Soot Measurements in an Air and Oxy-fired Coal Flame

Curtis Stimpson, Todd Reeder, Dale Tree
Brigham Young University

Andrew Fry
Reaction Engineering International

Thanks to funding from U.S. Dept. of Energy DOE Cooperative Agreement No.: DE-NT0005288 and Reaction Engineering
Appreciative of University of Utah, Their Facility and Invitation to be Involved

24th Annual ACERC Conference
Feb. 25, 2010

BYU Mechanical Engineering

Introduction

- Oxy-combustion is a carbon capture enabling technology
- One of the differences between air and oxy combustion is the amount of heat transfer
- One of the potential differences in heat transfer is caused by differences in soot concentration

Objectives

Measure in-situ, line-of-sight soot extinction in an air and oxy-fired coal flame using laser extinction method

- Collect measurements at one or two locations in the near burner zone.
- Obtain measurements for a series of Air/Fuel ratios
- Obtain measurements for two coals, Utah Bituminous, and a PRB sub-bituminous coal

BYU
Mechanical Engineering

Background

Visible light will be absorbed by particles in a coal flame according to Beer's law.

$$\tau = \frac{I}{I_0} = e^{-\kappa L}$$

Where κ is an extinction coefficient for the particles and *L* is the path length.

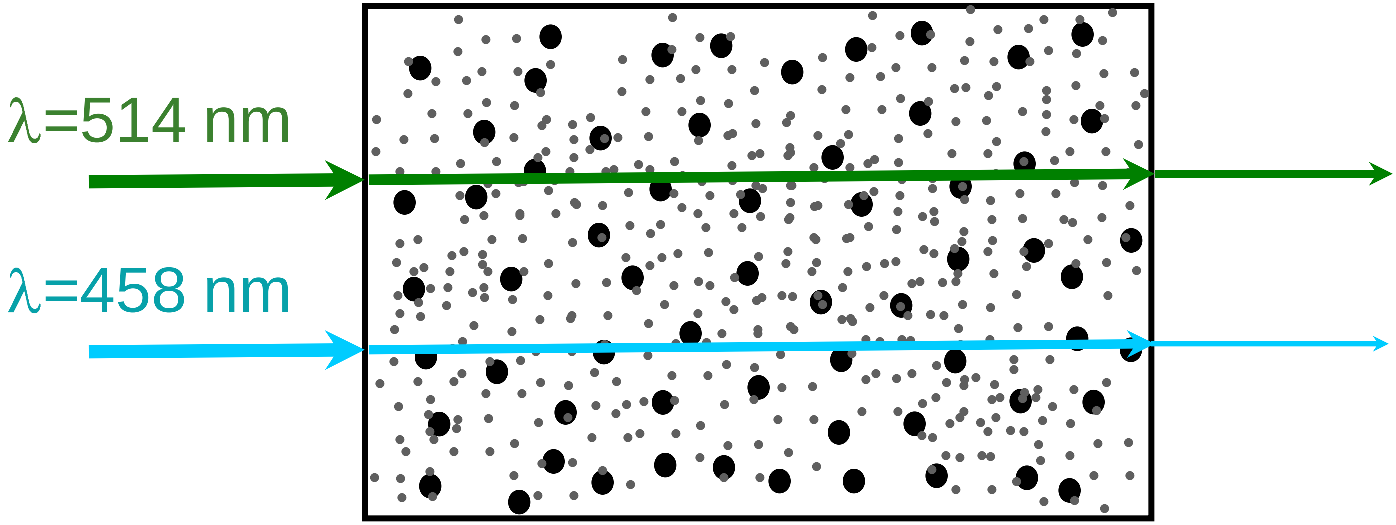
There are several types of particles in a coal flame: coal, char, ash, and soot.

$$\tau_{total} = \frac{I}{I_0} = e^{-\kappa_{soot} L} \times e^{-\kappa_{coal} L} \times e^{-\kappa_{char} L} \times e^{-\kappa_{ash} L}$$

