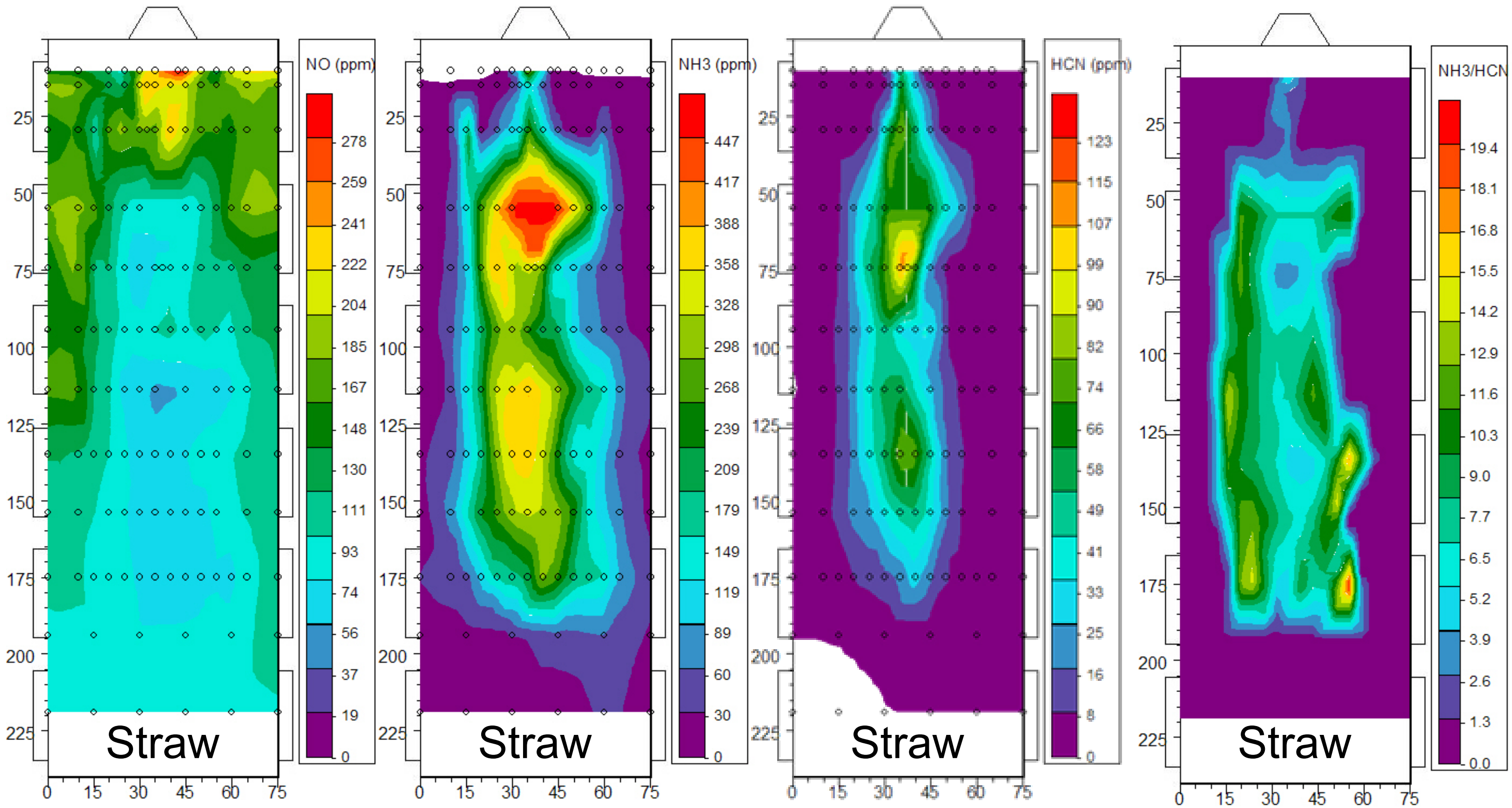
z = 124 cm:
Only straw knees, slightly charred, 94% total burnout based on CO_2

