Oxy-Fuel Combustion: Laboratory and Pilot Scale Experiments

Plus some initial calculations (Qiao)!

E. J. Miklaszewski, Y. Zheng, L. Qiao and S. F. Son

Department of Mechanical Engineering

Purdue University

West Lafayette, IN 47907

Presentation Outline

- Oxy-fuel motivation
- Laboratory Experiments
- Initial Numerical Simulations
- Pilot Scale Experiments
- Continuing Work

Oxy-fuel Motivation

PURDUE UNIVERSITY

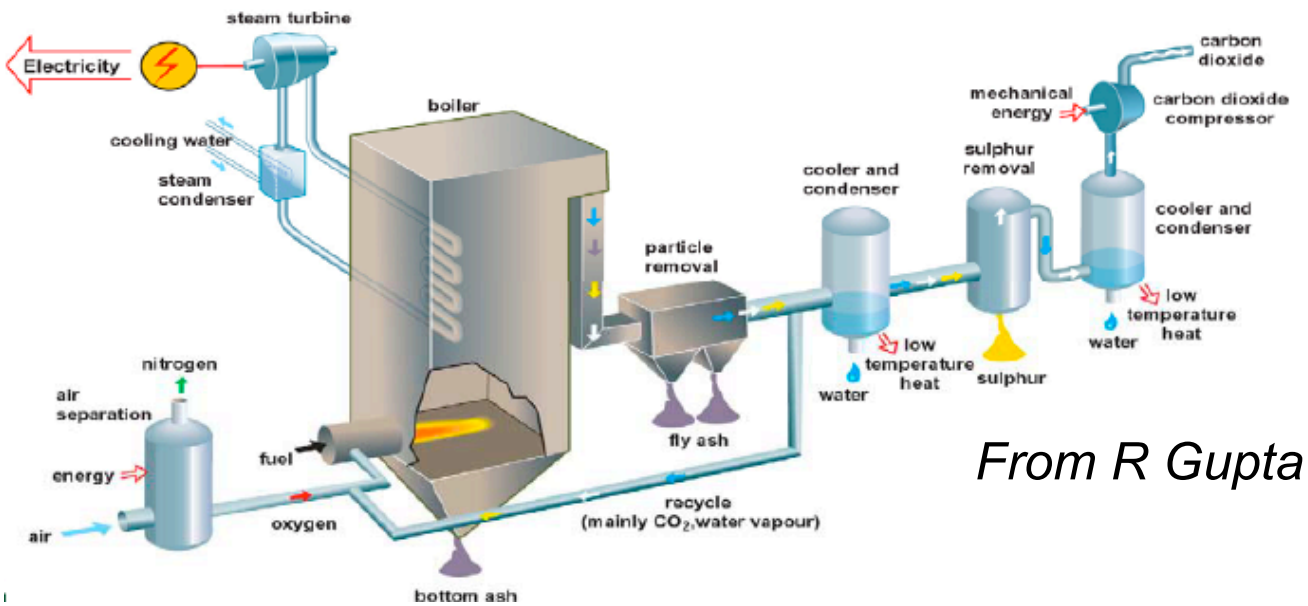
- Clean Coal Options:
  - **Oxygen combustion (Oxyfuel)**
    - Concentrated CO_2 in products
  - **Amine (or others) scrubbing** for new or existing plants
    - Extracts the CO_2 from the flue gas using a regenerable sorbent-catalyst such as momoethanolamine (or MEA)
    - More expensive by some estimates
  - **Integrated Gasification Combined Cycle** (**IGCC)**
    - Also concentrates CO_2
    - Attractive approach, but challenges include complexity of operation

Oxy-fuel Motivation

- Oxyfuel
  - Pure oxygen as oxidizer (often diluted with flue gas)
  - Reduces or eliminates NOx (no Nitrogen in oxidizer flow)

- Increases CO_2 concentration
  - Easier to recover

Could be used in retrofit coal plants



From R Gupta

Oxy-coal is gaining momentum internationally

PURDUE UNIVERSITY

- Oxy-combustion boilers have been studied in laboratory
  - scale and small pilot units of up to 3 MW
  - Two larger pilot units at 30 MW are operating
    - Babcock & Wilcox (B&W), and Swedish power company Vattenfall.
- An Australian-Japanese project team is pursuing a 30 MW repowering project at the CS Energy's Callide A station in Queensland, Australia
    - "stands to benefit from developments in oxygen separation such as membrane-based air separation technology, which could replace energy-intensive cryogenic process air separation technology"
    - More work needed in this area!

"Advanced Coal Power Systems with CO_2 Capture: EPRI's CoalFleet for Tomorrow Vision",*A Summary of Technology Status and Research, Development, and Demonstrations, 1016877, Interim Report, Electric Power Research Institute, September 2008*

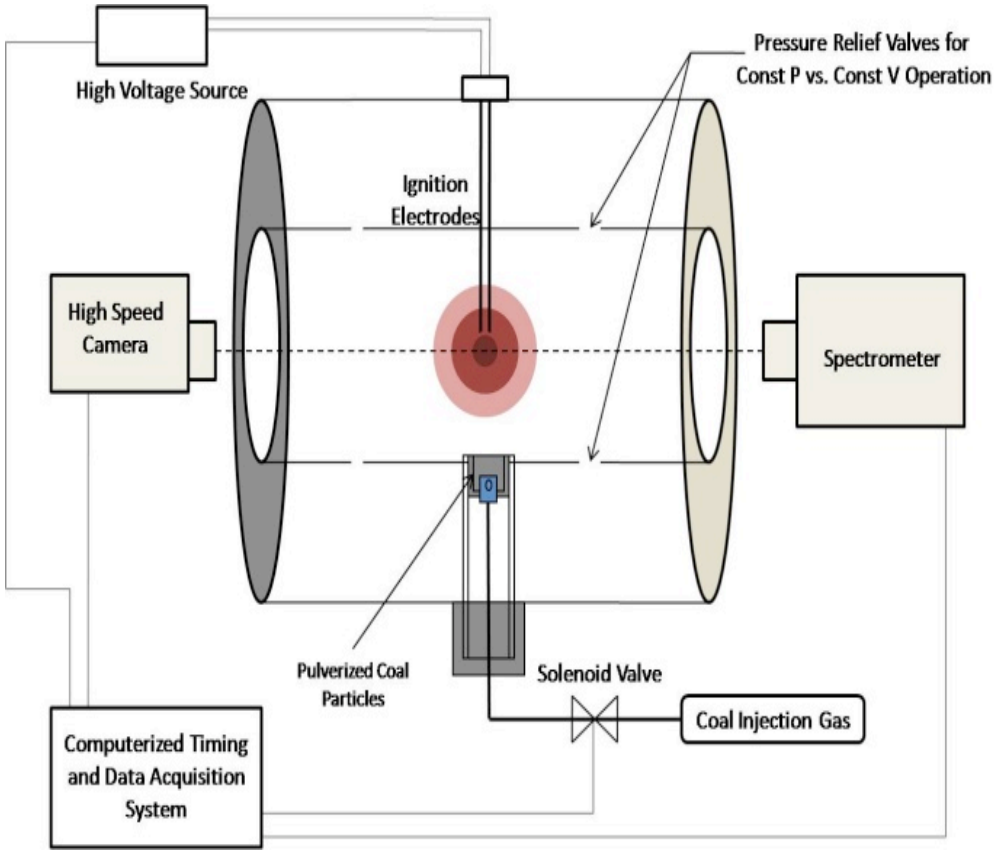
Some key areas

- Radiative Heat Transfer
  - More dominant heat transfer mode in boiler furnace
  - Non-gray body behavior (spectral dependence)

- Temperature Measurements in Oxy-Fuel Boilers
  - Pilot scale
  - Above 3,000 K in Jupiter burner
  - Challenging to measure

PURDUE UNIVERSITY

Oxy-Coal Dust Cloud Combustion Experiment Configuration



Objectives

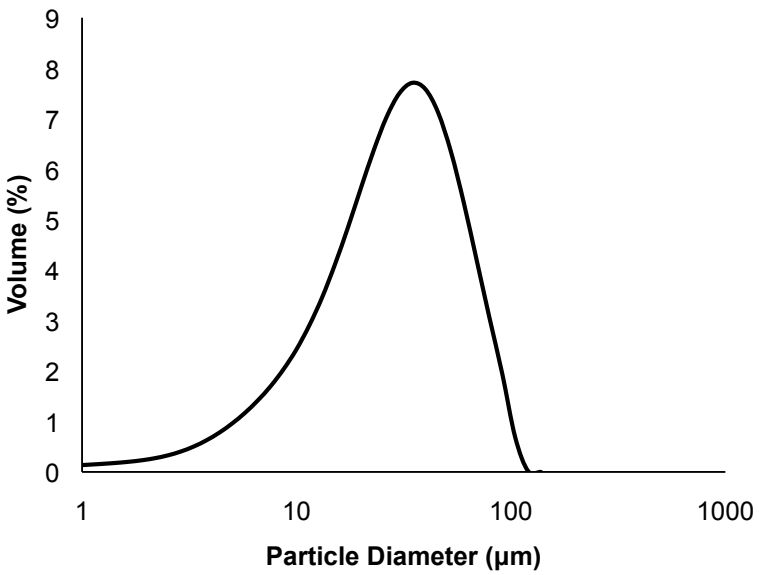
Document
- Flame Speed
- Spectral Radiation
- Data for Models

