

Emission Tomography in Turbulent Flames



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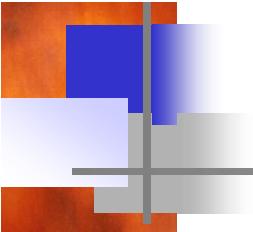
<http://www.enurga.com>



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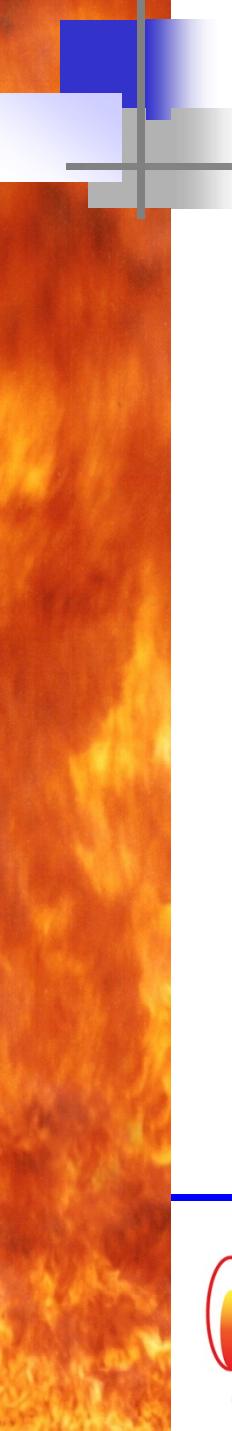
Innovations in Quality Control

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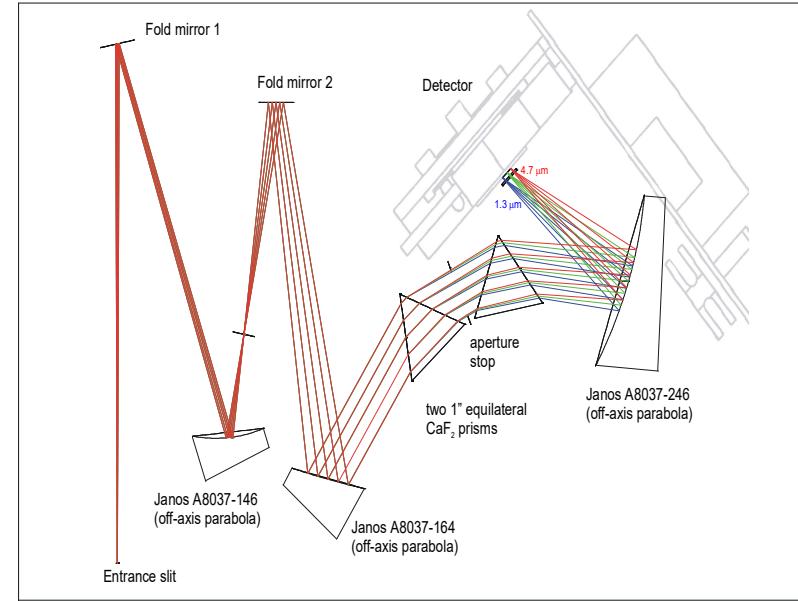
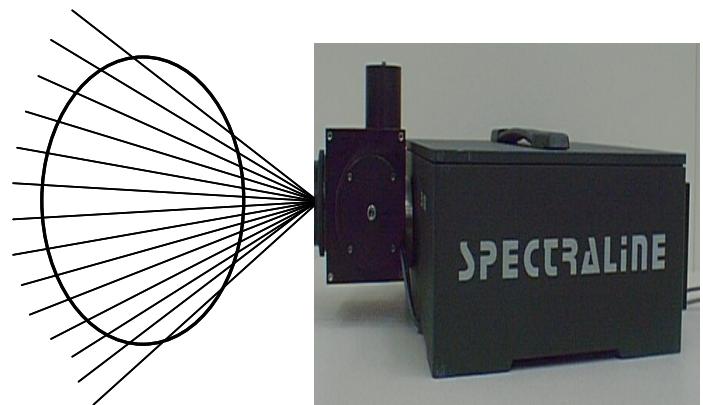
Outline

- Experimental Arrangement
- Theoretical Method
- Example Results



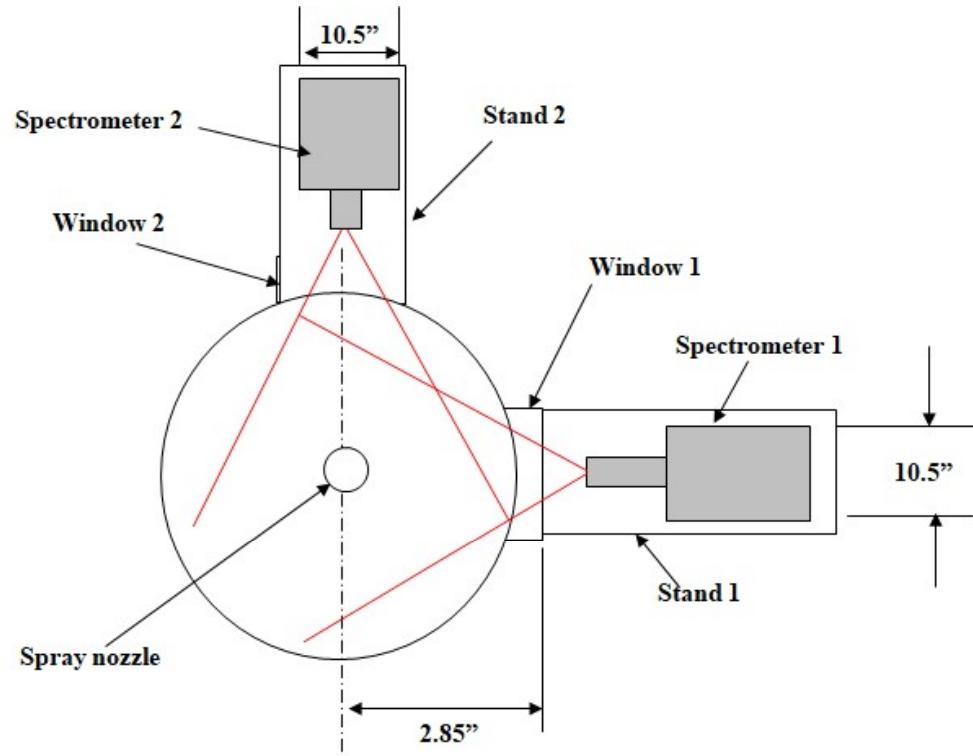
Experimental Arrangement

One Spectrometer (Homogeneous)