Background

The much smaller soot particles absorb light preferentially at shorter wavelengths while coal char and ash absorb light equally at all visible wavelengths

$$\tau_{tot} = \frac{I}{I_0} = \exp\left(-\frac{K_{soot}L}{\lambda^{1.39}}\right)\exp(-K_{c,c,a}L)$$



Background

Using two wavelengths, the absorption due to soot can be separated

$$\ln(\tau_{tot})_{\lambda_1} = -\frac{K_{soot}L}{\lambda_1^{1.39}} - K_{c,c,a}L$$

$$f_v = \frac{K_{soot}}{A_\lambda}$$

$$-\ \ln(\tau_{tot})_{\lambda 2} = -\frac{K_{soot}L}{\lambda_2^{1.39}} - K_{c,c,a}L$$

$$\ln\left(\tau_{\lambda_1}/\tau_{\lambda 2}\right) = -\frac{K_{soot}L}{\lambda_1^{1.39}} + \frac{K_{soot}L}{\lambda_2^{1.39}} = K_{soot}\left[\frac{L}{\lambda_2^{1.39}} - \frac{L}{\lambda_1^{1.39}}\right]$$

Background

Several models may be selected to relate the extinction coefficient to the soot volume fraction

We have selected the Rayleigh limit equations with optical constants for soot from Dalzell and Sarofim (1969)

$$\tau_{soot} = \exp\left(\frac{-K_{soot}L}{\lambda^{1.39}}\right) = \exp\left(-Q_{ext}\frac{\pi d^2}{4}\frac{f_v}{\pi d^3/6}L\right)$$

$$Q_{ext} = 4\frac{\pi d}{\lambda}\operatorname{Im}\left(-\frac{m^2-2}{m^2+2}\right)$$

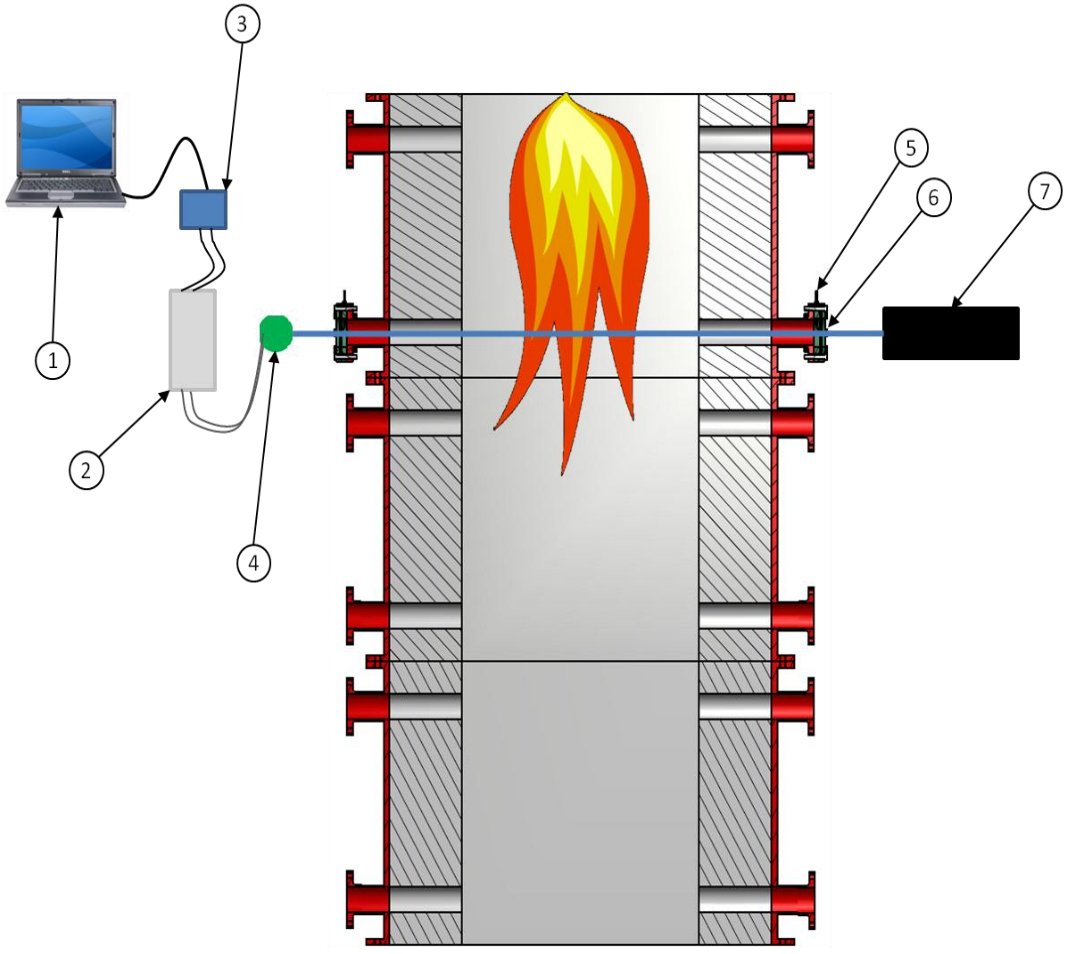
$$f_v = \frac{K_{soot}}{6\pi \operatorname{Im}\left(-\frac{m^2-2}{m^2+2}\right)\lambda^{0.39}} = \frac{K_{soot}}{4\lambda^{0.39}}$$