Vary
- Coal type
- Particle size
- Oxygen content
- Diluent

PURDUE UNIVERSITY

Coal Analysis

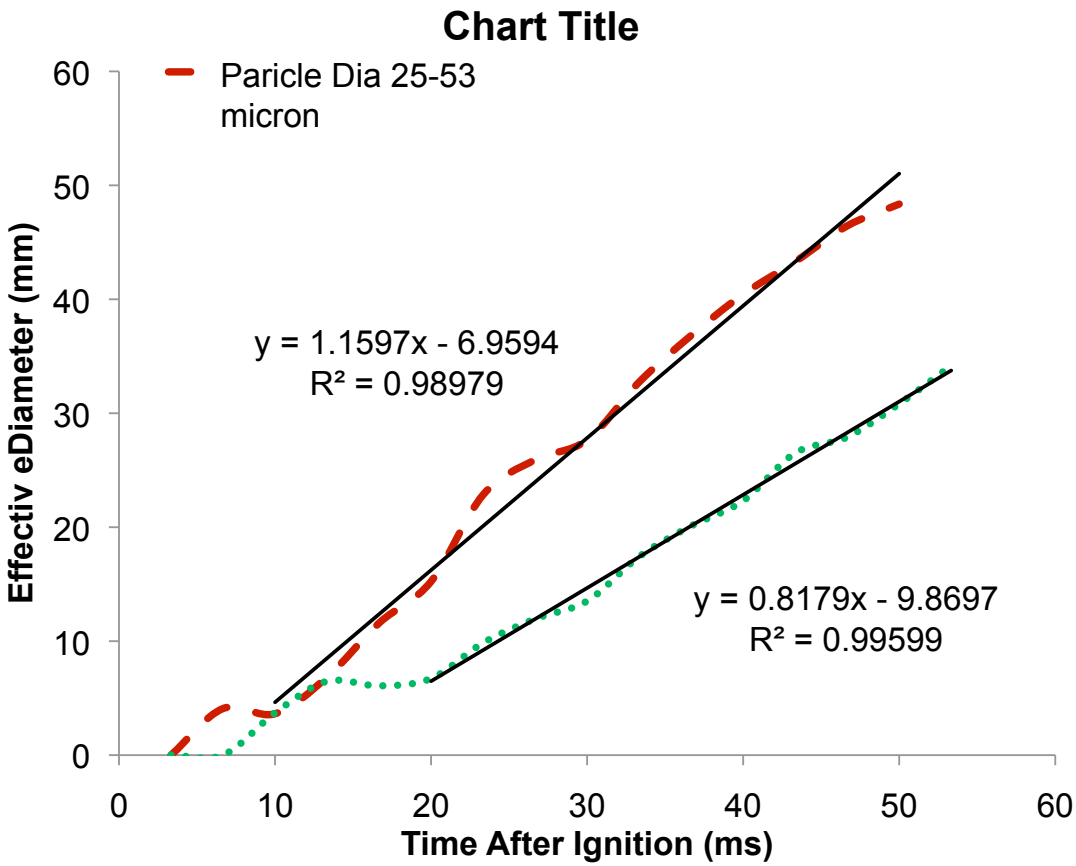
Coal Type	**Indonesian Coal**	**Illinois Basin #6**
Coal Classification	Bituminous (low sulfur, low ash)	Bituminous
	Ultimate Analysis (%)	
Carbon	73.70%	68.30%
Hydrogen	5.20%	5.00%
Oxygen	18.80%	13.80%
Nitrogen	1%	1.30%
Sulfur	0.10%	3.50%
Ash	1.30%	8.10%
	Typical Proximate Analysis (%)	
Moisture	16.12%	10.10%
Ash	1.06%	7.30%
Volatile	42.59%	35.90%
Fixed Carbon	40.23%	46.70%

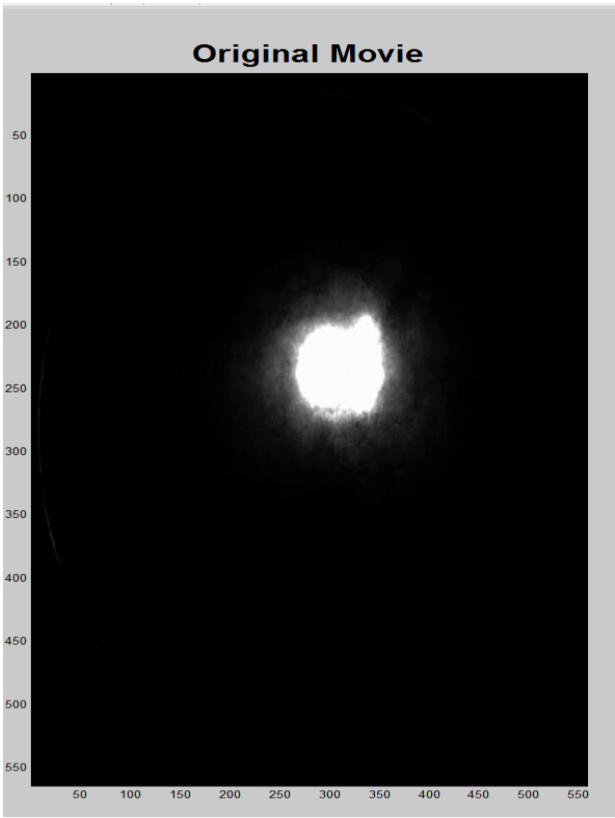


Further Classify Coal using Sieves:
- >106 µm
- 106 µm - 75 µm
- 75 µm - 53 µm
- 53 µm - 25 µm
- < 25 µm

PURDUE UNIVERSITY

How Flame Speed was Obtained



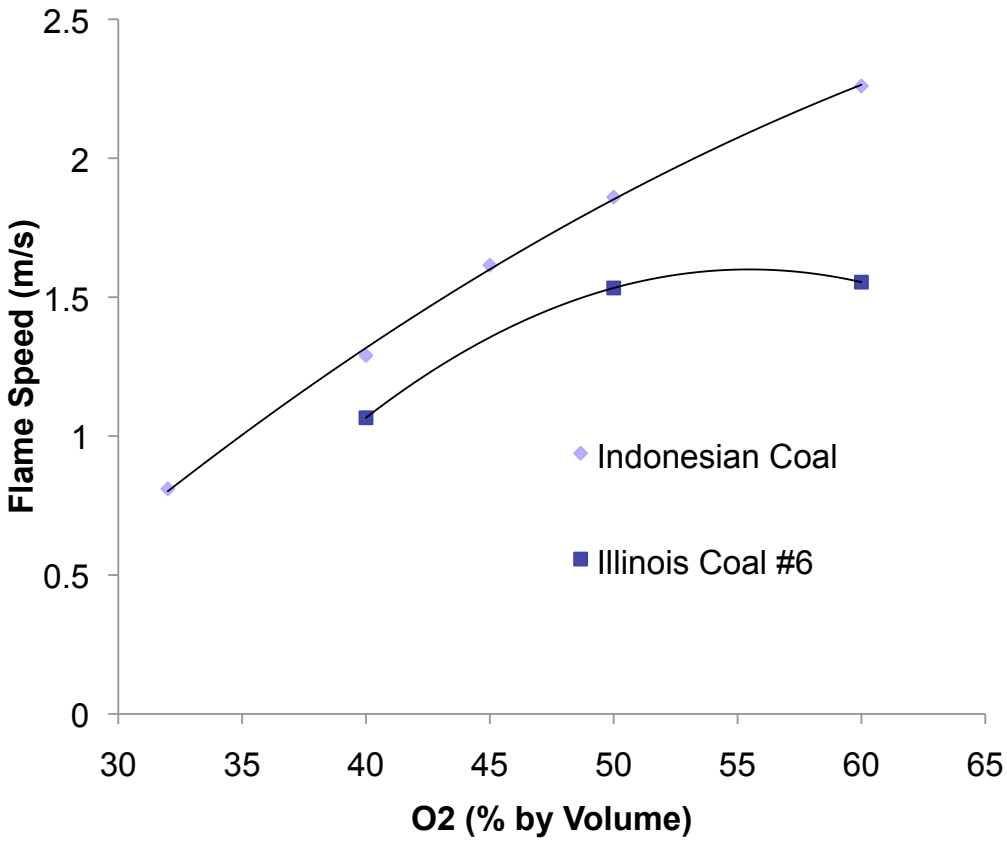


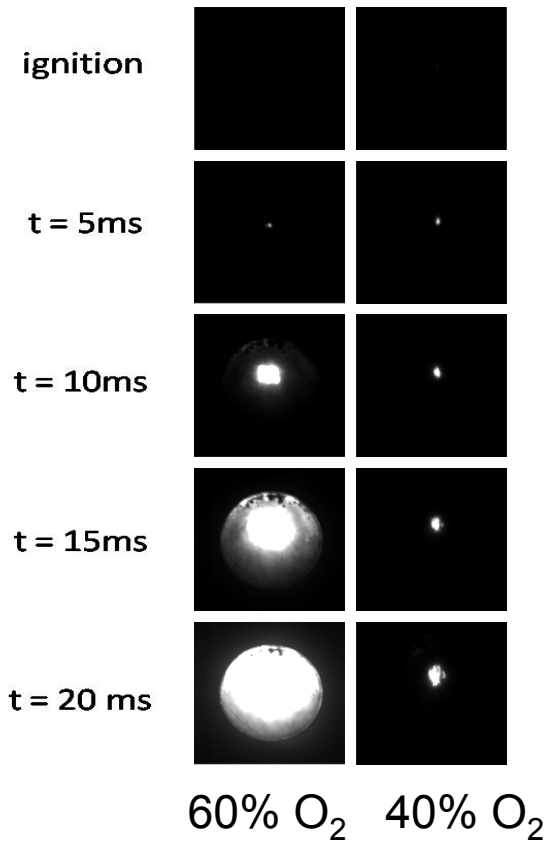
•Less Sensitive to Human Error in choosing effective diameter