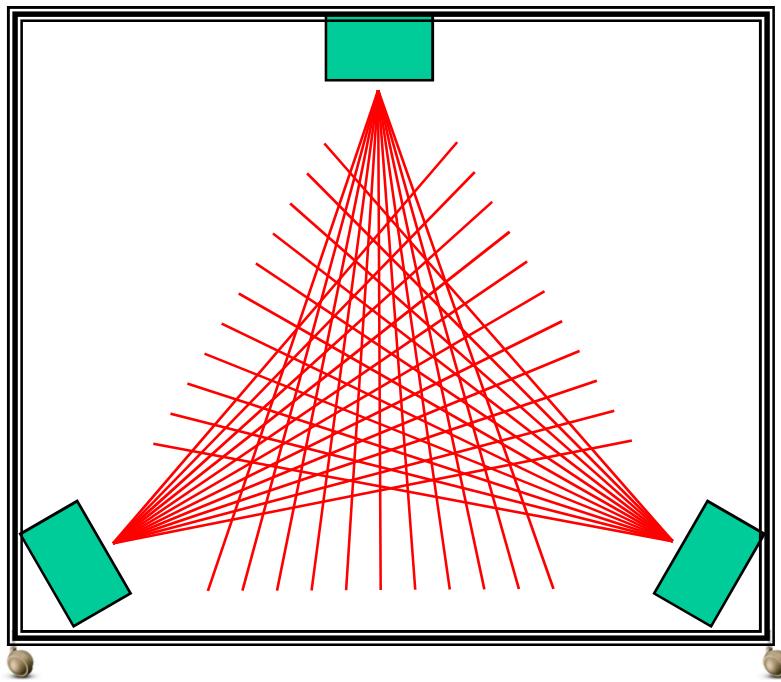
- *Either parallel path or fan beam arrangement*
- *128 view angles, 256 wavelengths (1.3 - 4.8 μm)*
- *Deconvoluted using tomography*

Two Spectrometers (Non-homogeneous)

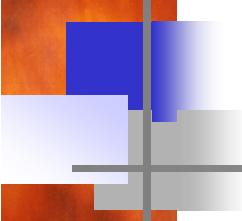


- Two ES200 imaging spectrometers, with SS100 scanners
- 128 view angles per spectrometer, 90 deg angular resolution
- Spectra at 1320 Hz, full planar data at approximately 11 Hz

Three Spectrometers (Non-homogeneous)

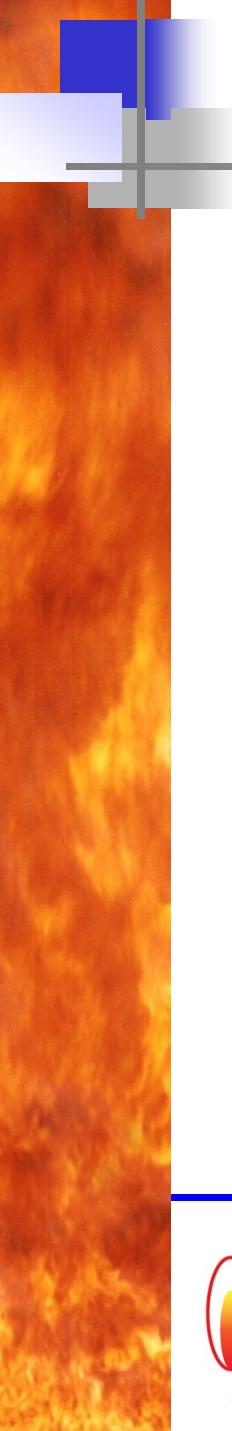


- *Three spectrometers*
- *128 view angles, 256 wavelengths (1.3 - 4.8 μm) for each*
- *Deconvoluted using tomography*
- *Higher angular resolution (30 degrees)*



Measurement Considerations

- High temperature objects (typically flames)
- Intensity is related to temperature and emissivity
- Highly non-linear in temperature
- Emissivity is typically unknown
- Multiple wavelength measurements used
- Self absorption for optically thick systems

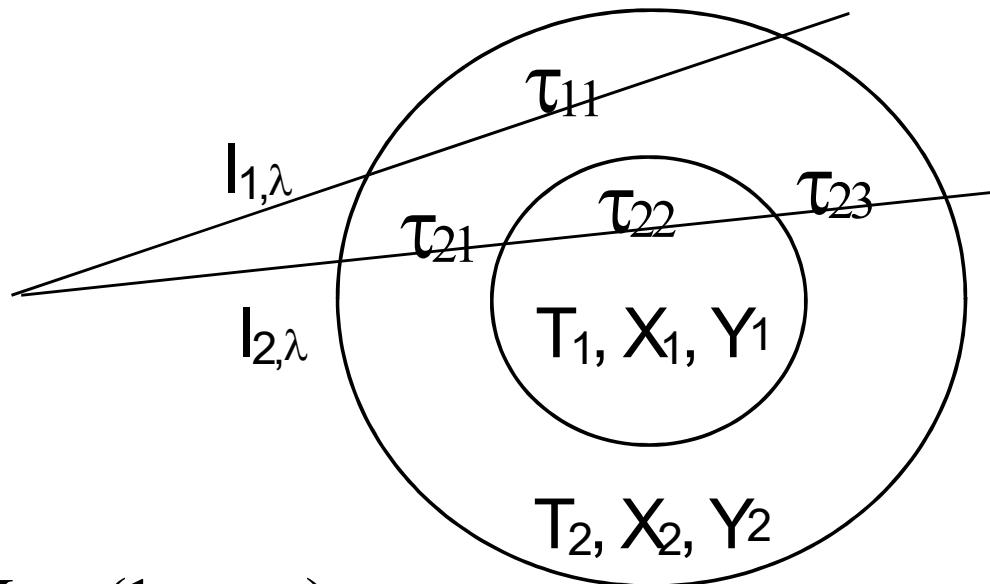


Theoretical Methods



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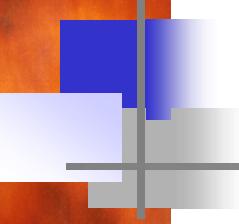
Relevant Equations



$$I_{1,\lambda} = I_{1,b\lambda}(1 - \tau_{11})$$

$$I_{2,\lambda} = I_{1,b\lambda}[(1 - \tau_{23}) \cdot \tau_{22} \cdot \tau_{21} + (1 - \tau_{21})] + I_{1,b\lambda}(1 - \tau_{21}) \cdot \tau_{21}$$

Non-linear equations, difficult to solve



Linearize Equations

$$I = I_b \cdot (1 - e^{-k\Delta})$$

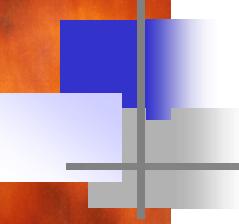
$$\log(I) = \log(I_b) + \log(1 - \tau)$$

$$\log(I_b) \approx A + BT$$

$$\log(1 - e^{-k\Delta}) = \log(1 - \tau) \approx C + DX + EY + FT$$

$$\log(I) = D \cdot X + E \cdot Y + (B + F) \cdot T + A + C$$

. J. Lim, Y. Sivathanu, J. Ji, and J. Gore, (2004), "Estimating Scalars from Spectral Radiation Measurements in a Homogeneous Hot Gas Layer," Combust. Flame, vol. 137, p. 222-229