Discussion – Fuel-N

Flame	N content (dry, mass%)	N content (dry, mg/kJ)	Effluent NO (ppm)	NO conversion efficiency (%)	lbNO/MMBTU
Coal	1.53	49.8	165	5.8	0.15
Straw	0.54	29.2	108	6.6	0.10
Cofiring 1.0	0.87	40.5	127	5.8	0.12
Cofiring 2.0	0.93	39.2	137	5.5	0.12
Fine Straw	0.54	29.2	86	5.0	0.08
Wood	0.14	7.1	64	14	0.05



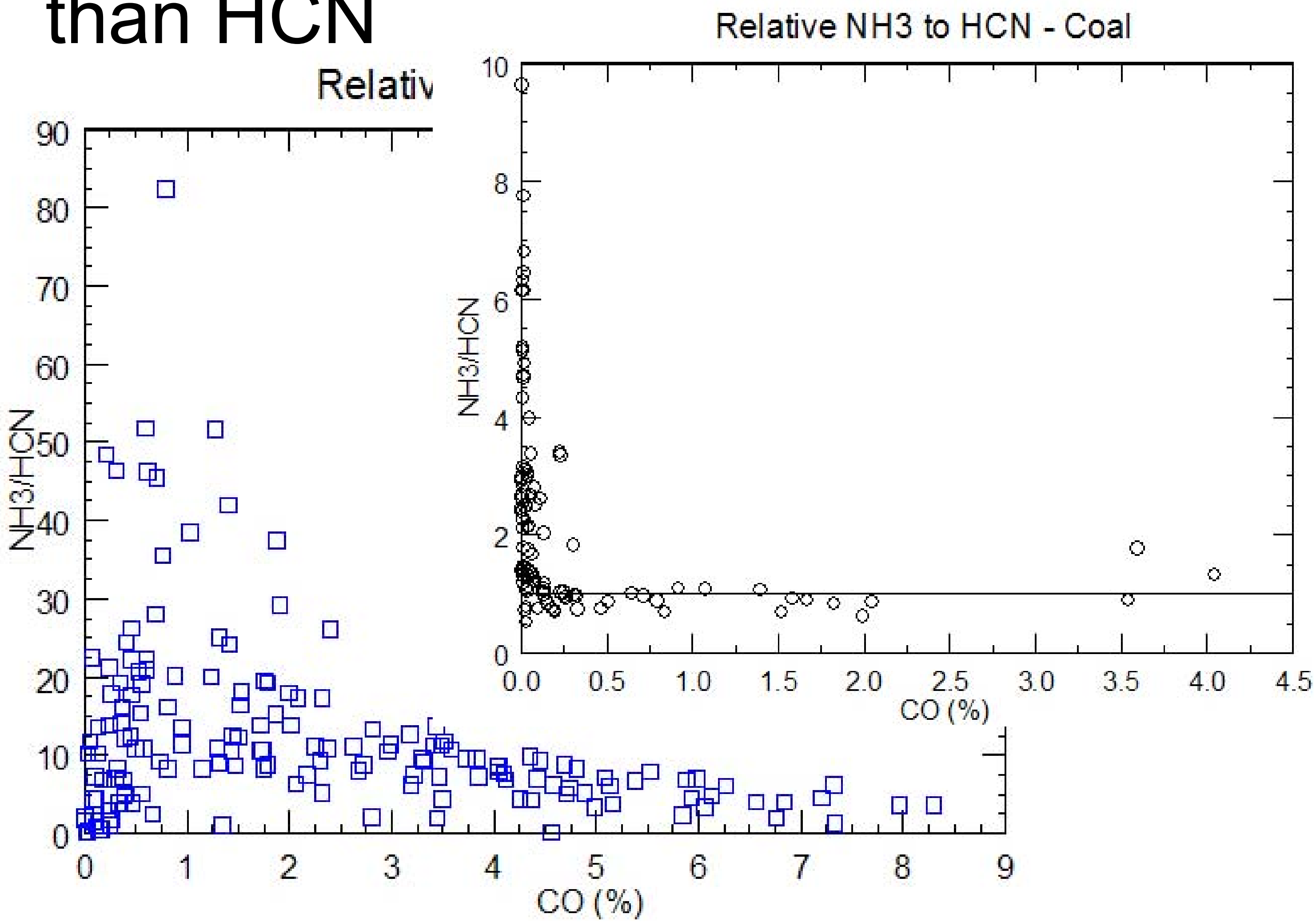
NO, NH_3, & HCN



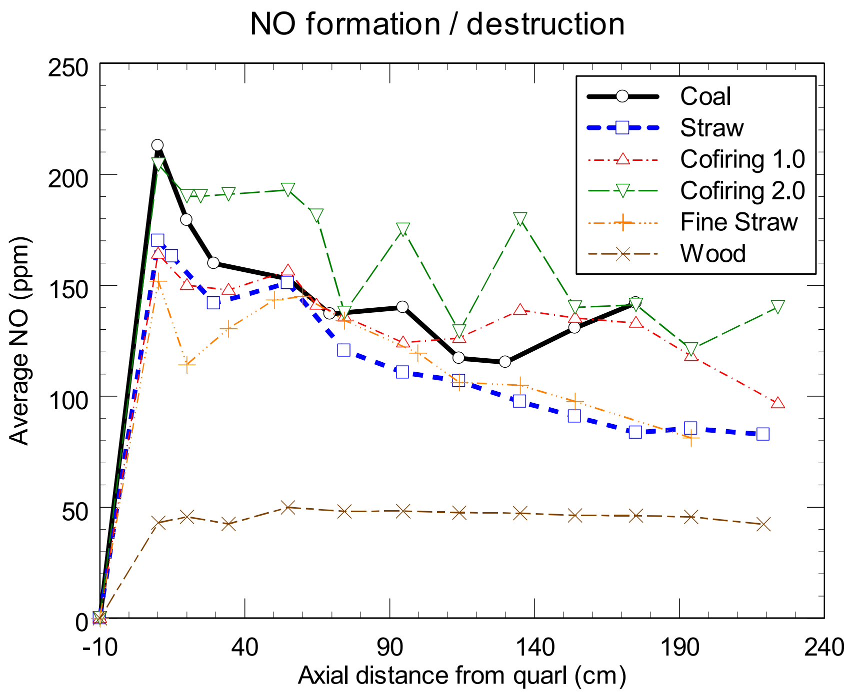
- NH_3 is much more prevalent than HCN in biomass flames