Both cases:
Cloud density - 0.539 kg/m^3
40% O_2 and 60% CO_2
Indonesian Coal

PURDUE UNIVERSITY

Effect of Oxygen On Flame Speed

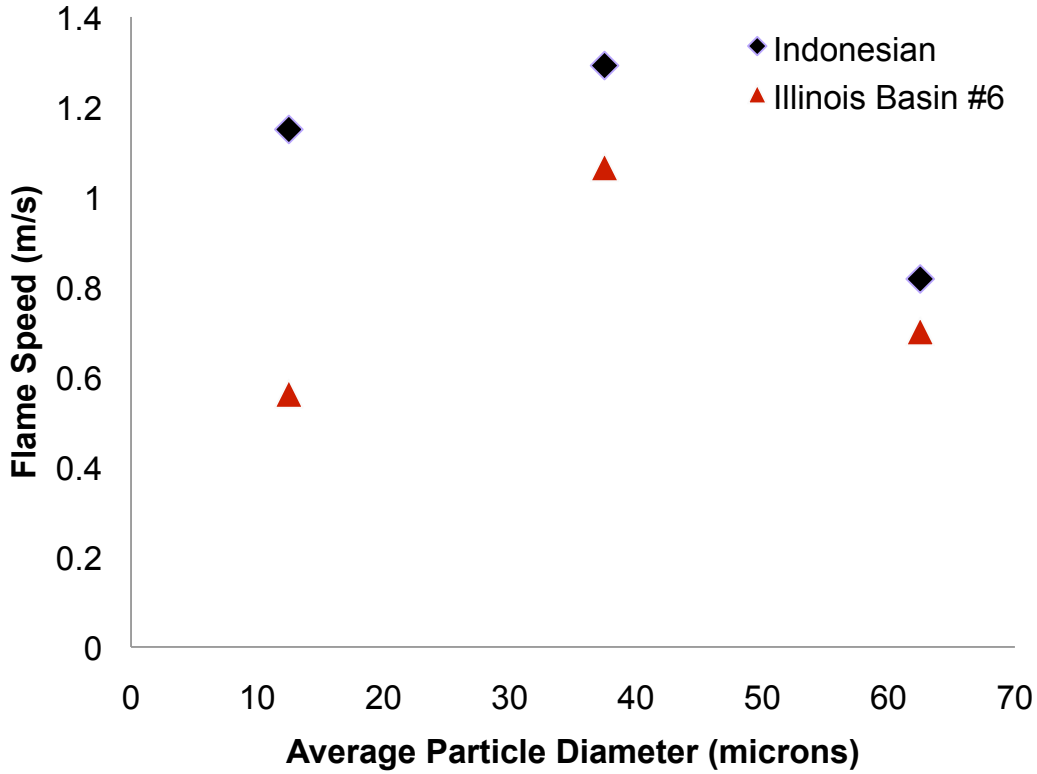


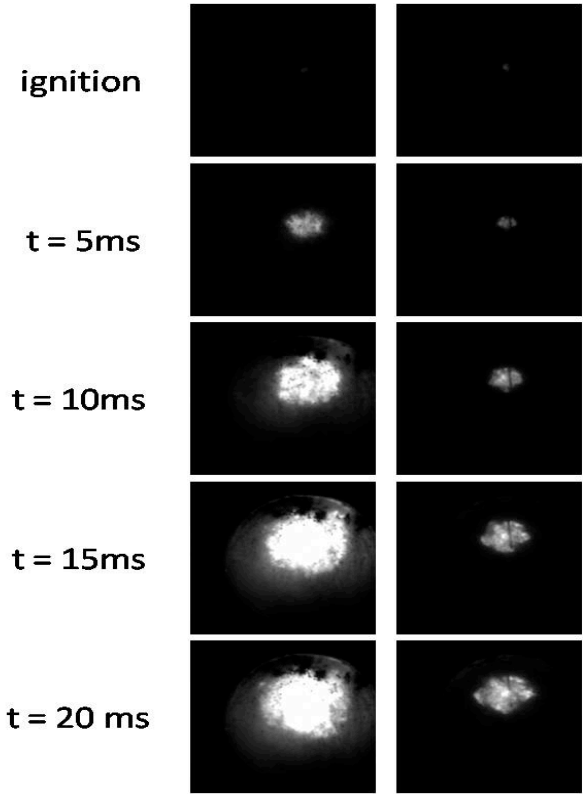


All cases:
Cloud density - 0.539 kg/m^3
Particle Dia. – 25-53 μm
Carbon Dioxide Diluent

PURDUE UNIVERSITY

Effect of Particle Diameter On Flame Speed





Dia. <25 μm Dia. 53-75 μm

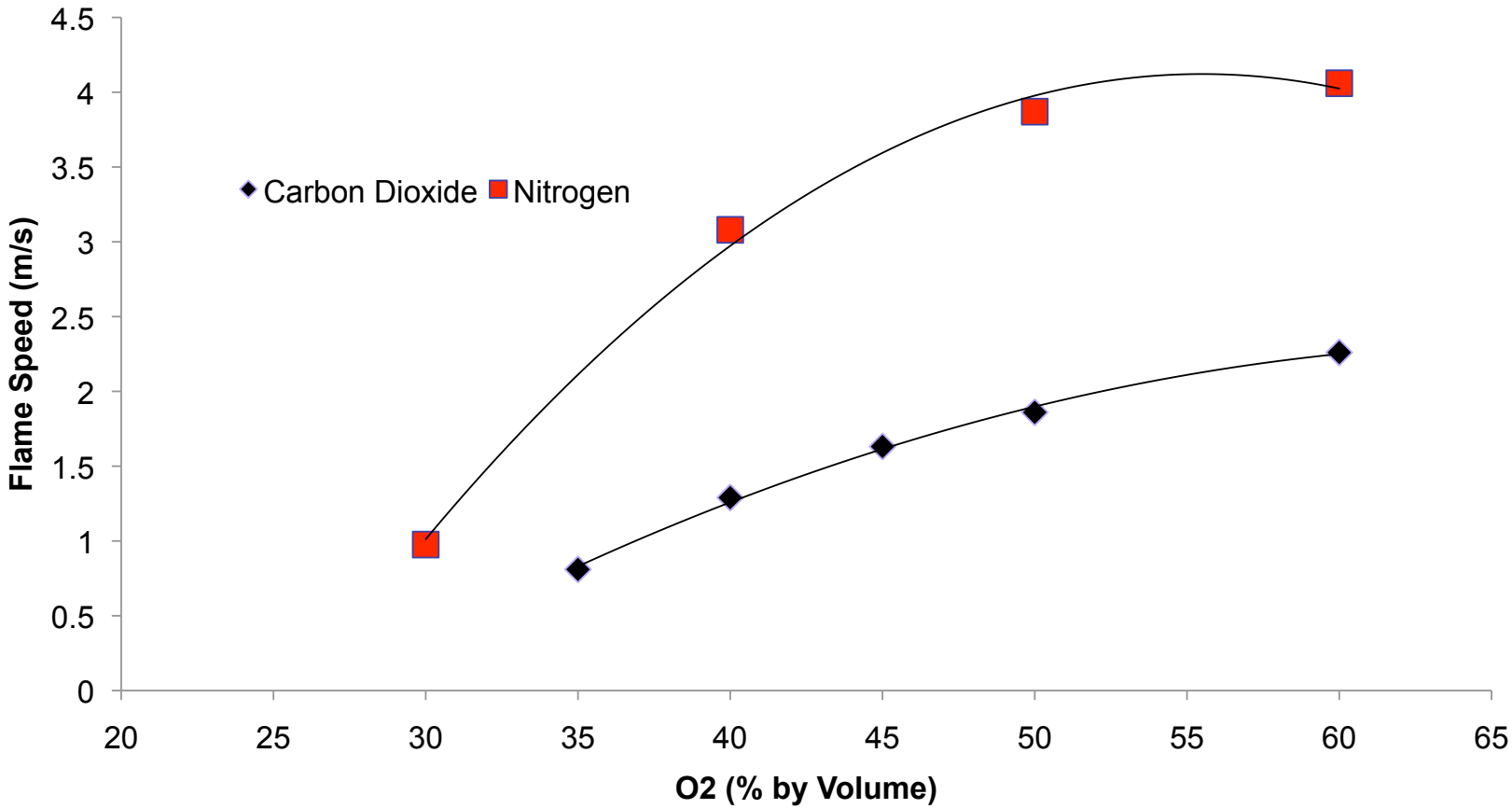
All cases:
Cloud density - 0.539 kg/m^3
40% O_2 and 60% CO_2

Decrease in flame speed with smallest particle size can be attributed to:

- Material Sticking to windows (leaner mixture)
- Agglomerations (can be seen in videos)

PURDUE UNIVERSITY

Effect of Diluent On Flame Speed



All cases:
Particle Dia – 25-53 microns
Indonesian Coal
Cloud density - 0.539 kg/m^3

Due to property differences between CO_2 and N_2.

Laboratory Experiments – Results (Spectral)

- Fast Infrared Array Spectrometer (FIAS)
  - •Portable
  - •Staggered PbSe linear array sensor cooled by TEC
  - •160 wavelengths from 1.4 to 4.8 *u*m
  - •Scan frequency: 6,250 Hz
  - •Acquisition frequency: 1,320 Hz

Laboratory Experiments – Results (Spectral)

