A Modular Sensor Suite for Propulsion Testing

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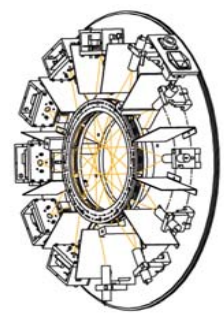


Outline

- Background and motivation
- Description of hardware and software
- Results from demonstration experiments

Background

Several planar and non-intrusive methods available to study turbulent reacting and non-reacting flows

- Fan Beam Emission Tomography (Sivathanu et al., 2007)
- Planar Laser Induced Fluorescence (Zhou et al., 2015)
- Tunable Diode Laser Absorption Spectroscopy (Xu et al., 2016)
- Pattern Imaging Velocimetry (Sivathanu et al., 2018)
- Two color thermometry (Brisley et al., 2005)
- Statistical Extinction Tomography (Lim et al., 2003)

The disadvantages with current techniques are that each technique requires its own set up and provides information on only a few properties

Motivation and Objective

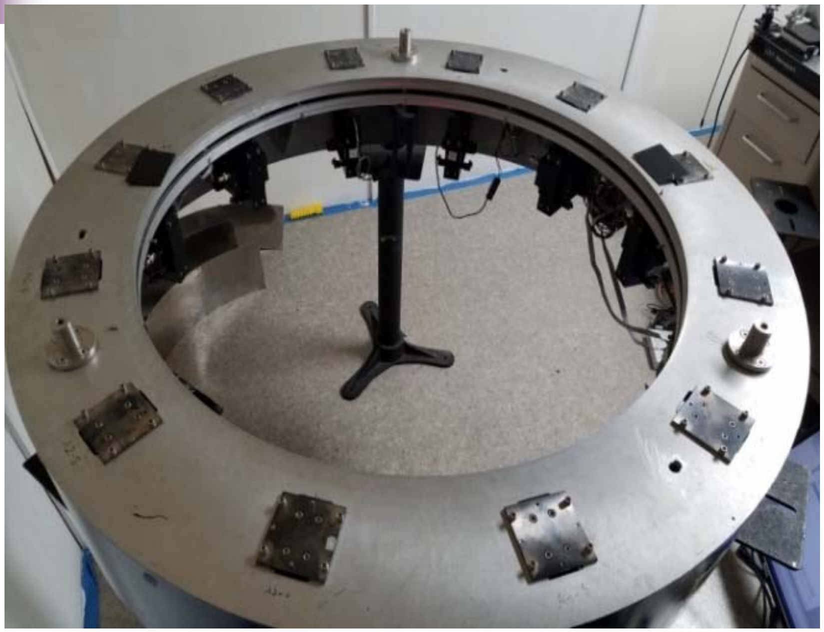
Develop a plug and play non-intrusive sensor suite that can be used for measuring a wide variety of properties in turbulent reacting and non-reacting flow.

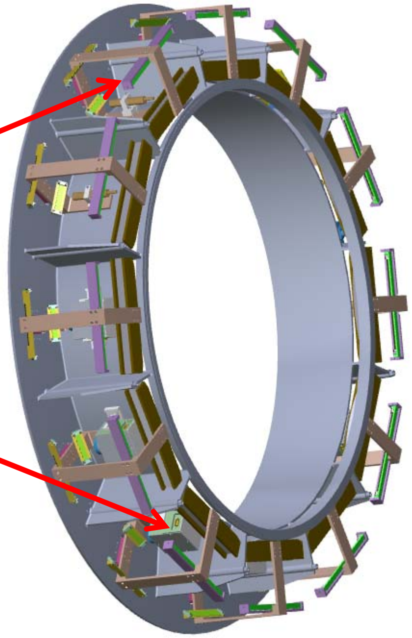
The two key requirements for the system are: (1) a modular tomographic sensor system to measure path integrated radiation emission, extinction, or scattering in turbulent flows, and (2) an configurable statistical deconvolution method to provide local information from path integrated measurements.

Establish validity of the sensor suite by using demonstration experiments in flames and sprays and comparing with published data if possible. For this study, chemiluminescence, soot volume fraction, and temperatures were obtained in flames.