Constants in Equations

From databases such as RADCAL, HITRAN

$$A = -\frac{\partial \log(I_b)}{\partial T} T_0 + \log(I_b(T_0))$$

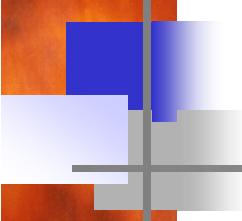
$$B = \frac{\partial \log(I_b(T_0))}{\partial T}$$

$$C = -\frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial X} X_0 - \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial Y} Y_0 - \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial T} T_0 + \log(\alpha(X_0, Y_0, T_0))$$

$$D = \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial X}$$

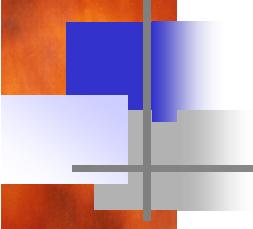
$$E = \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial Y}$$

$$F = \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial T}$$



Flow Chart for Solution

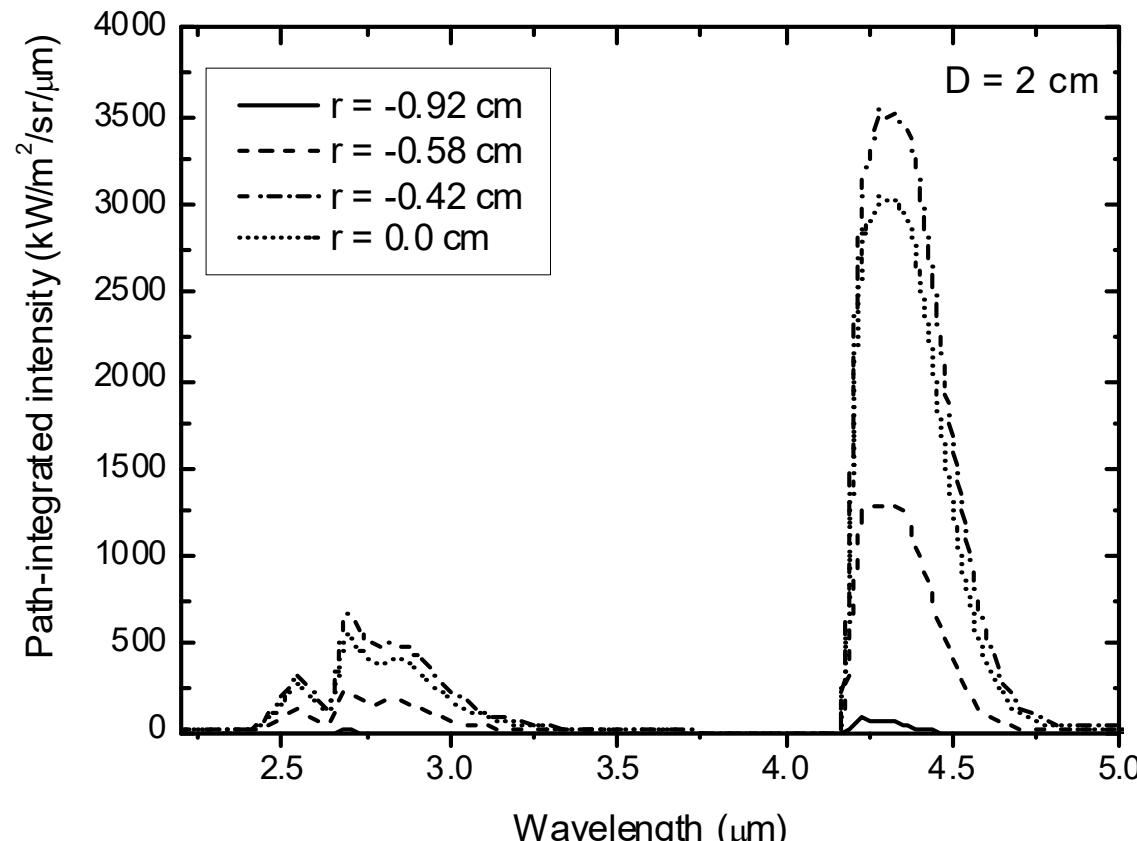
- Linearize equations
 - Guess transmittance
 - Use MLE to obtain local intensities
 - Estimate local properties based on intensities
 - Calculate transmittance from local properties
 - Utilize transmittance in updated guess
 - Continue until convergence achieved
-



Validation method

- 
- Use a well characterized flame
 - Calculate intensities emitted using equation of radiative transfer
 - Use calculated intensities as input to algorithm
 - Compare algorithm output with input flame properties

Calculated Intensities (input to algorithm)