ignition

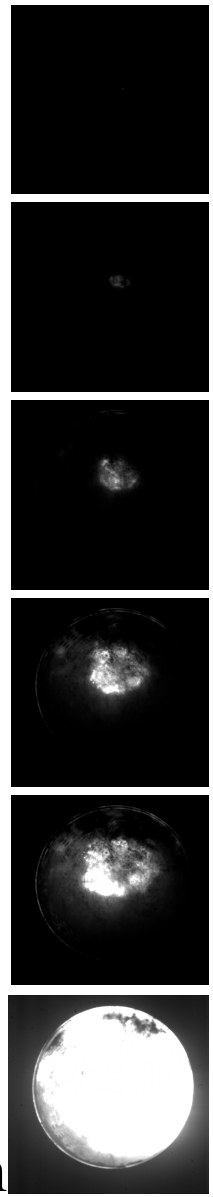
t = 10ms

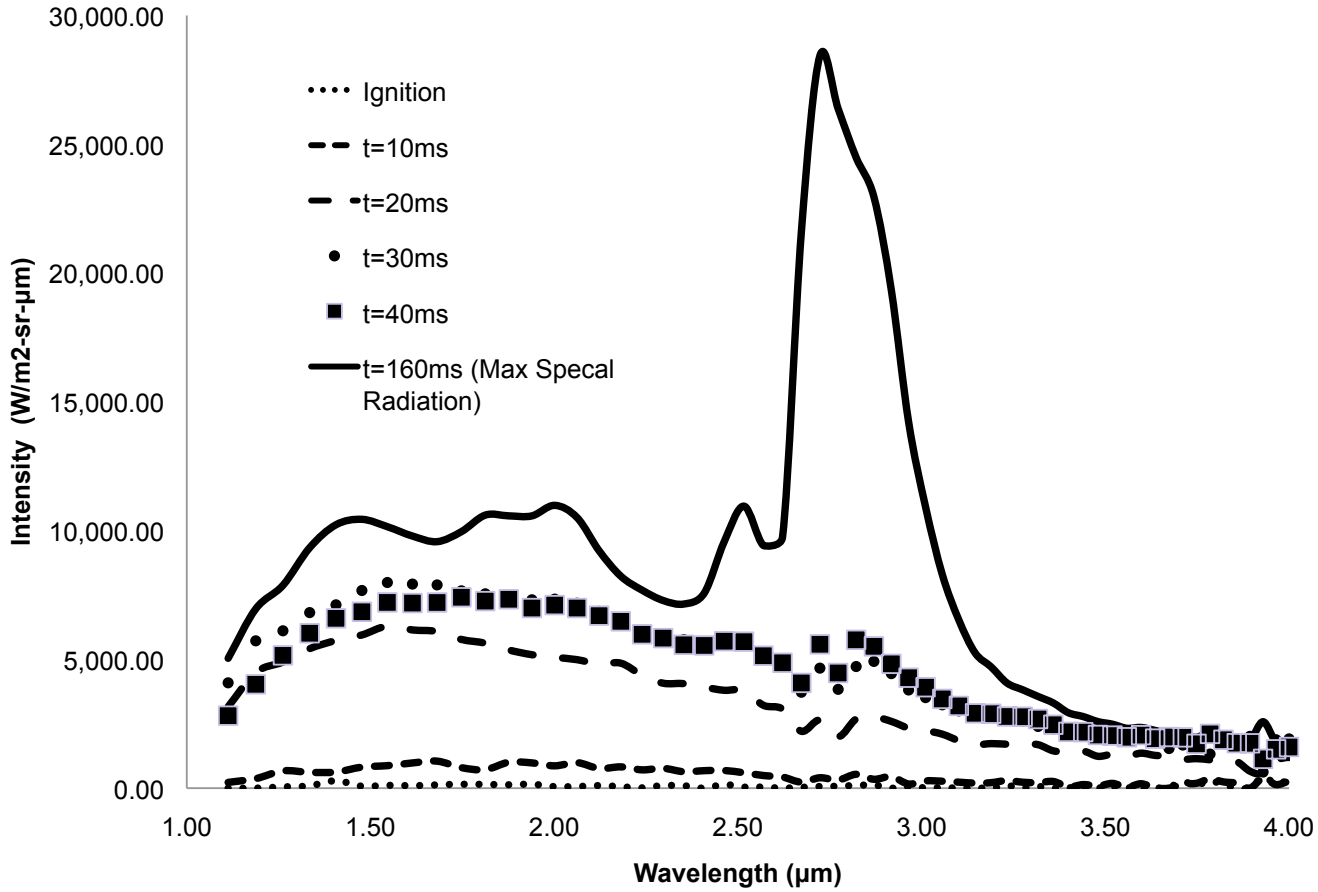
t = 20ms

t = 30ms

t = 40ms

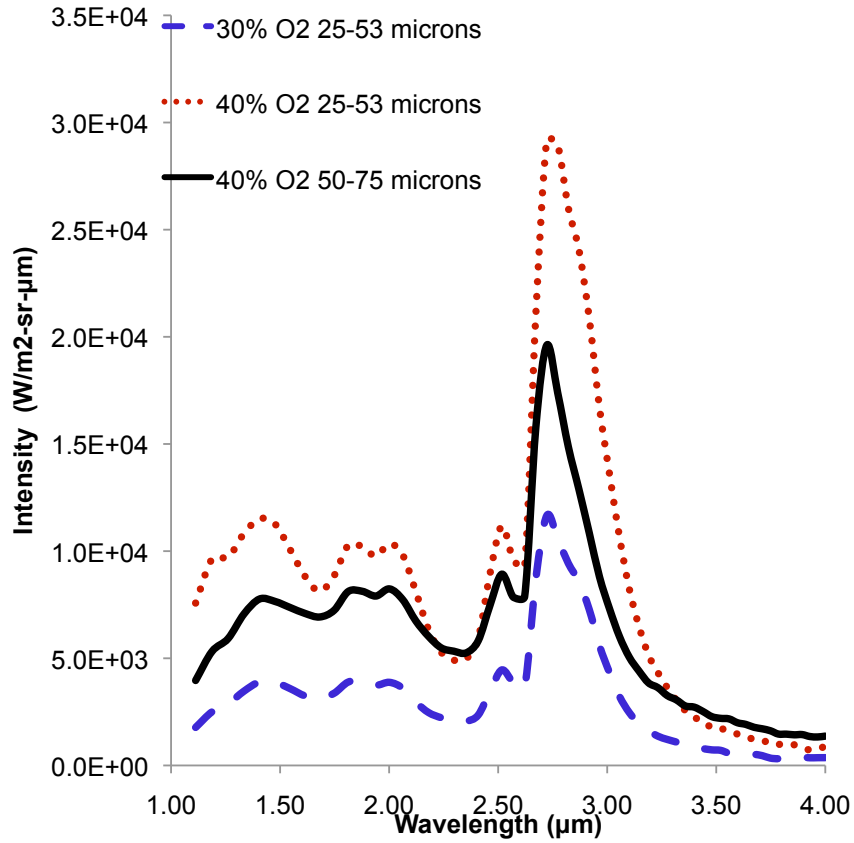
t = 160ms (Maximum Radiation)





Test Specs:
40% CO_2, 60% O_2
Particle Dia – 25-53 microns
Cloud density - 0.539 kg/m^3

Laboratory Experiments – Results (Spectral)



Maximum Peaks for N_2 Diluent

Trends

- Same General Shape
- Carbon Dioxide
  - Combating factors of increase in temperature vs. increased radiative potential
- Nitrogen
  - Increase in Intensity for increase O_2 , decrease in Diameter
- Peak at 2.7 microns for Water and CO_2

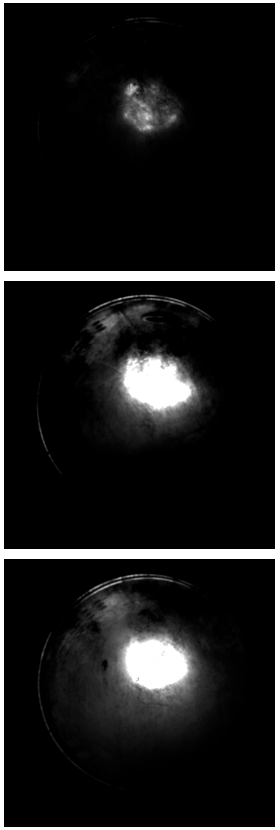
Laboratory Experiments – Results (Spectral)