$Q_{ext} = extenction\ efficiency$

$m = complex\ refractive\ index$

BYU Mechanical Engineering

Method – Optical Setup on L-1500 Reactor



Top cut-away view of L1500

1. Personal Lap-top computer
2. Amplifier
3. Analogue to Digital Converter
4. Integrating sphere, band pass filters, photo diodes
5. Purge CO_2
6. Window
7. Multi-line, 100 mW, Ar+ laser , 34 mW 514.5 nm, 8 mW 457.9 nm

BYU Mechanical Engineering

Method – Optical Setup on L-1500 Reactor

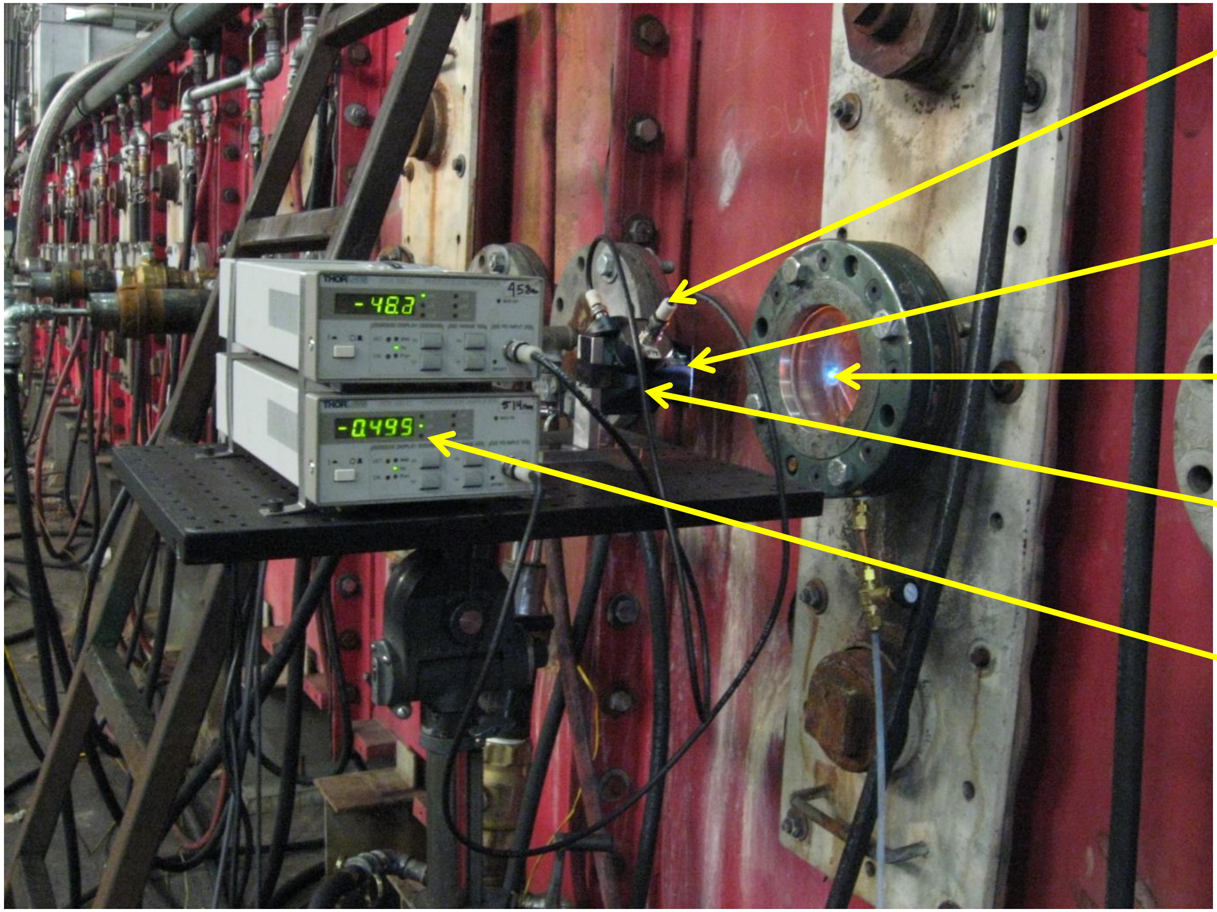
University of Utah, L -1500 Furnace

- Furnace has been retrofit for oxy-combustion
- Exhaust gas is cooled and then recycled
- The burner can split O_2 between primary, inner and outer secondary streams
- The fraction of O_2 in the oxycombustion tests is nominally 30%.
- Firing rate is 3.5 Mbtu/hr