H_2O (2.7 μm) and CO_2 (4.3 μm) clearly visible

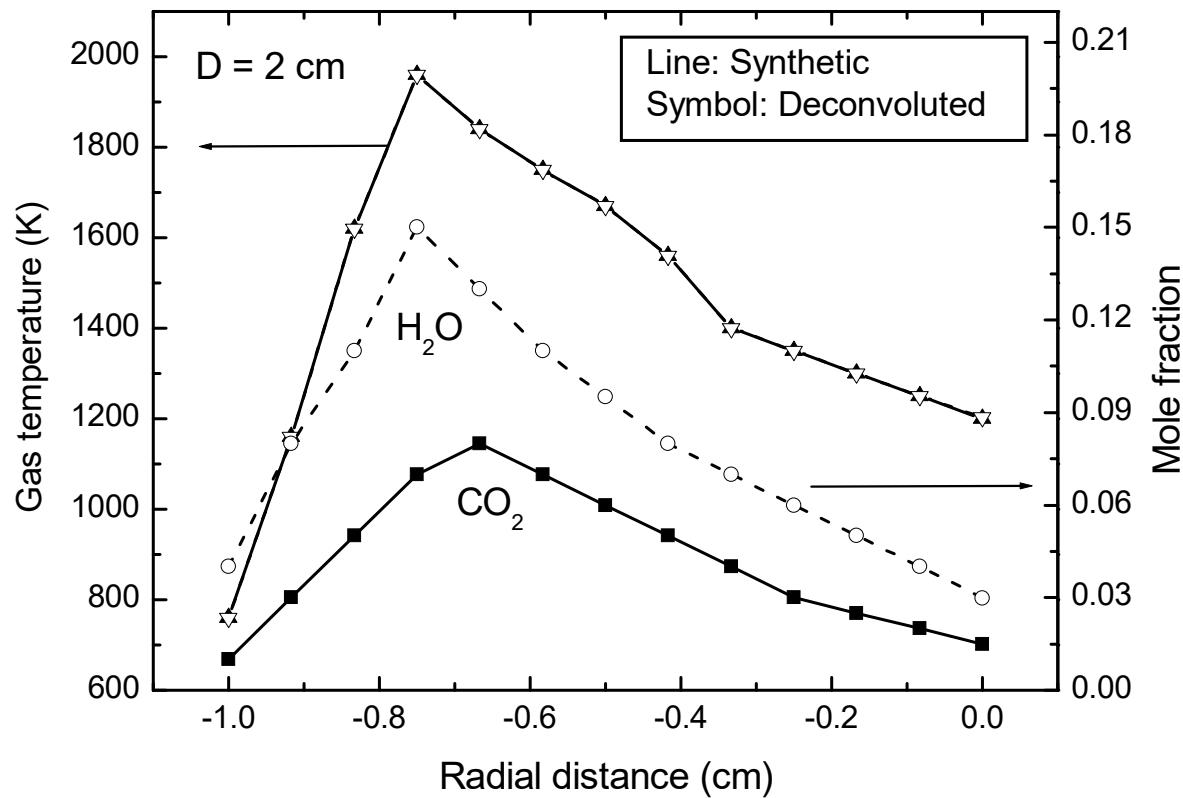


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Converged Properties

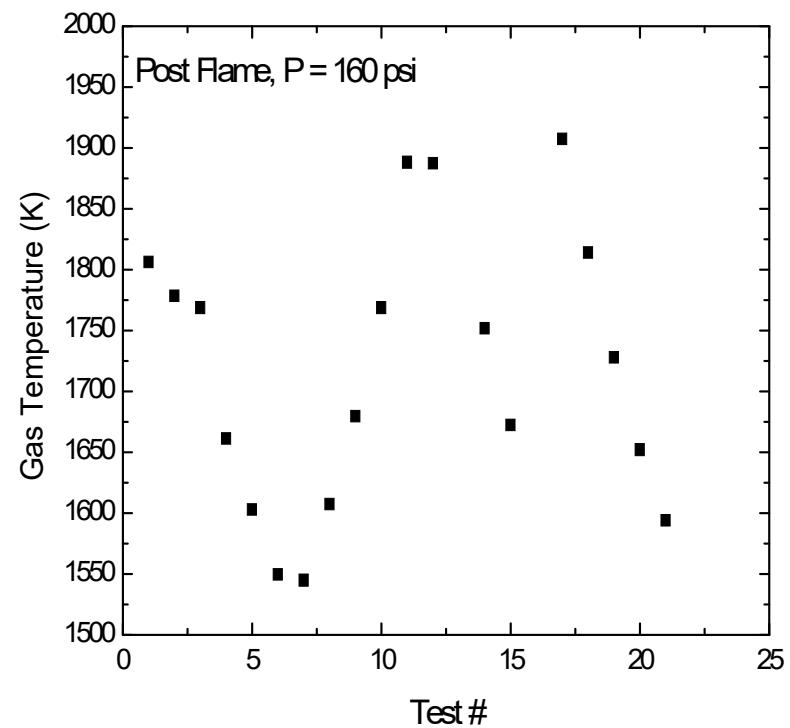
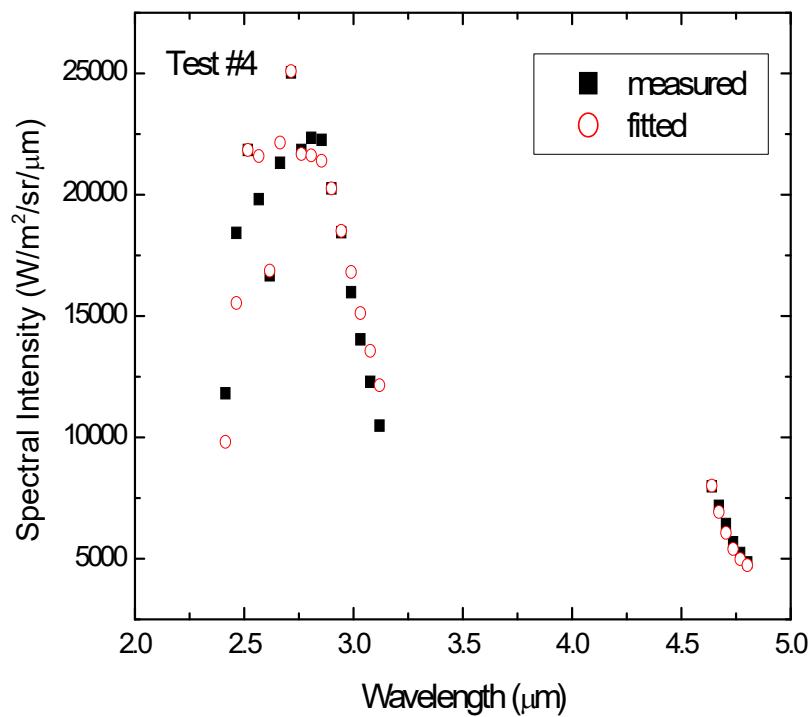


Excellent convergence showing deconvolution is accurate



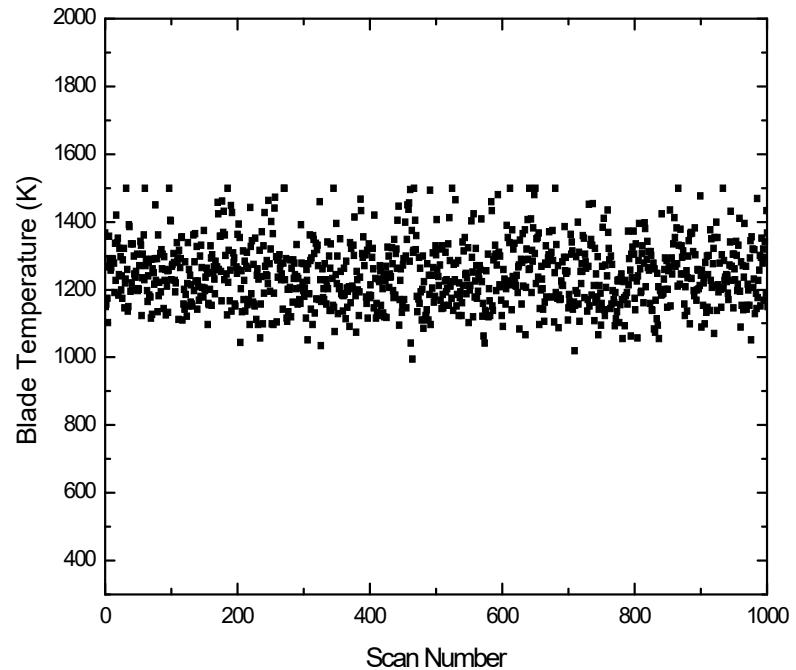
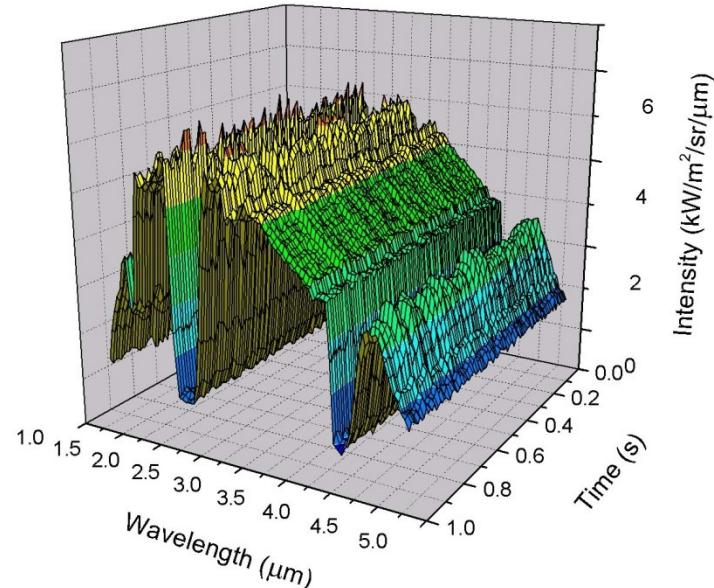
Example results