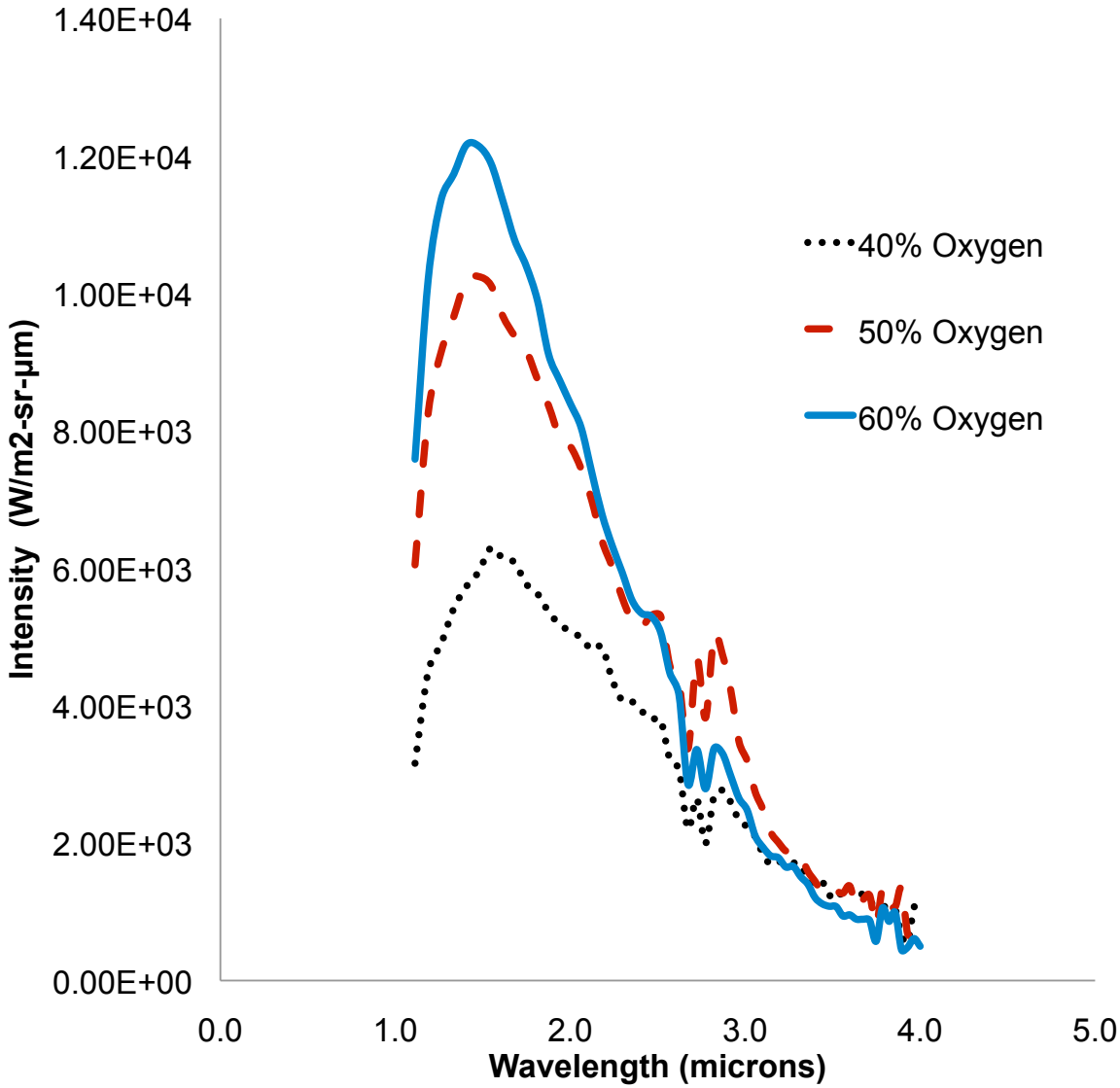
PURDUE UNIVERSITY

40% O_2

50% O_2

60% O_2

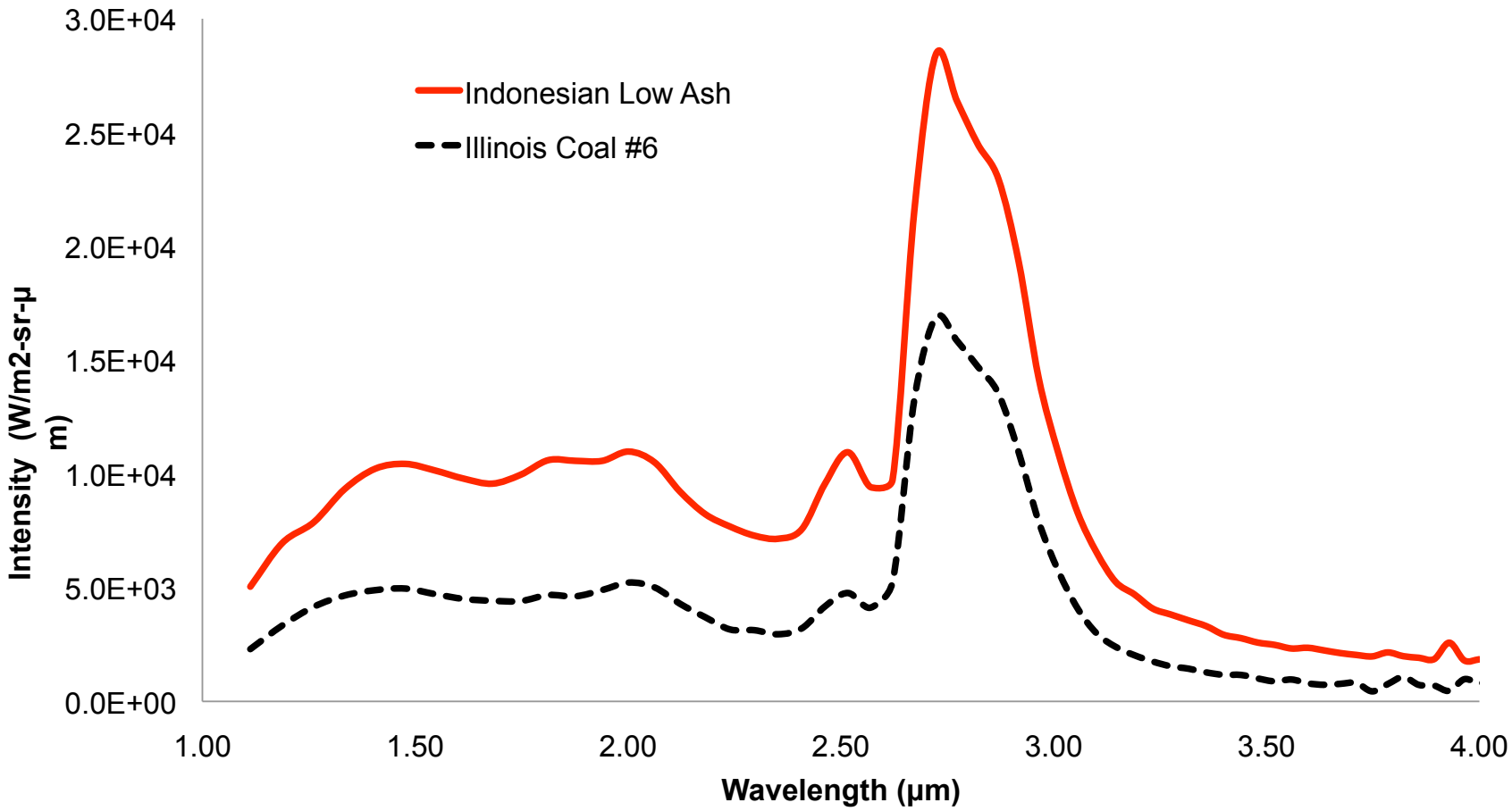




Test Specs:
Fire Ball Diameter ~ 48mm
CO_2 Diluent
Particle Dia – 25-53 microns
Cloud density - 0.539 kg/m^3

Similar features in pilot scale measurements

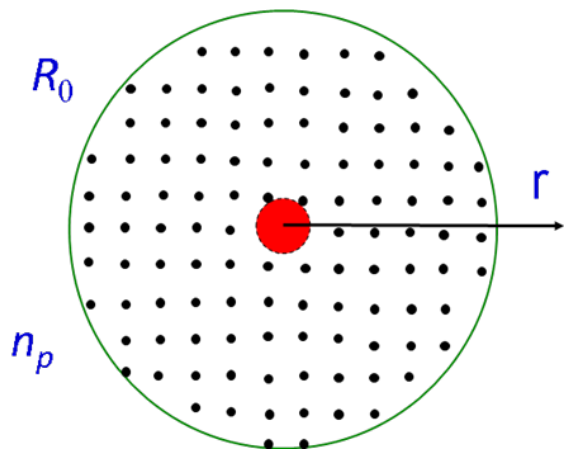
Laboratory Results – Experimental (Spectral)



Test Specs:
40% O_2, 60% CO_2
Particle Dia – 25-53 microns
Cloud density - 0.539 kg/m^3

Simulations (Qiao)

- We investigated the transient combustion characteristics of a spherically symmetric cloud containing coal particles, as shown in Fig. 1.
- The cloud has a radius of R_0. Coal particles, with diameter d_p and number density n_P, are uniformly distributed in the cloud.
- The cloud is numerically ignited using a hot spot.



- The Three-Level Fully Implicit (TLFI) scheme of second-order accuracy was applied to transient terms of the gas phase equations.
- The convective and diffusive terms are discretized using QUICK scheme and second order central difference, respectively.
- The time dependent equations of particle phase were solved using a standard ODE solver for stiff system, DVODE.

Assumptions

The transient combustion is modeled by conservation equations for mass, species and energy with detailed consideration of devolatilization, homogeneous gas phase reaction, heterogeneous char surface reaction, and radiative heat transfer.

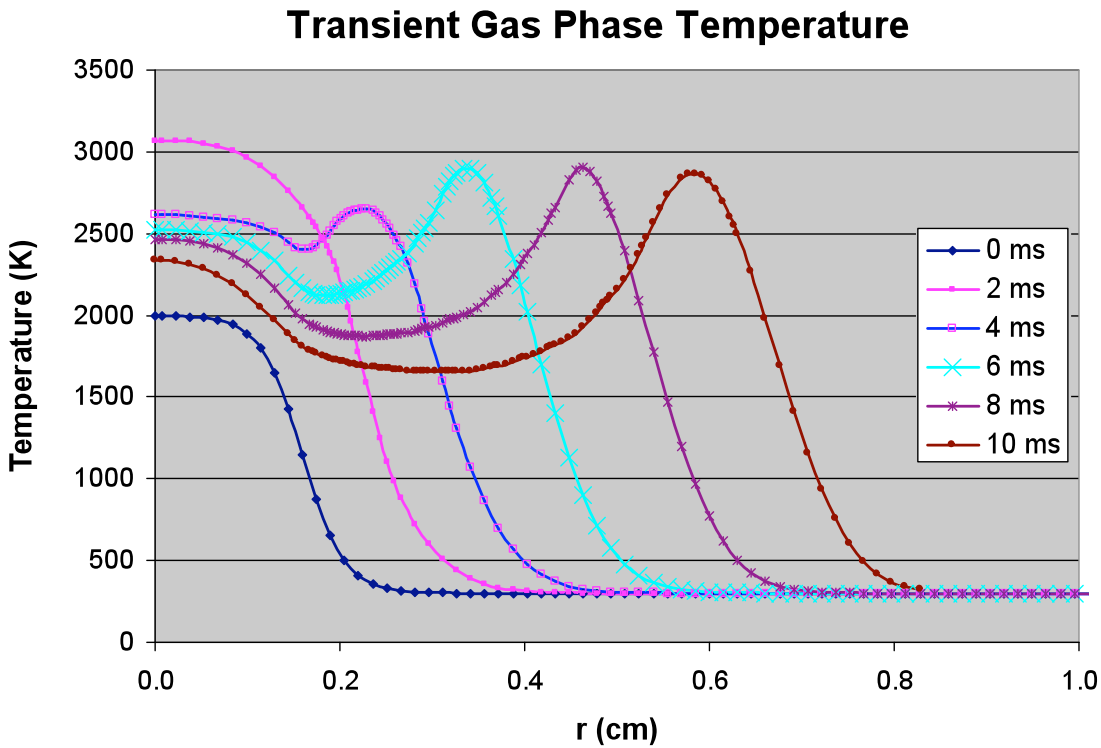
Assumptions:

(1) Gas phase and particles are uniformly mixed in space;
(2) The particles remain quiescent;

(3) Coal particles are spherical of various sizes;

(4) Each particle has uniform temperature because of its small size.