Method – Optical Setup on L-1500 Reactor

Soot Measurement in second port, approximately 1.75 m from burner

Method – Optical Setup on L-1500 Reactor



Photodiode

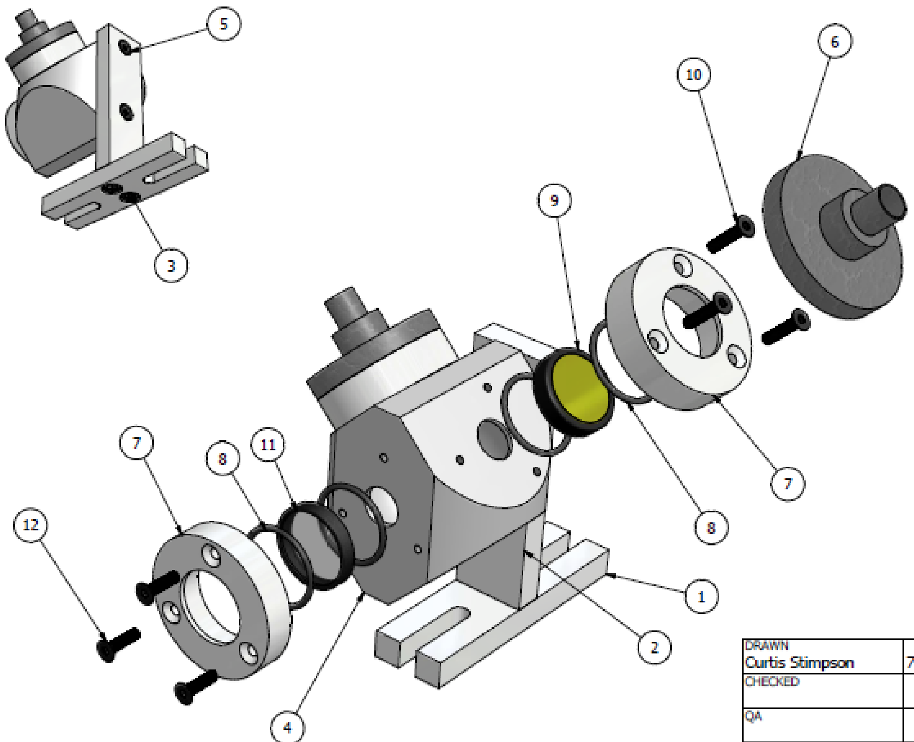
Iris type aperture

Laser exiting a window

Integrating Sphere

Photo Diode Amplifiers

Method – Optical Setup on L-1500 Reactor



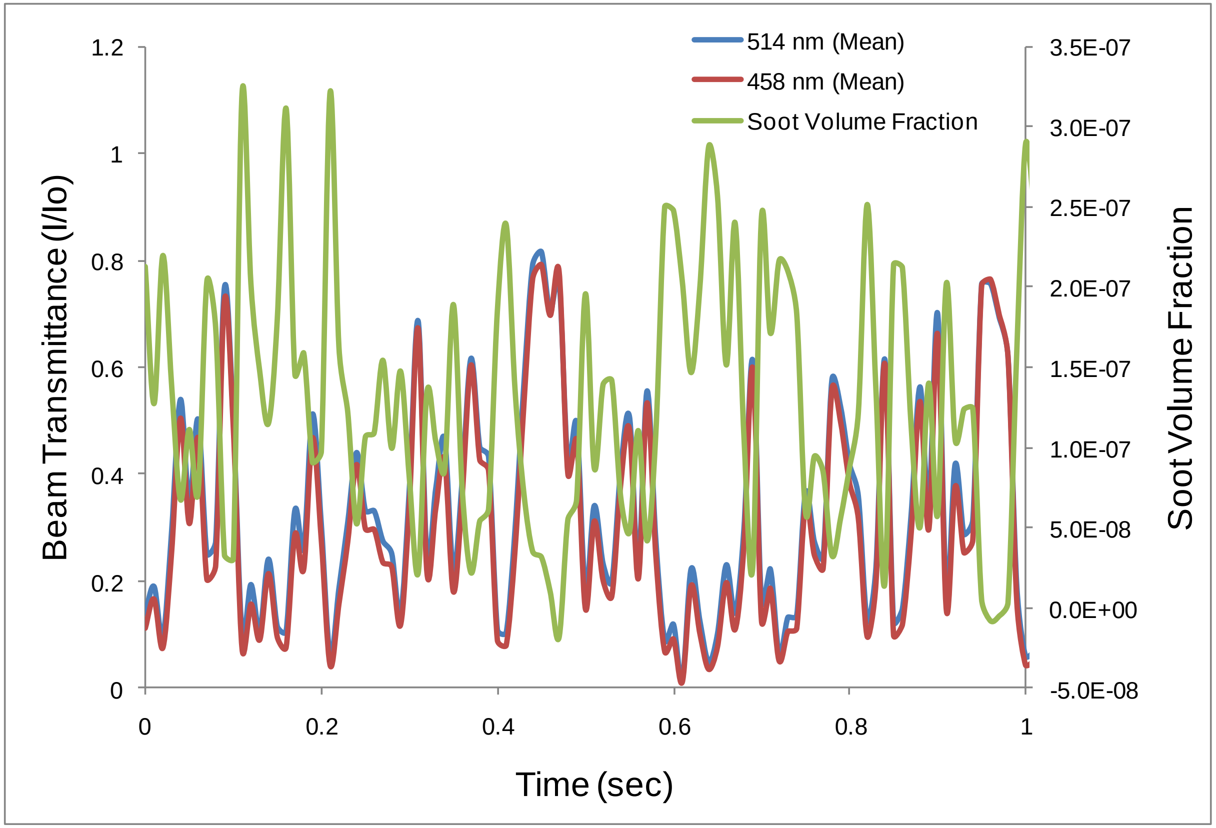
PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Stand: Horizontal Member	
2	1	Stand: Vertical Member	
3	2	Hex Socket Cap Screw	1/4 - 20 UNC x .75
4	1	Integrating Sphere	
5	2	Hex Socket Flat Head Cap Screw	M4 x 0.7 x 16mm
6	2	Lense Holder	
7	3	Polarizer Holder	
8	6	O Ring	AS568A Dash Number 020
9	2	Filter Assembly	
10	6	Hex Socket Flat Head Cap Screw	M3 x 0.5 x 14mm
11	1	Polarizer	
12	3	Hex Socket Flat Head Cap Screw	M3 x 0.5 x 12mm