Description of Hardware and Software

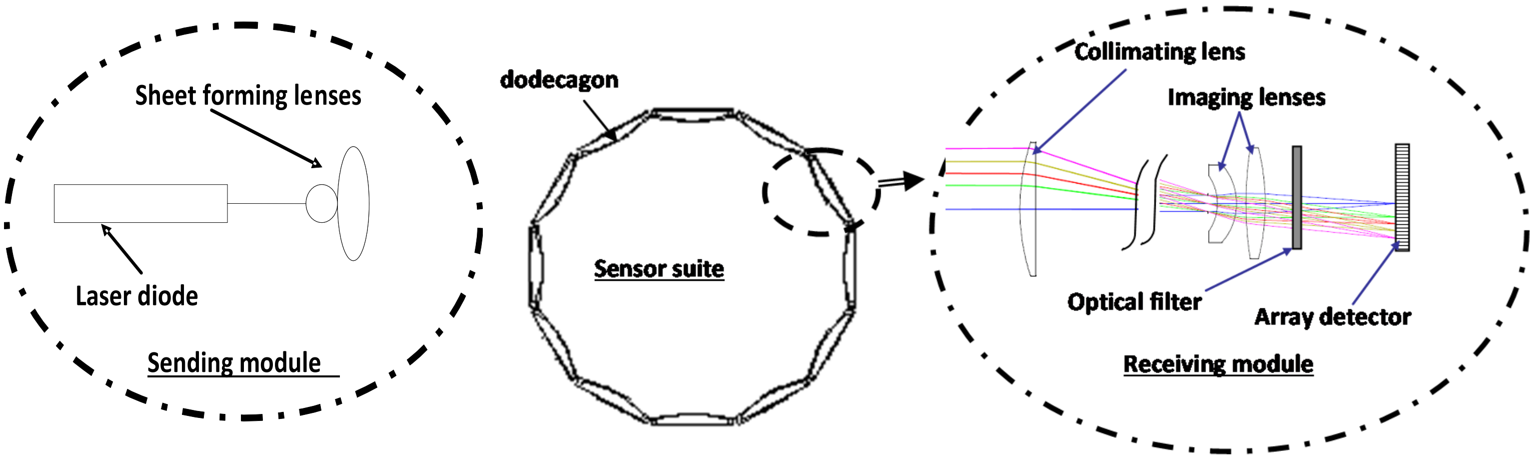
Sensor Suite Platform





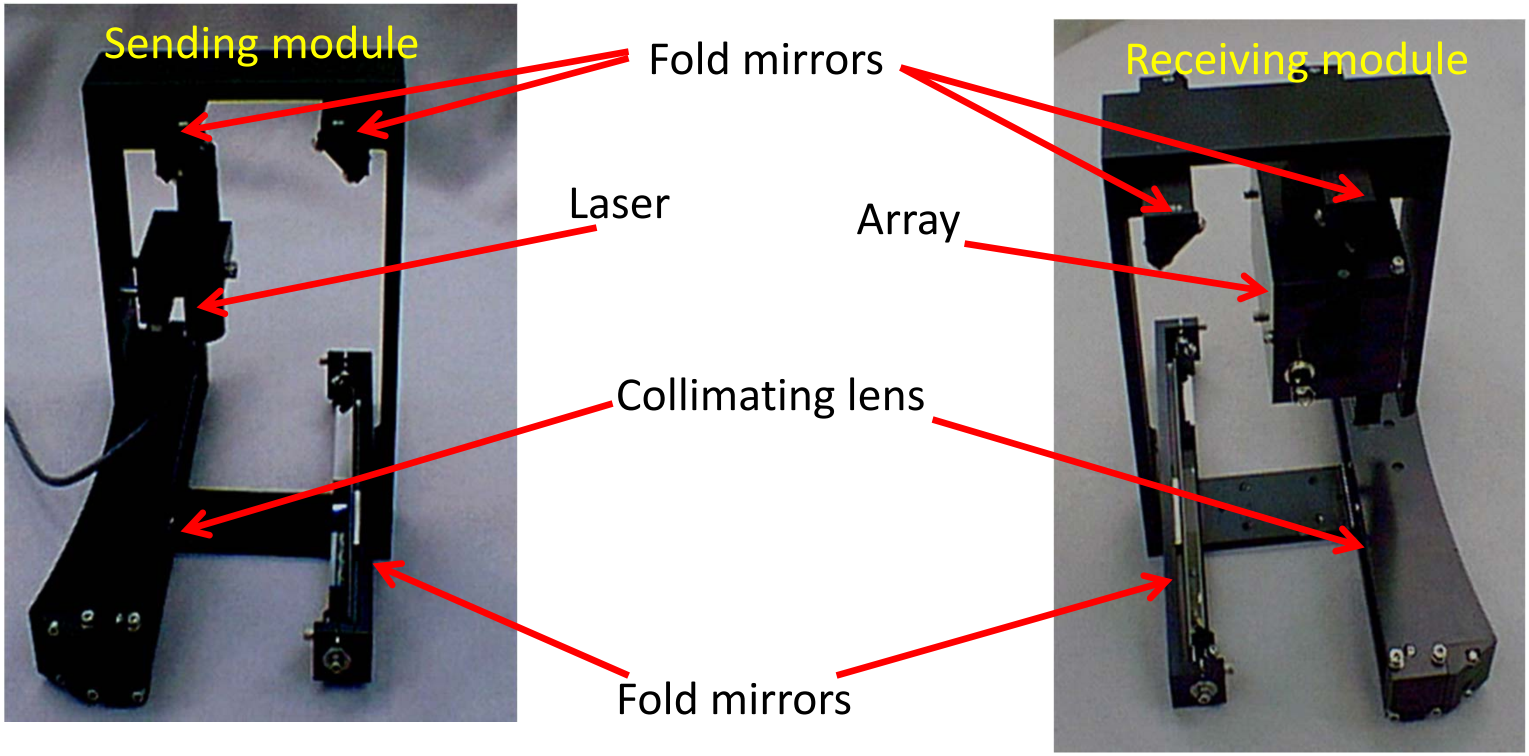
- En'Urga Inc. optical patternator (PD-600) used as platform
- Currently used for planar drop sizes and number density
- 175 mm diameter interrogation area
- 1 meter inner diameter (can be increased) enabling sufficient clearance from flames and sprays.

Basic elements of the sensor suite



- Twelve collimating lens
- Six sending modules and six receiving modules for extinction
- Twelve receiving modules for emission
- Linear or 2-D high speed arrays (visible, IR, or X-Ray)
- Sending modules can be tunable or fixed wavelength lasers, X-Ray sources, or infrared lamps