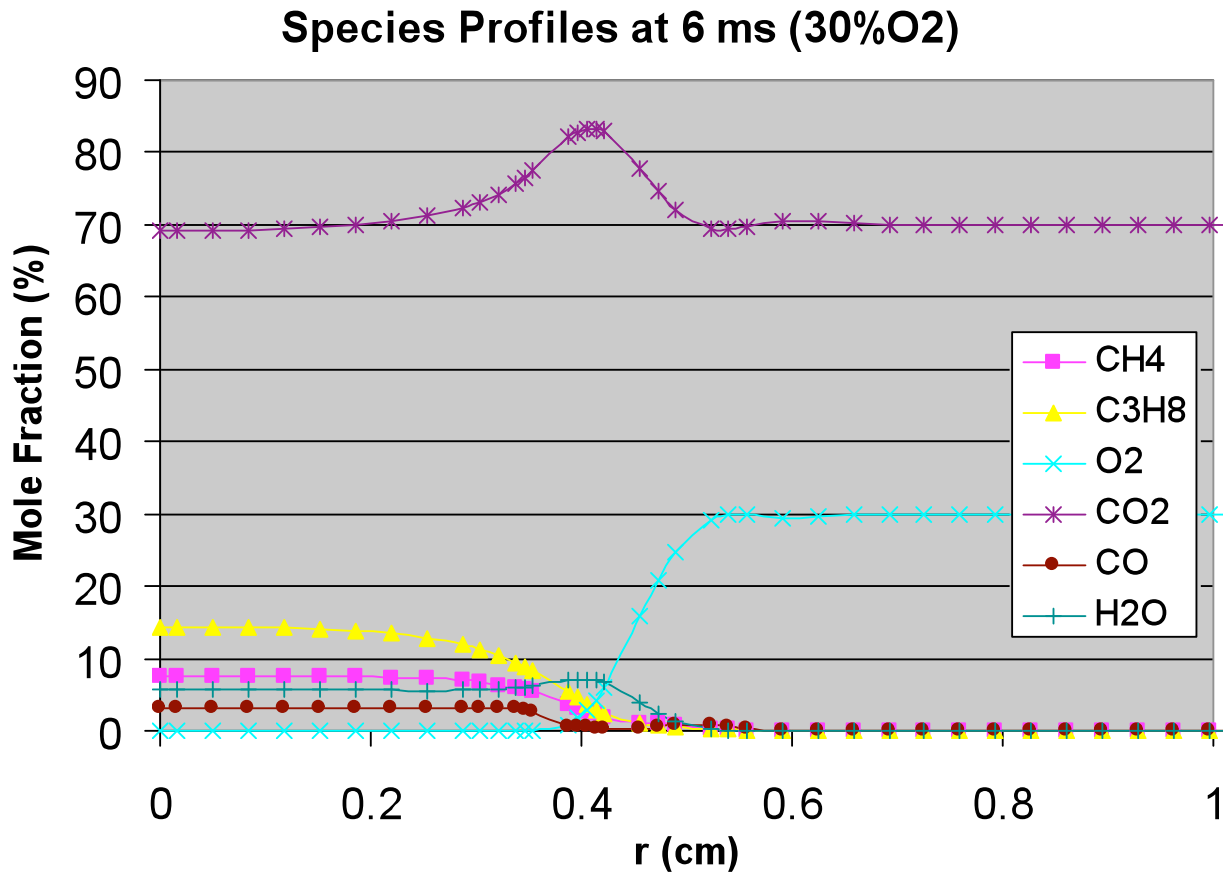
Temperature profile



Note:

1. The above figure shows the transient gas-phase temperature as a function of radius.
2. The initial coal particle temperature is assumed to be room temperature.
3. This is for O_2/CO_2=30/70 case.

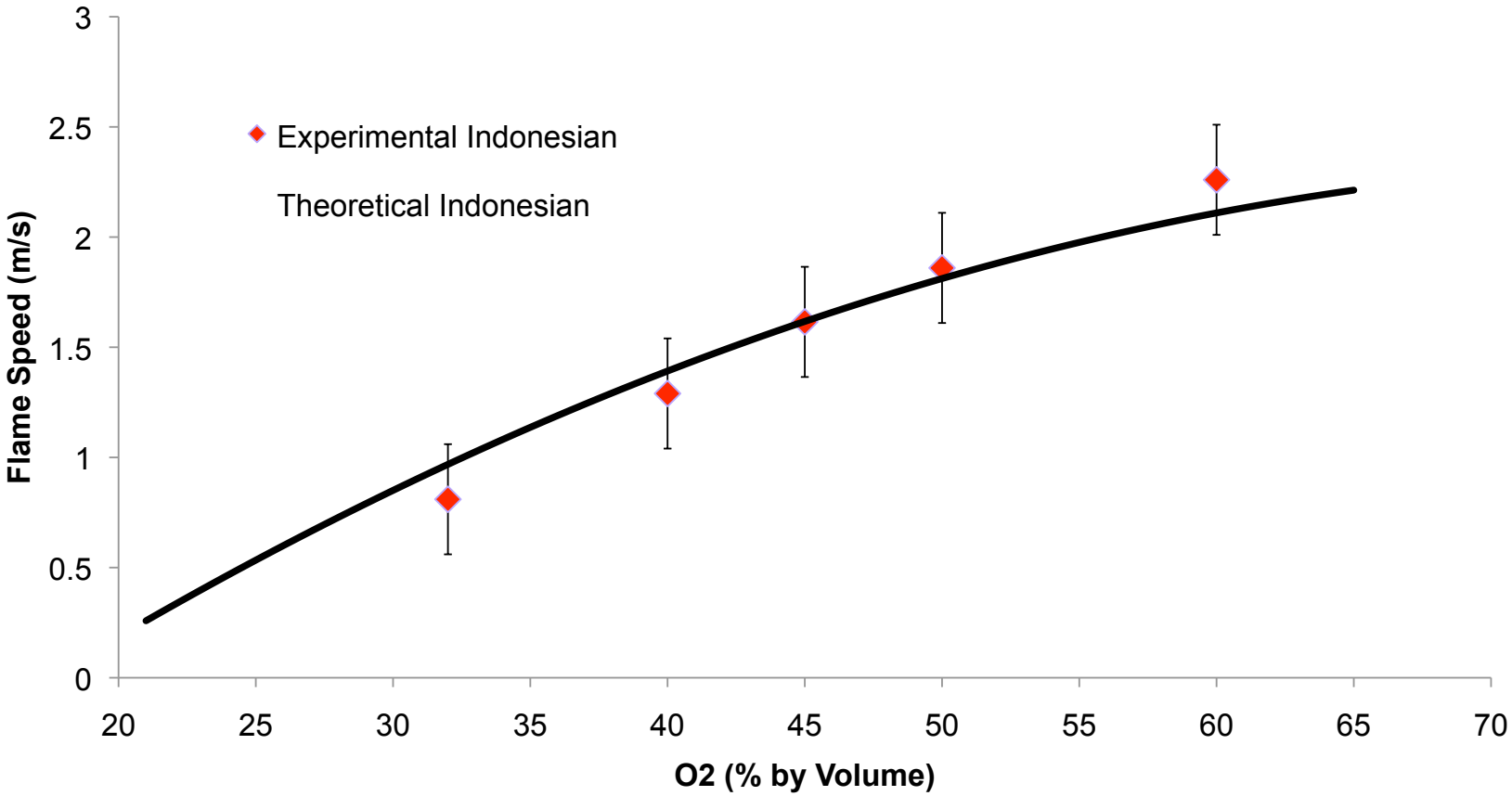
Flame Structure



Note:

1. The above figure shows the species concentration profiles at 6 ms.
2. This is for O_2/CO_2=30/70 case.

Experimental vs Theoretical Flame Speed



All cases:
Cloud density - 0.539 kg/m^3
Particle Dia. – 25-53 μm
Carbon Dioxide Diluent
Indonesian Coal

Pilot Scale Experiments

From Jupiter Oxygen in Hammond Indiana

Some funding from Jupiter Oxygen

Pilot Scale Experiments - Objectives

PURDUE UNIVERSITY

- Measure spectral radiation intensities of a pilot-scale oxy-fuel boiler at various locations (by Jupiter engineers)
- Analyze measured radiation data
- Estimate temperate profile at one cross-section of the boiler furnace using inverse radiation interpretation

Pilot Scale Experiments - Objectives

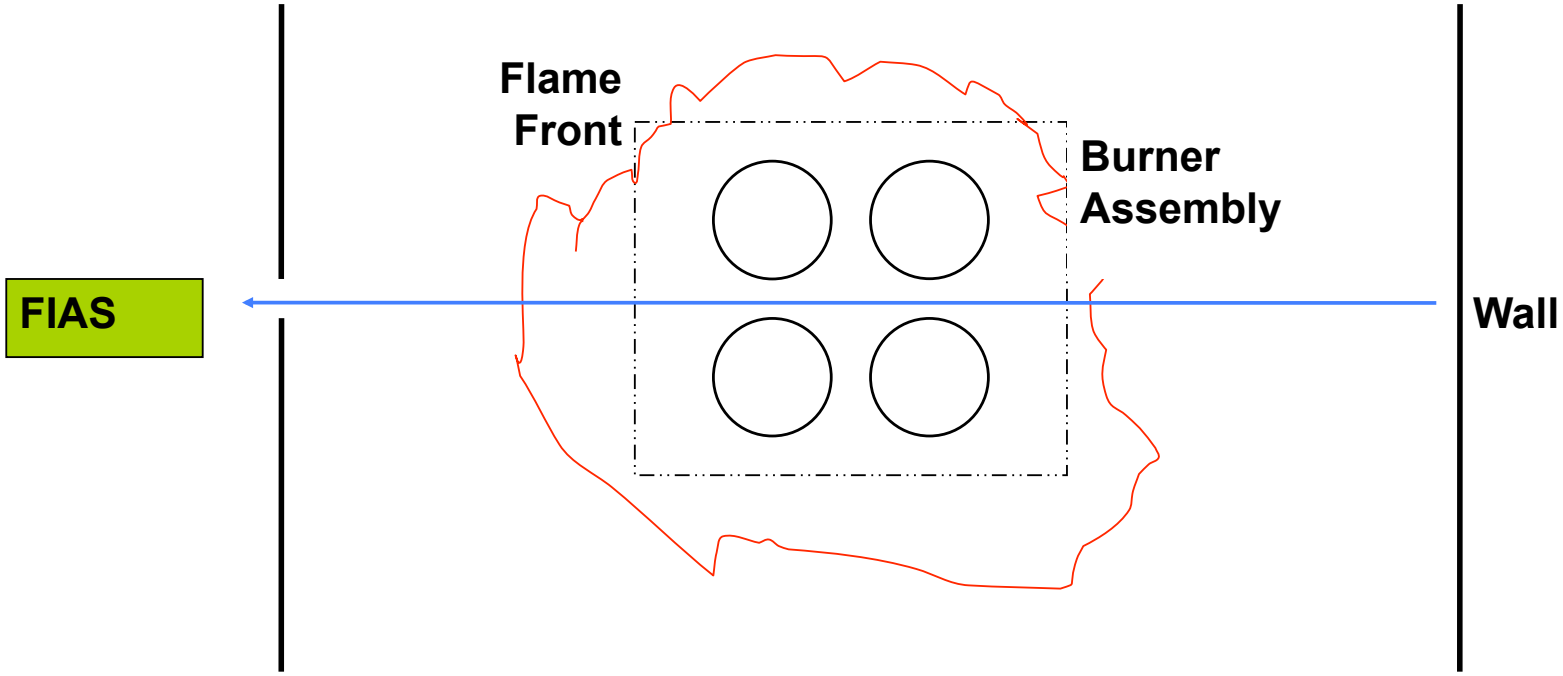
PURDUE UNIVERSITY

- The Pilot Scale Boiler
  - Doosan Backcock 23.4 MW boiler
  - Four Maxson 2.93 MW
  - Total heating rate during tests: < 8.79 MW
- Test Matrix
  - HT oxy-natural gas without CO_2 recycling
  - HT oxy-natural gas with CO_2 recycling (blanket)*
  - LT oxy-natural gas with CO_2 recycling (synthetic air)
  - Air firing natural gas
  - HT oxy-coal without CO_2 recycling