DRAWN			
Curtis Stimpson	7/17/2009	Brigham Young University	
CHECKED		TITLE	
QA		Integrating Sphere and Stand Assy	
MFG			
APPROVED			
Dale Tree		SIZE B	DWG NO / REV
		SCALE	SHEET 2 OF 2

BYU Mechanical Engineering

Results – BYU BFR Air Flame

Transmittance and calculated soot volume fraction for a one second period

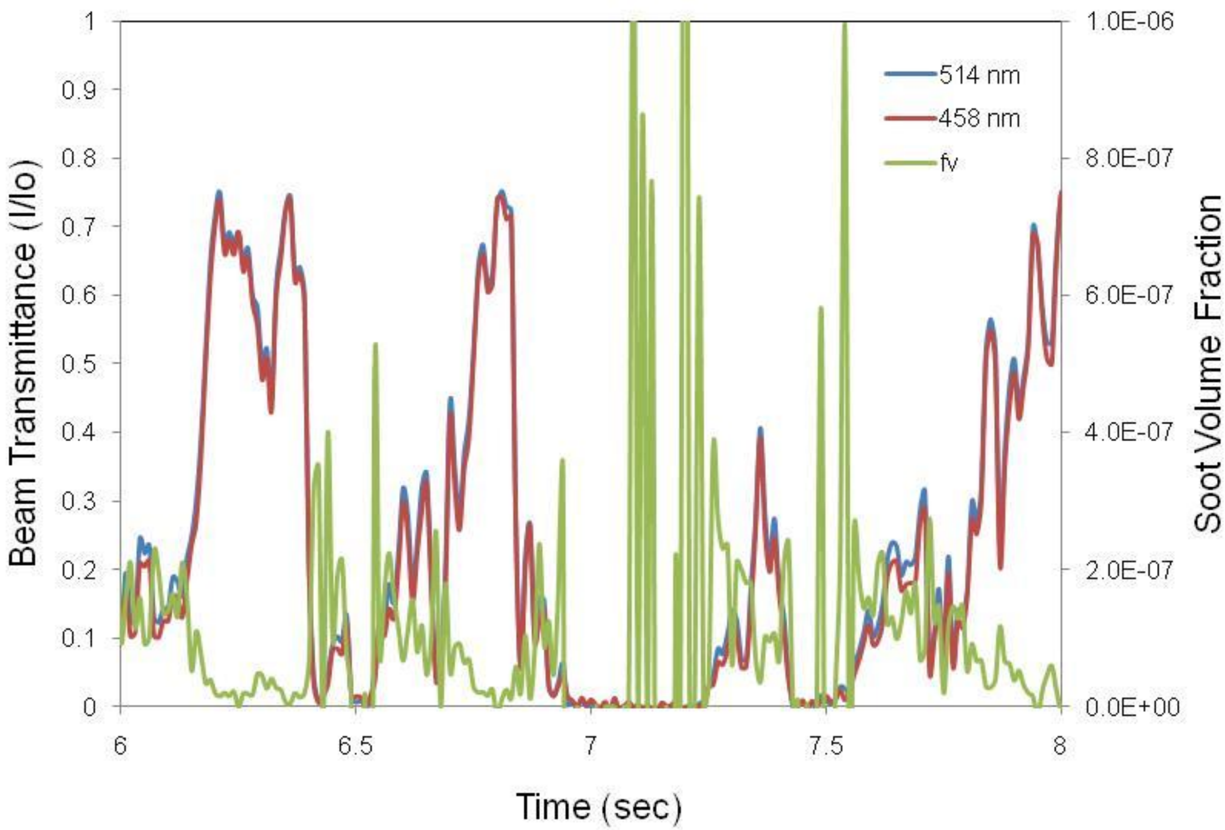


- Transmittance is highly variable with rapid fluctuations.
- Transmittance of the shorter wavelength is below the longer wavelength indicating soot.