Implementation (Turbine Inlet – no scanner)

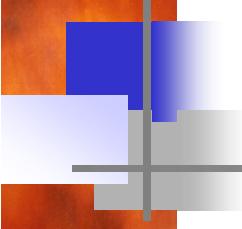


Gas temperature successfully estimated by method using homogeneous layer assumption

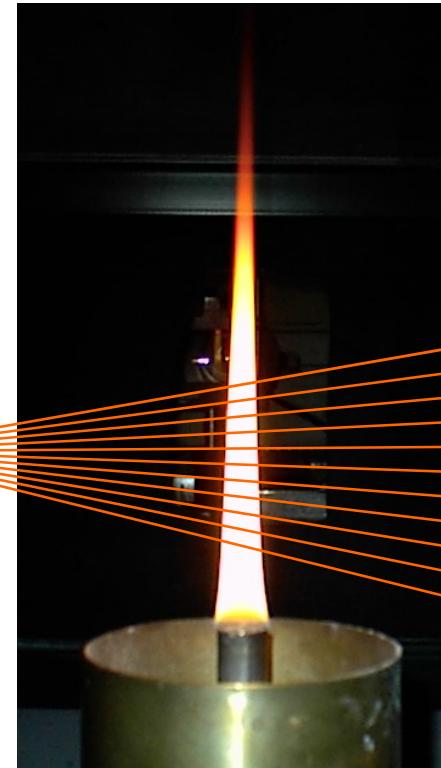
Implementation (Turbine Blade)



30 bar power turbine, emission from blade (3.7-4.0 μm)
Blade temperature & emissivity at high frequency (TBC monitoring)

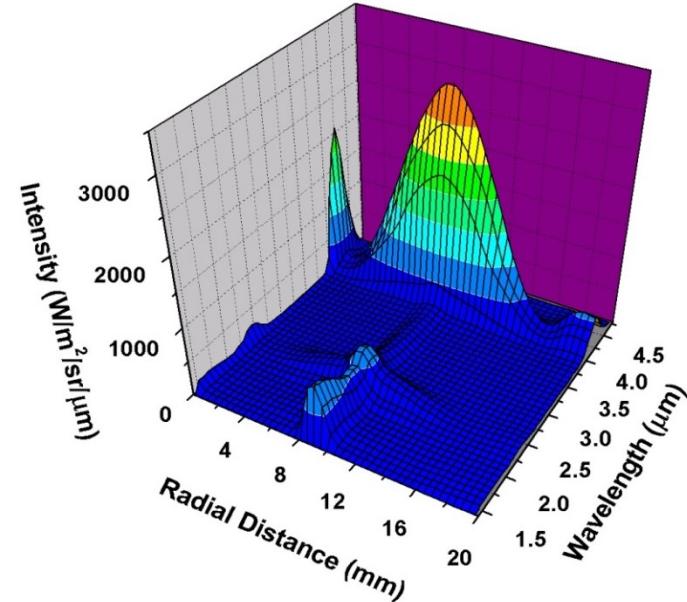


Implementation (Axisymmetric system)



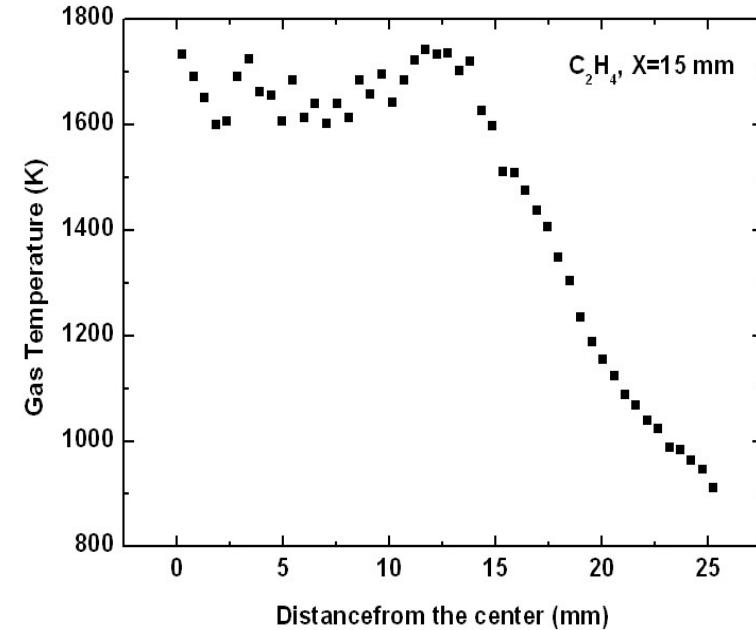
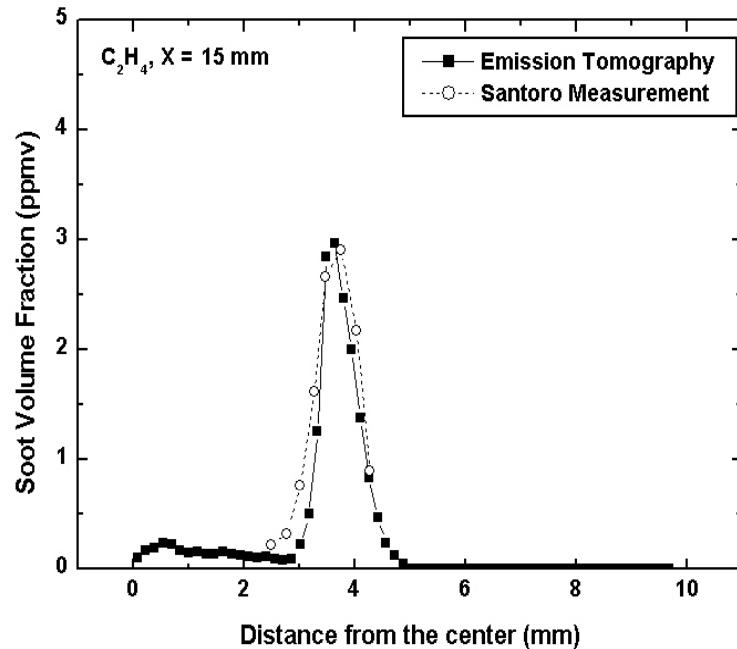
Emission measured at 128 view angles
256 wavelengths obtained with ES200 imaging spectrometer