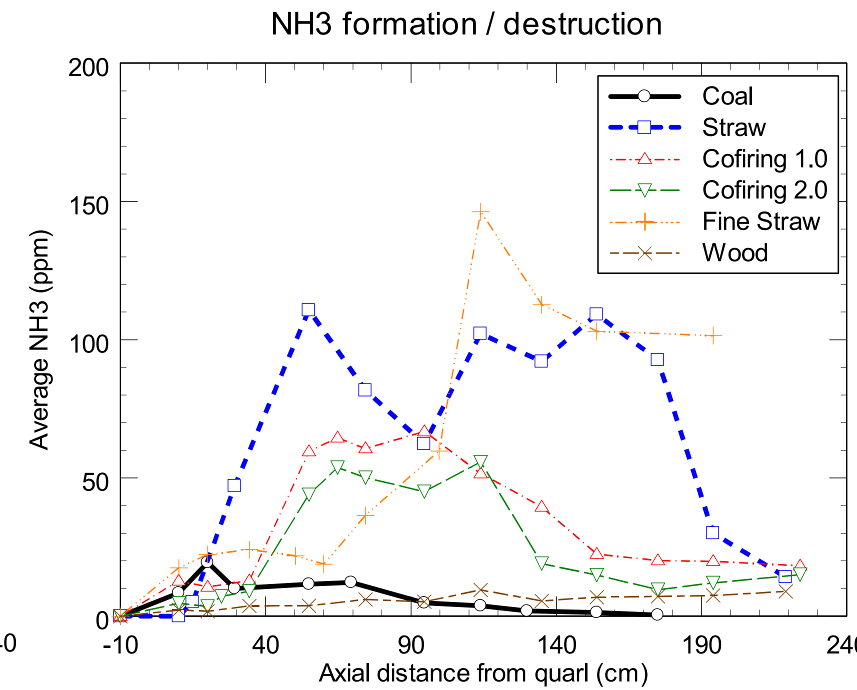
NO, NH_3, & HCN

- NH_3 is more thermally stable in flames than HCN



In-Flame NO reduction

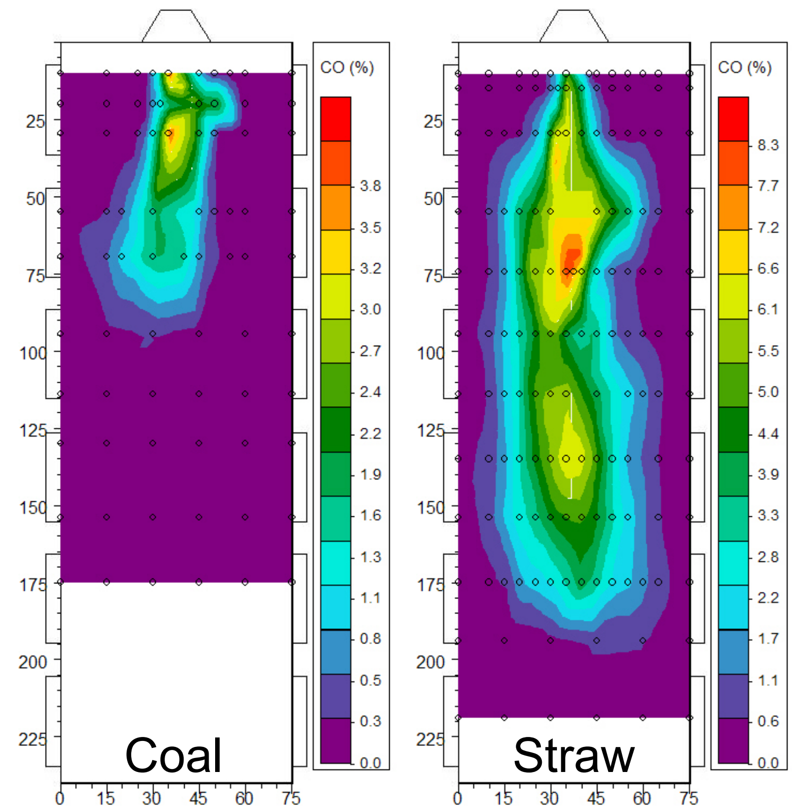




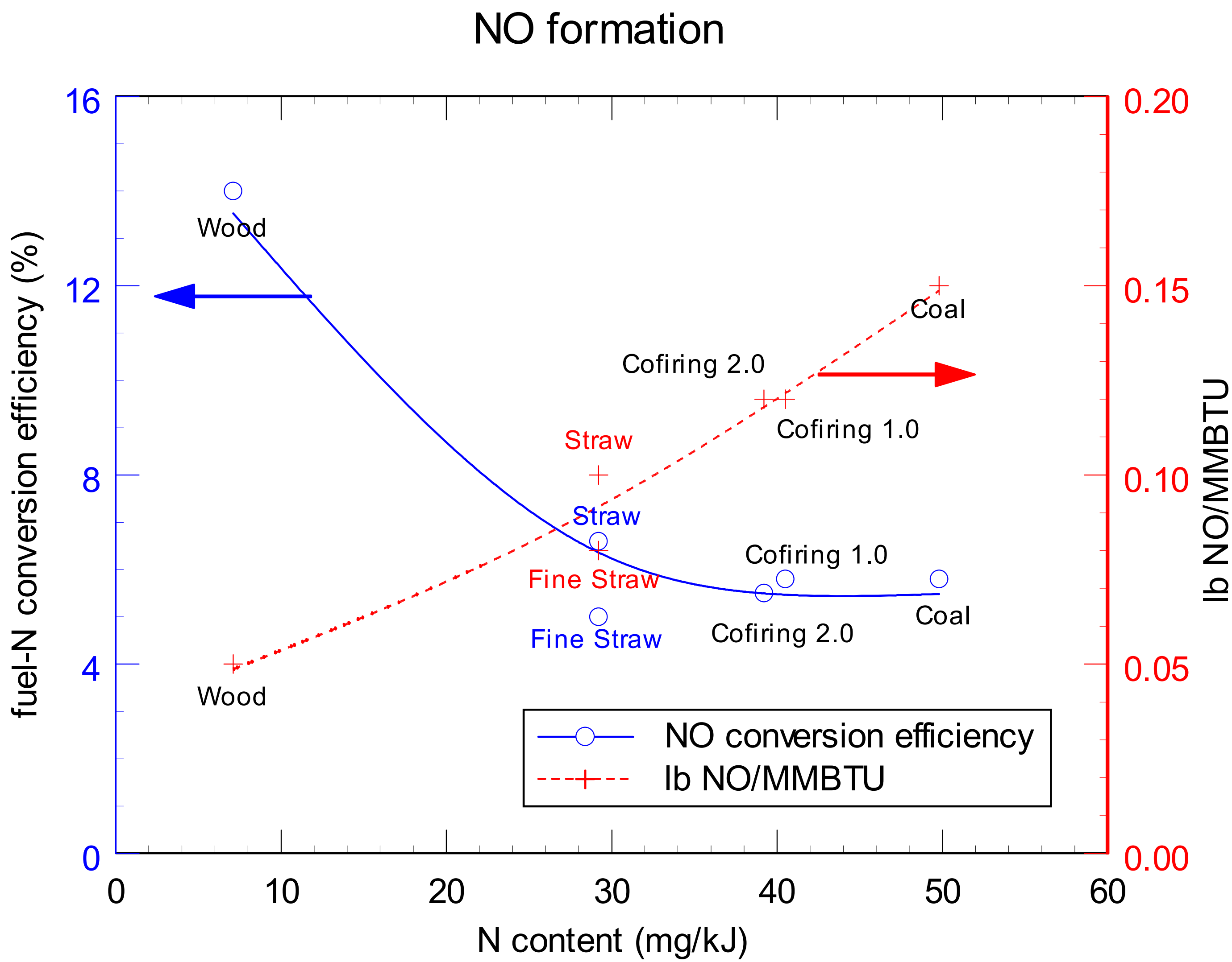
- Reduction coincides spatially with presence of NH_3 and HCN, suggesting reburning / advanced reburning reactions

Effluent NO

- Larger flame volume in biomass flames
- Reburning / advanced reburning reactions
- Lower fuel-N content



Fuel-N to NO conversion



Conclusions

- Data from 6 flames (coal, biomass and cofiring) is available:
  - Gas Species: Major, minor, and N-intermediates
  - Particle samples from coal, straw, and 2 cofiring flames
- These data are good for interpreting flame behavior and fuel-N evolution, as well as a CFD model benchmark

Conclusions – Flame Structure

- Biomass containing flames are much larger
  - Greater primary momentum
  - More volatiles
  - Larger particles, different shape
- Straw flames showed secondary flame structures due to the straw "knees"

Conclusions – Nitrogen Chemistry

- Biomass flames had lower effluent NO
- Biomass flames favored fuel-N evolving through NH_3 rather than HCN
- NH_3 is more stable in flame environment than HCN
- In-flame destruction of NO is observed and attributed to reburning / advanced reburning reactions due to the presence of NH_3

Acknowledgements

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