Hardware developed

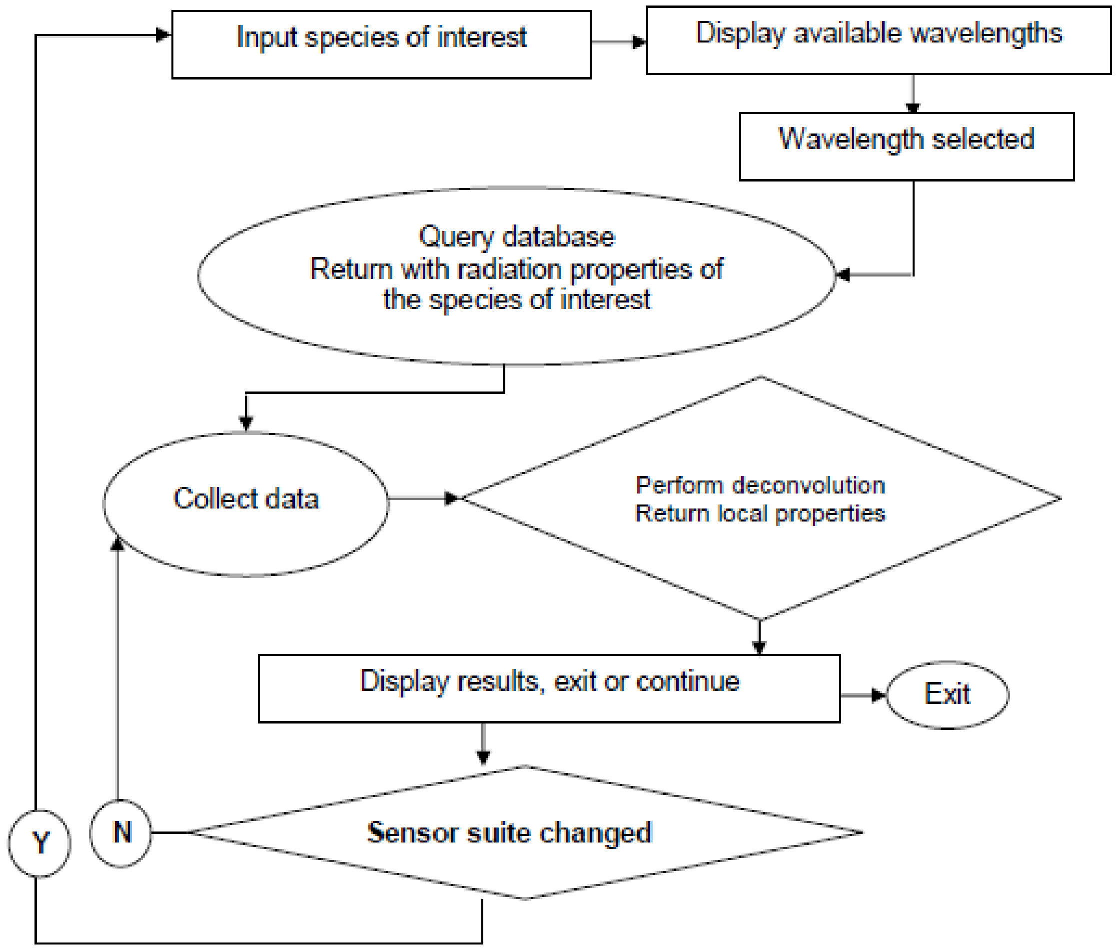


- Linear visible arrays and fixed wavelength lasers
- Soot volume fraction, temperatures, & OH chemiluminescence
- Folding mirrors used to reduce path length

Deconvolution method

- In general, the radiative transfer equation is linearized
- Grids laid out depending on the number of lines of path integrated intensities in the sensor suite
- The grids are sized to provide close to equal radial and angular resolution (Sivathanu and Lim, 2005)
- The grid settings can be changed to increase radial resolution while sacrificing angular resolution
- Set of equations then cast as a Linear Inverse Problem with a Positivity constraint (LINPOS)
- Typically an over specified since the number of equations > number of unknowns