Laminar Flame Details



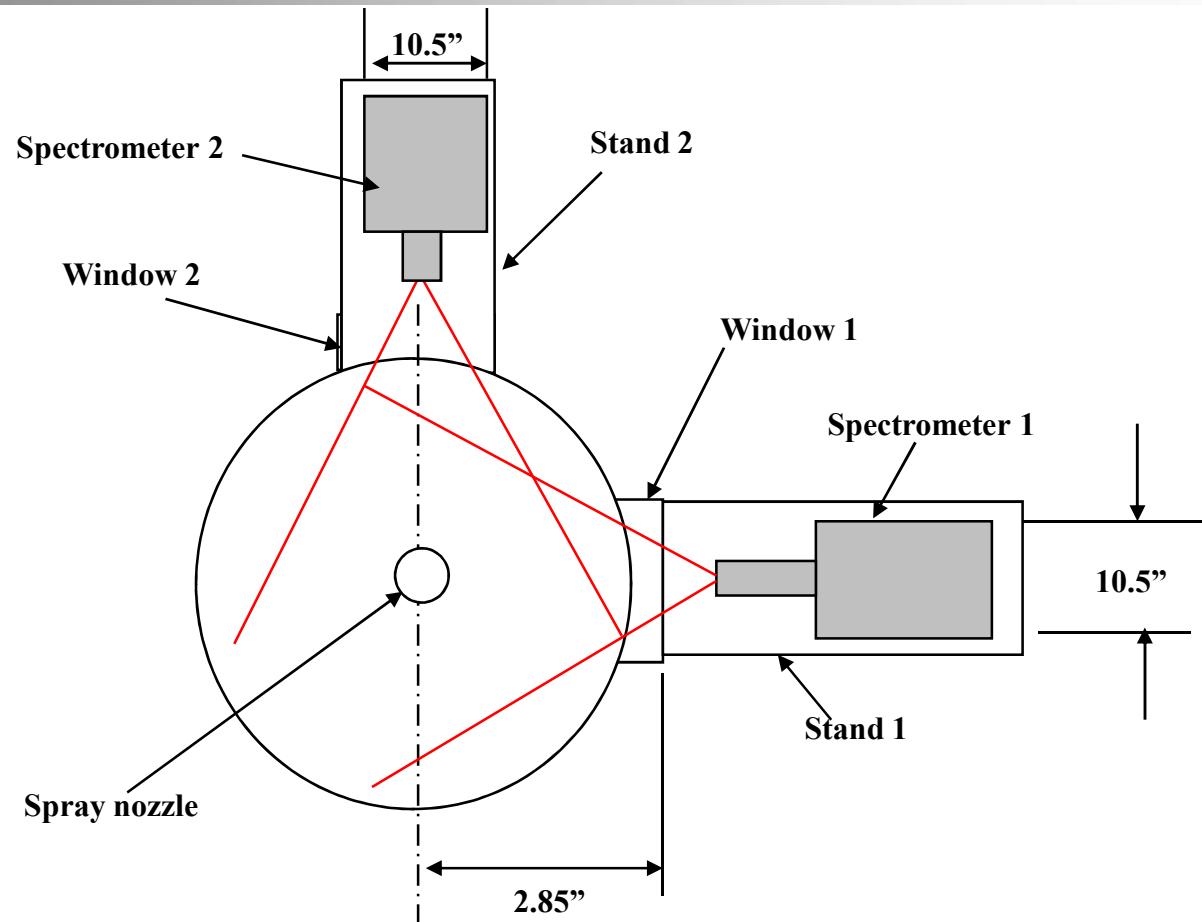
Measured spectral radiation intensities above burner exit
Incipient Sooting Ethylene Flame
Fuel Flow Rate: 2.30 cm³/sec
Coflow Air: 713.3 cm³/sec

Laminar Flame Results



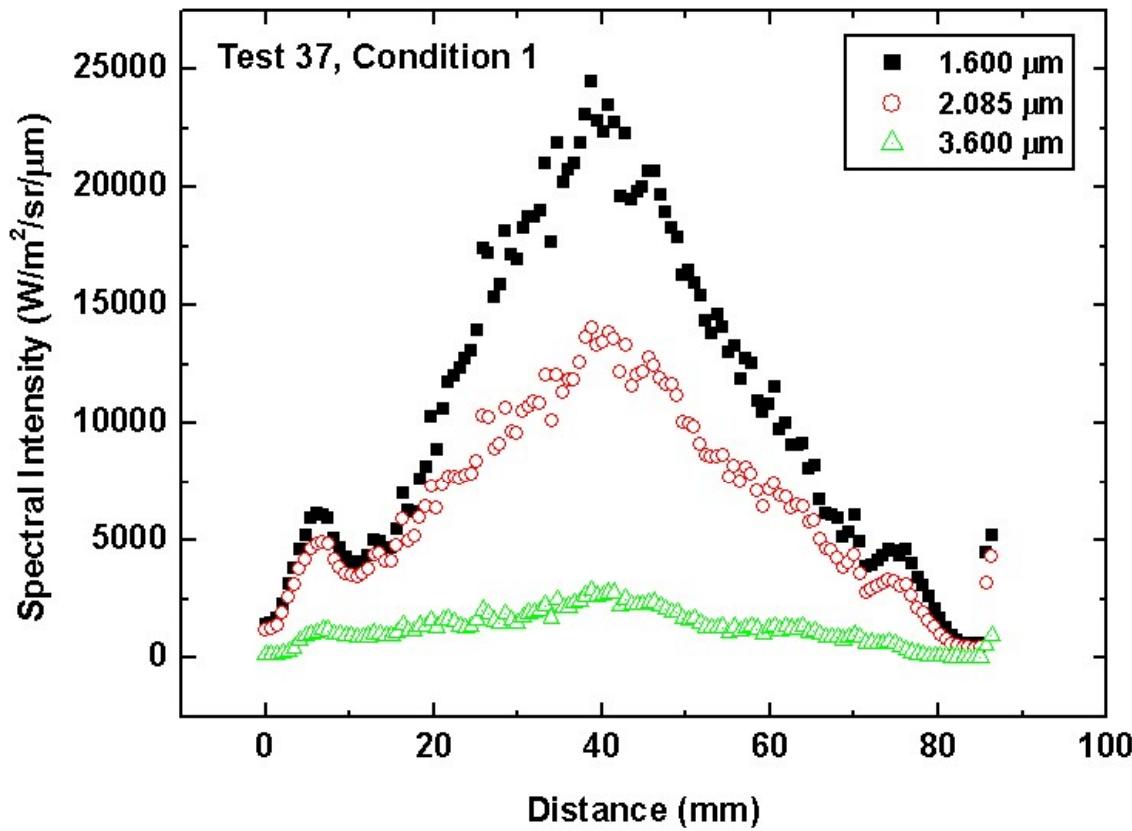
Estimated particulate concentrations, temperatures, and gas concentrations reasonably well (agrees with published values in the literature)