- Soot volume fraction is rapidly fluctuating between 5.0E-08 and 2.5 E-07. This is a moderate level of soot.

BYU Mechanical Engineering

Results – L1500

Transmittance and calculated soot volume fraction, S.R. = 0.9

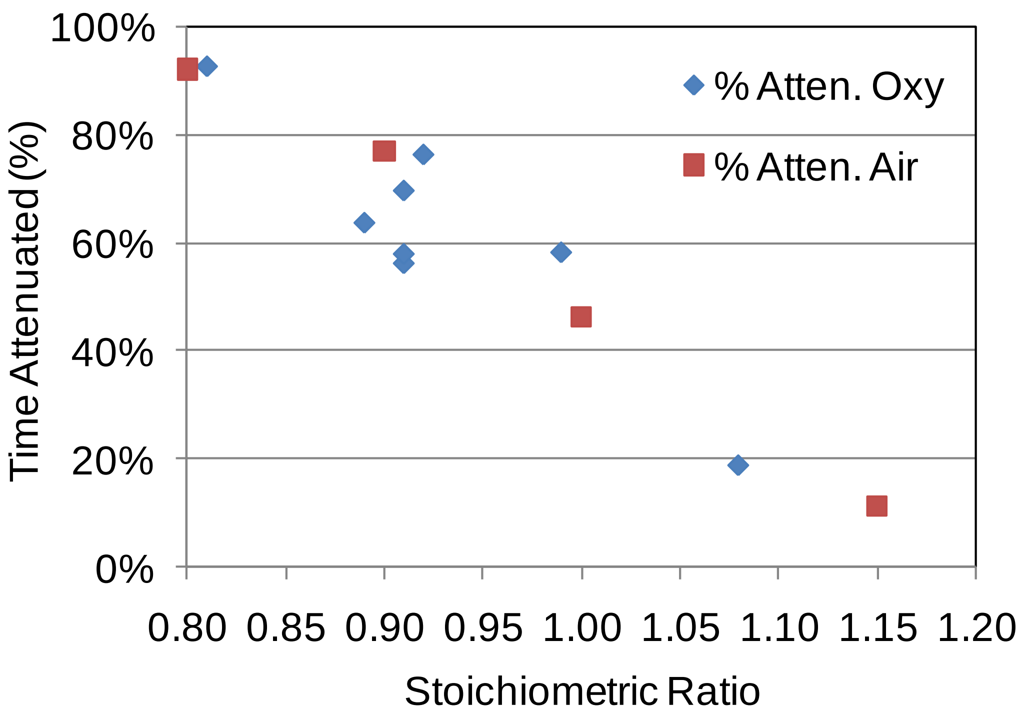


- Transmittance is not as variable as the smaller BYU reactor
- Both beams are attenuated a significant fraction of the time (avg. 77% of time)
- When transmittance is too low, uncertainty is large
- We have averaged the data when transmittance is above 0.02.