- Solved using the Maximum Estimation Method

Configurable algorithm



Current modules

Soot volume fraction $\Rightarrow f_v = \dfrac{\ln(-K_i^j).\lambda}{H_\lambda \Delta_i^j}$

Intensity $\Rightarrow I_\lambda^i = \sum_{k=1}^{N} I_{b\lambda}^k.[1-\exp(\alpha_{k\lambda}.\Delta_k)]$

Temperature $\Rightarrow T = \dfrac{hc}{k}.(\dfrac{1}{\lambda_1} - \dfrac{1}{\lambda_2})/\ln[(\dfrac{I_{\lambda 1}}{I_{\lambda 1}})(\dfrac{\varepsilon_{\lambda 1}}{\varepsilon_{\lambda 2}})(\dfrac{\lambda_2}{\lambda_1})^5]$

Concentrations (CO_2, H_2O, and OH) $\Rightarrow I_\lambda = I_{b\lambda}.[1-\exp(\tau_\lambda.(T, X_i)]$

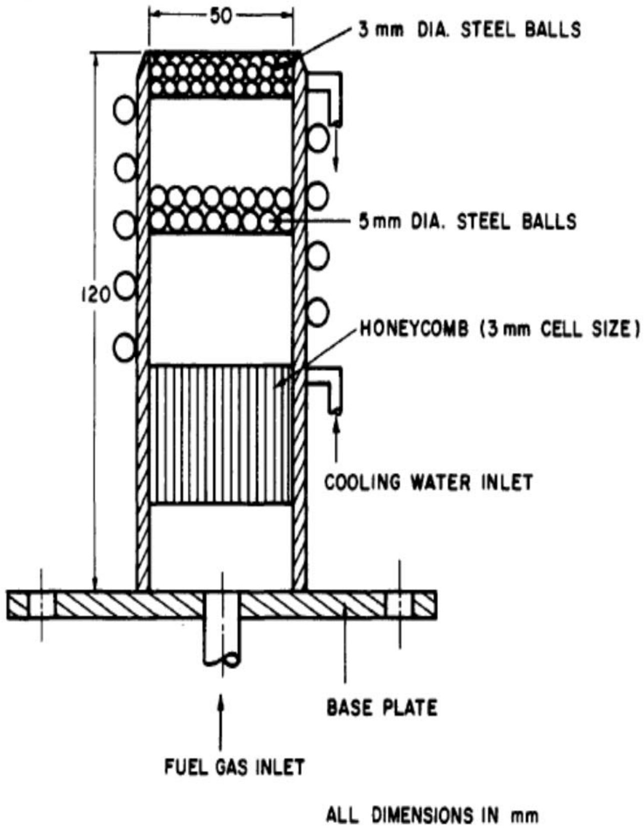
Drop surface area $\Rightarrow \dfrac{I(s+\Delta)}{I(s)} = \exp(-\Delta \int_0^\infty N(D) \dfrac{\pi D^2}{2} dD)$