Implementation (Combustion chamber)



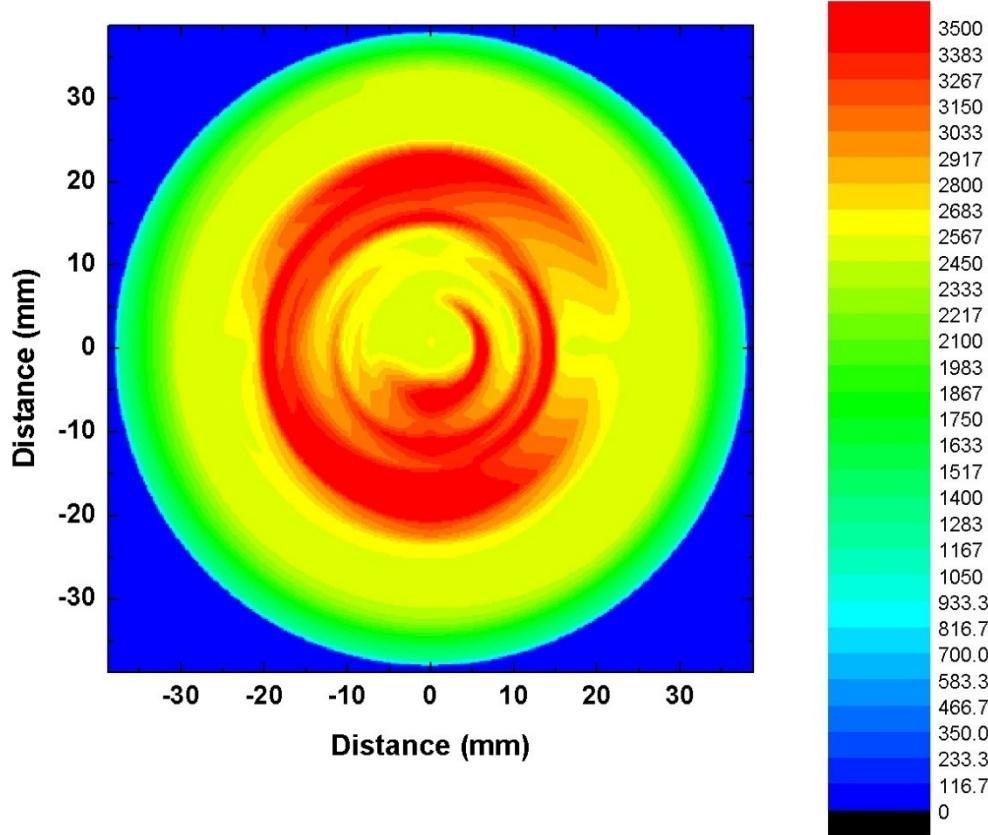
Hydrogen/oxygen rocket engine (NASA Marshall-1500 PSI)

Combustion Chamber (2 windows)



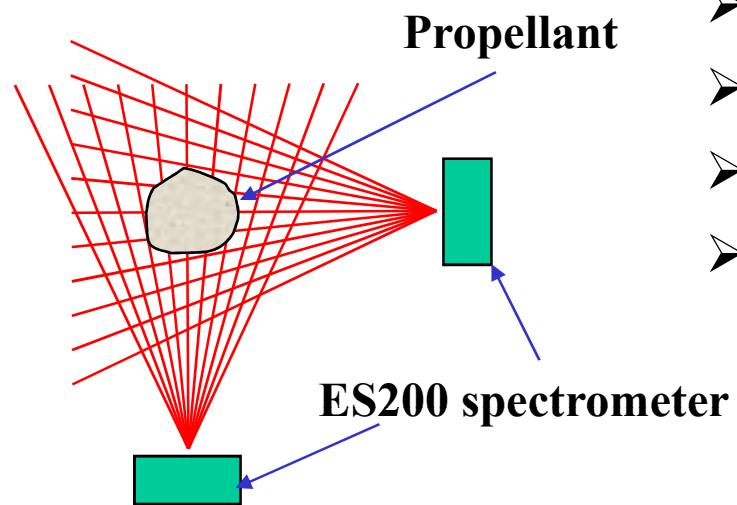
Intensities primarily at water vapor wavelengths

Combustion Chamber Results



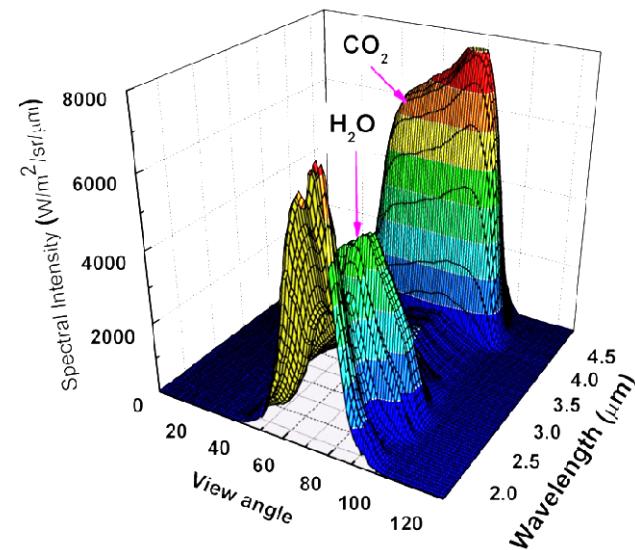
Temperature distribution inside chamber

Implementation (Solid Propellant Plume)