* http://www.jupiteroxygen.com

PURDUE UNIVERSITY

Spectral Measurement Configuration



Pilot Scale Experiments – Inverse Flame Temperature Technique

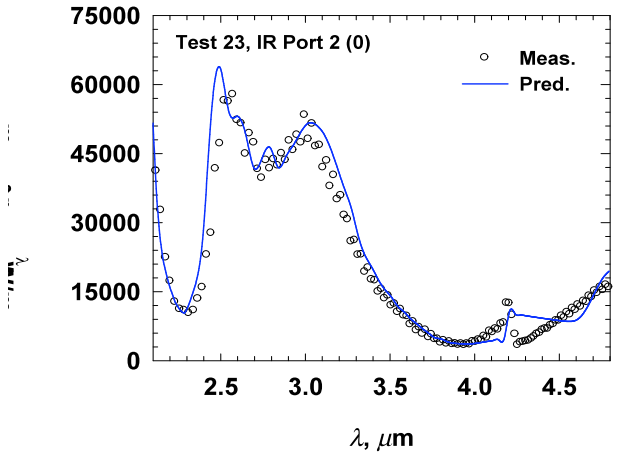
The temperature profile was described as the following:

$$T(r) = T_p \exp\left[-\left(\frac{r - r_p}{c}\right)^2\right] + T_b$$

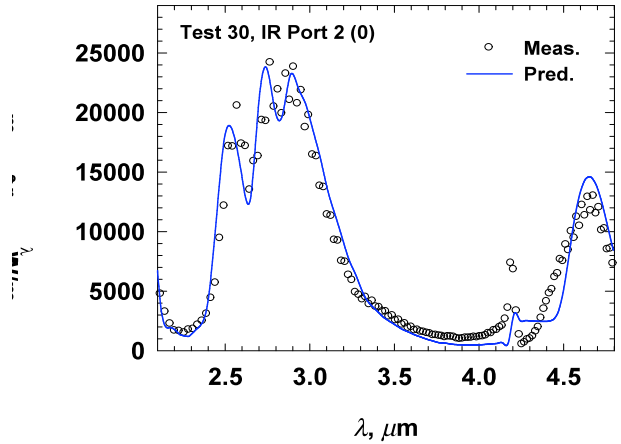
•Assumed Temperature Profile and best fit to boundary conditions and spectral data

•First time this technique applied to coal and pilot scale experiments

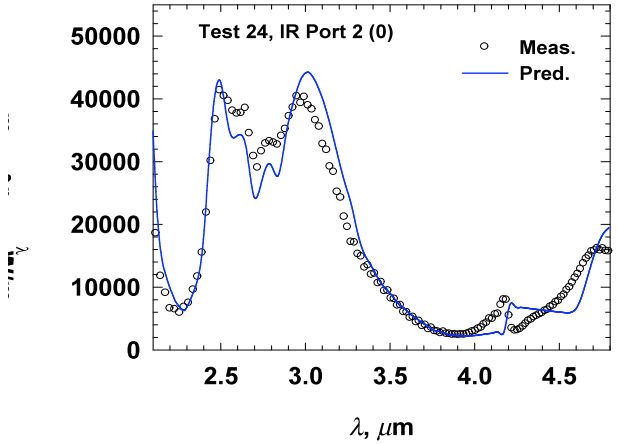
Pilot Scale Experiments – Results



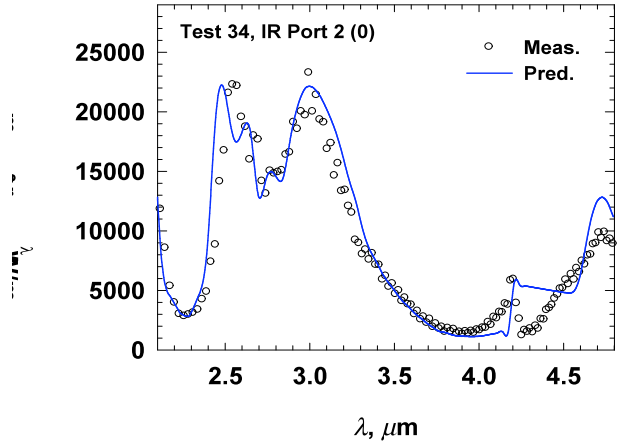
Spectral Emissions of HT oxy-fuel w/o CO_2 recirculation



Air-Fire Spectral Emissions

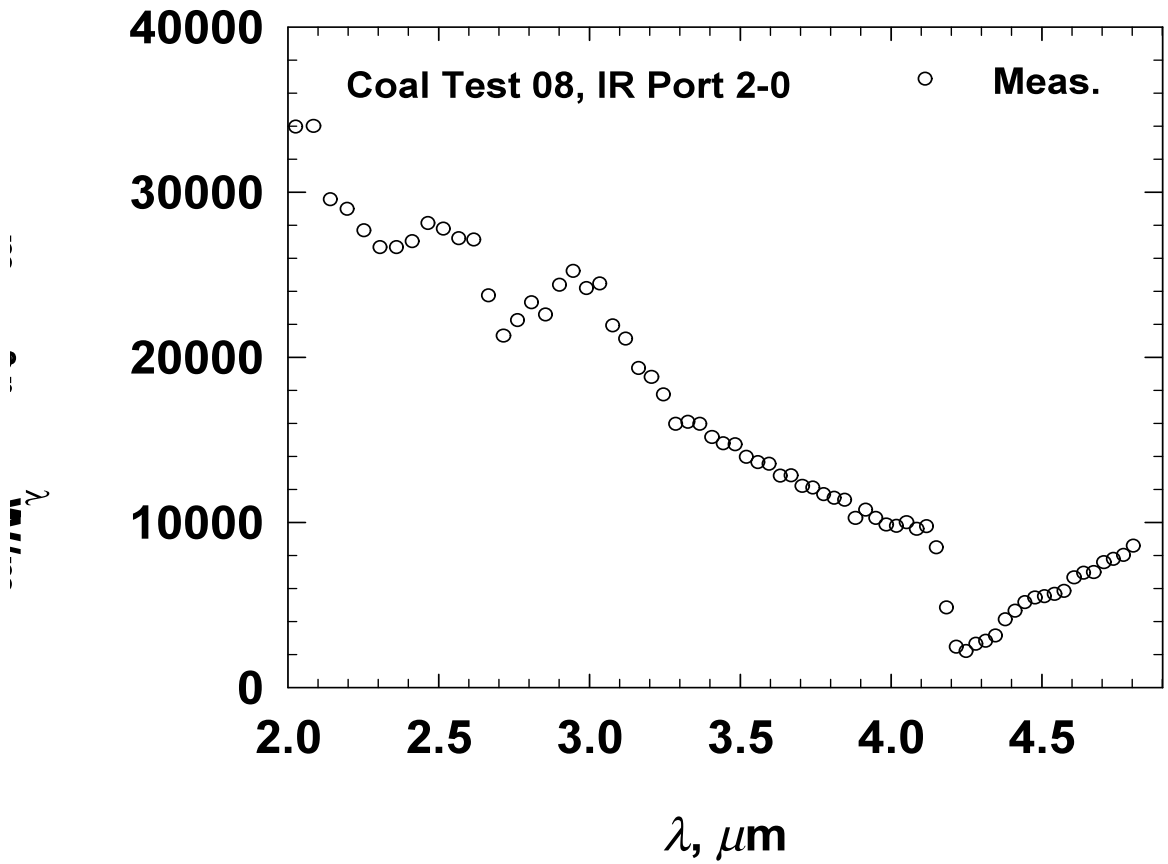


Spectral Emissions of HT oxy-fuel w/ CO_2 recirculation



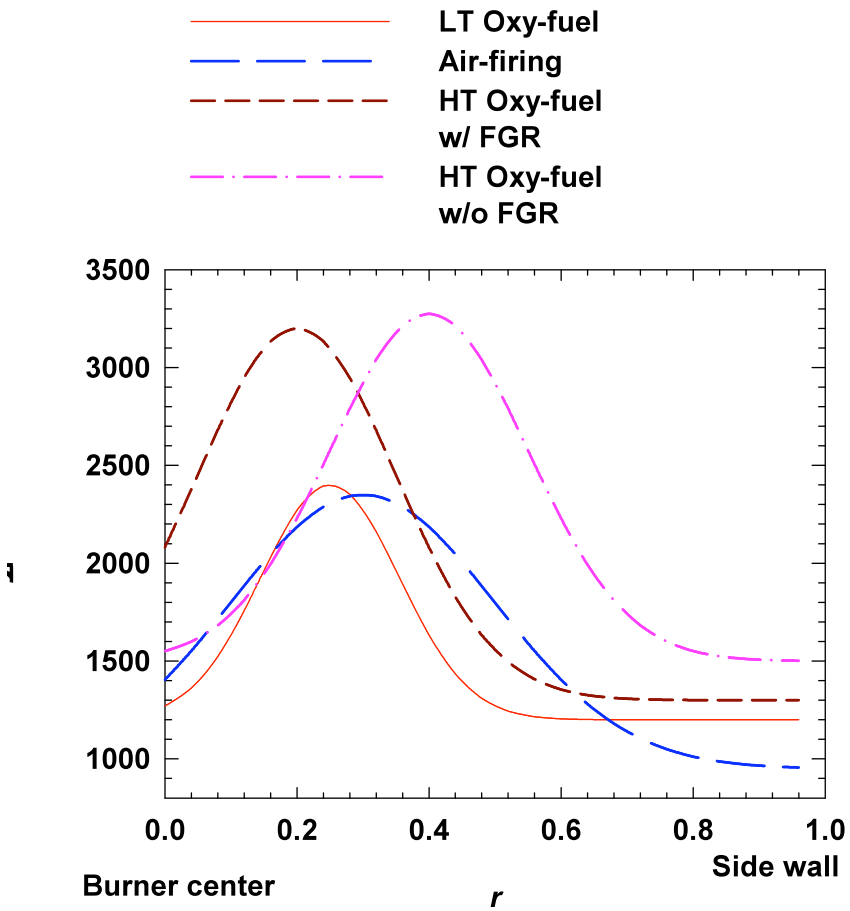
LT oxy-fuel Spectral Emissions (Synthetic Air with FGR)