BYU Mechanical Engineering

Results – L-1500 Air and Oxy Flames

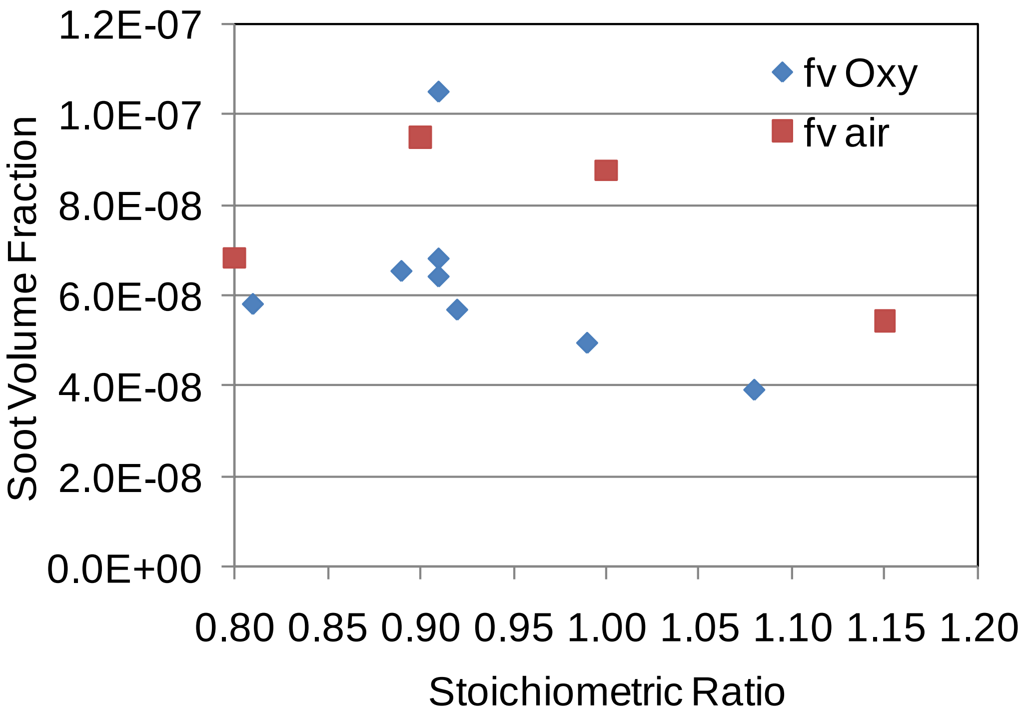
Fraction of time beams were attenuated – Air and Oxy fired – Utah Coal



- At low S.R. the beams were attenuated almost the entire time
- As overall mixture became leaner, beam attenuation decreases as expected
- Time of total beam attenuation is the same or lower for oxycombustion flame

Results – L-1500 Air and Oxy Flames

Soot volume fraction for line of sight – Air and Oxy-fired – Utah Coal



- Soot volume fractions generally decrease with increasing S.R.
- Soot volume fractions of oxycombustion flames are generally lower than air-fired flames.
- The beams may be attenuated too much at S.R. = 0.8 to obtain data

Summary and Conclusions

- Total line of sight soot concentration measurements have been made on a 3.5 Mbtu/hr air and oxy-fired coal flame.
- At low S.R. (0.8) the beam was fully attenuated 92% of the time for both air and oxy-fired flames making quantitative measurements difficult.
- At higher S.R. (1.0 and greater) the beam was fully attenuated half the time or less allowing for quantitative measurements.
- Soot volume fractions fluctuate rapidly as does the entire flame structures on the order of several Hz.

Summary and Conclusions

- Soot concentrations range from below the detection limit (1.0 E-08) to as high as 4E-07. These are moderate levels compared to other types of flames.
- Soot volume fractions were smaller in the oxy-fired flames in comparison to the same S.R. of air fired flames.
- Preliminary measurements of air and oxy-fired PRB coals show considerably less total attenuation for the same path length and location.

Thank You