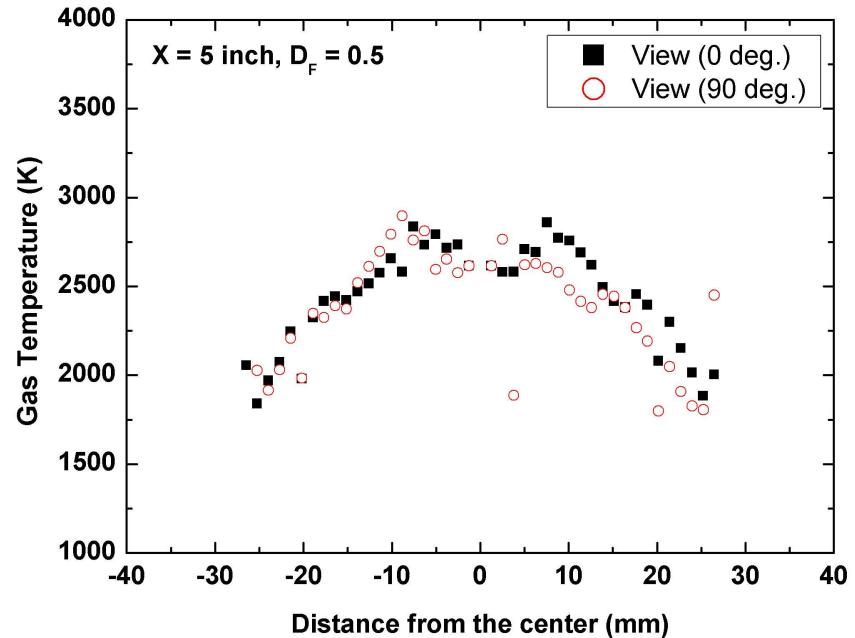
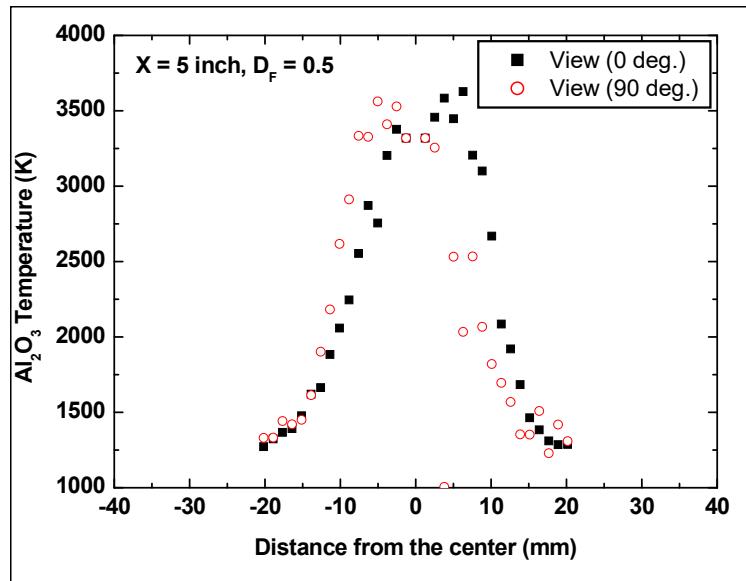


Test in solid propellants up to
18 inches in diameter

- Two orthogonal spectrometers
- 128 view angles per spectrometer
- 1.3 to 4.8 microns
- 1320 Hz for spectra
- Full planar measurement at 10.3 Hz

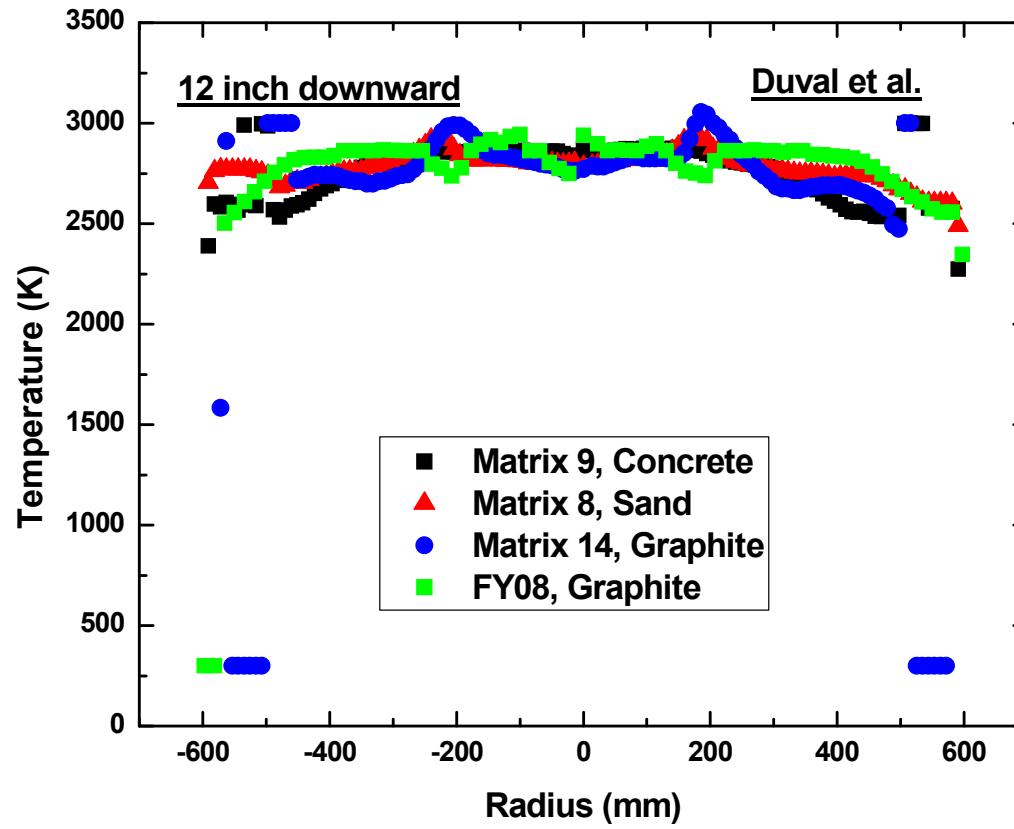


Solid Propellant Plume Properties

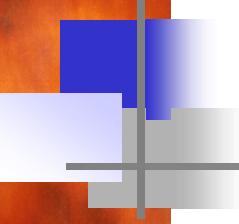


Y. Sivathanu, J. Lim, L. E. Reinhart, and R. C. Bowman, (2007), "Structure of Plumes from Burning Aluminized Propellant Estimated using Fan Beam Emission Tomography," AIAA Journal, vol. 45, No. 9, pp. 2259-2266.

Size scaling- Solid Propellant Plume



Works with very large flames (up to 18 inches diameter)



Conclusions

- Intensities measured at several wavelengths and multiple view angle using ES200 spectrometer
- Deconvoluted in axisymmetric and non-axisymmetric flames that have particulates
- Temperatures typically estimated within 100 K
- Gas concentrations and particulate volume fractions estimated within 20%