Pilot Scale Experiments – Results



Jupiter Oxy-Coal Spectral Results
More analysis needed
NETL is using this data with modeling efforts there

Pilot Scale Experiments – Results



Comparison of estimated temperature profiles

- Peak temperatures of HT oxy-fuel flames are MUCH higher
- Temperatures of LT oxy-fuel air-firing flames are comparable
- Gas temperature near the wall of the HT oxy-fuel without FGR configuration is the highest

Continuing Work

- Modify inverse temperature estimate code for dust clouds
  - Also, can take simulation results and calculate radiant emission
- More comparisons with calculations
  - About an hour for each simulation
- More spectral radiation analysis
- Repeat some nitrogen tests
- Do some tests with visible spectrometer
- Prepare final report

Future work?

- Would continue oxy-coal experiments with significant modeling effort (Qiao)

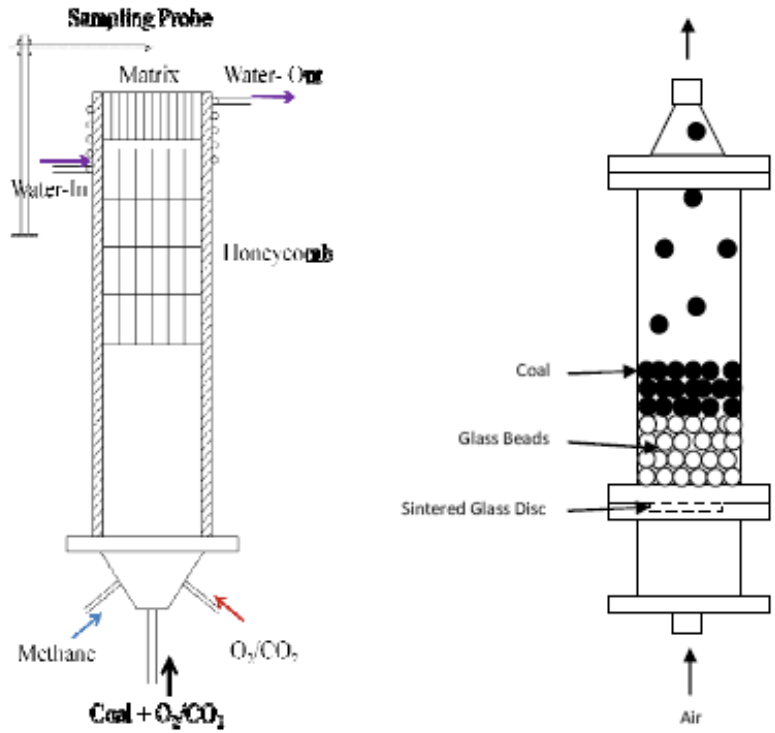


Fig. 3. Sketch of the flat dust coal flame burner and the fluidized bed feeder.

Future work?

- Diffusion HT burner

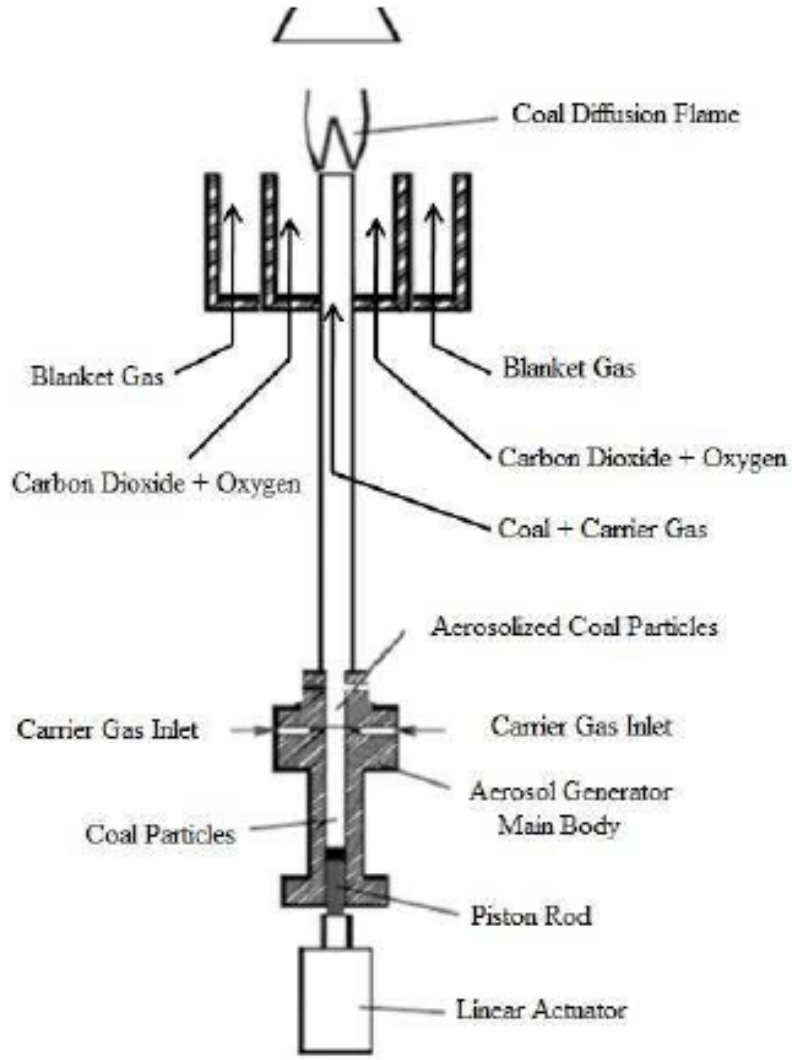


Fig. 4. Sketch of the Bunsen particle burner.

Future work?

- Benchscale 150 kW burner

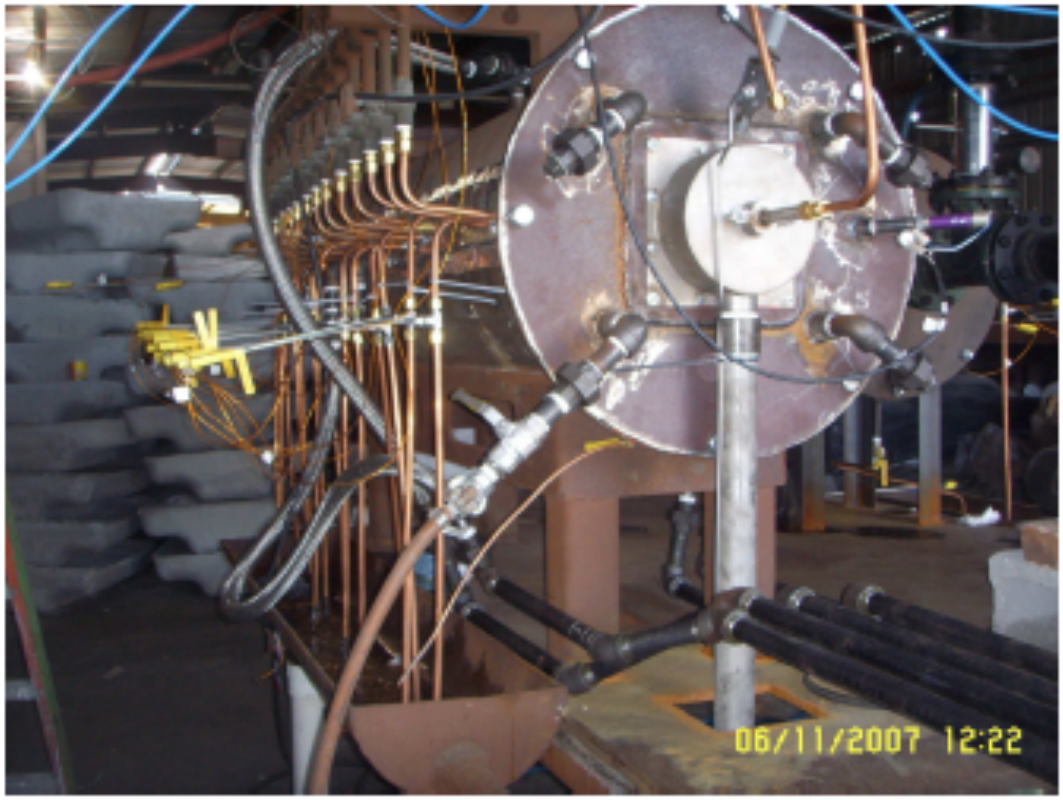


Fig. 5. Jupiter Oxygen's 150 KW furnace.

Also submitted white paper to DOE ARPA-E call

Acknowledgements

We'd like to thank Prof. Timothee Pourpoint for use of his Matlab Code for analyzing the high-speed images.

We thank Jupiter Oxygen engineers for gathering the data and providing pilot scale apparatus. In particular, we thank Brian Patrick and Steve Nied.

We thank the Center for Coal Technology Research for funding under contract number 7-PSC-CTR-002. In particular, we thank Marty Irwin and Brian Bowen for their support of this work.