Drop Sauter Mean Diameter $\Rightarrow S = \sigma_\lambda \int_\Omega I_S \bullet \Phi(\theta, D)$

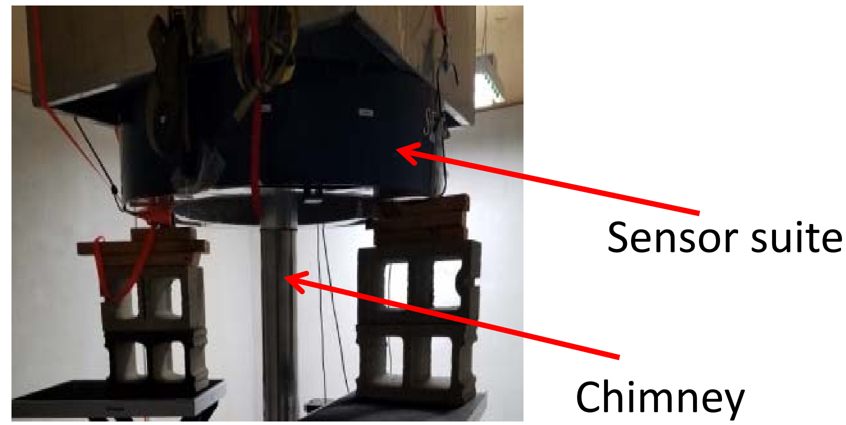
Different sensor modules and algorithm modules chosen for different properties within a spray or a flame

Results from the Demonstration Experiments

Experimental configuration (1): Overfire region



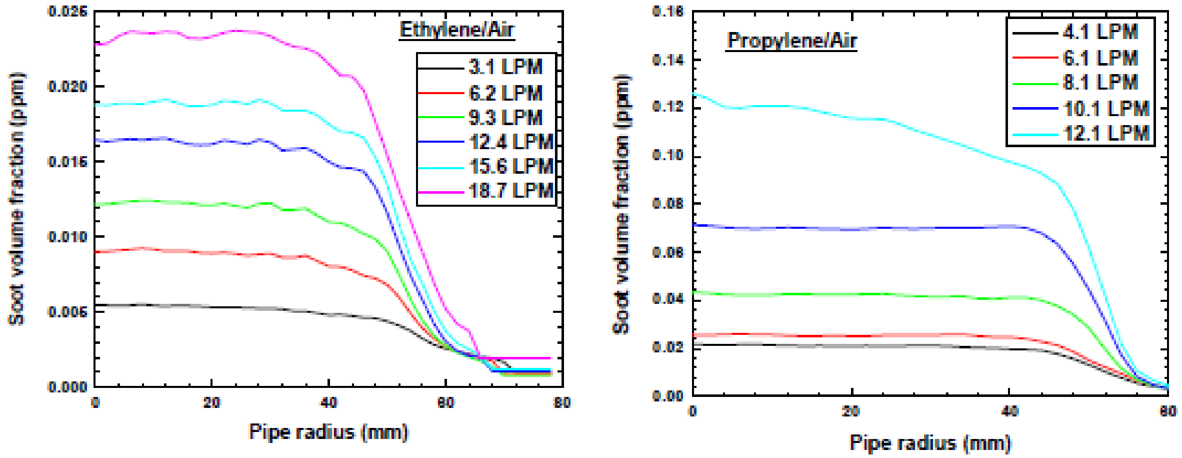
50 mm dia. burner
Extinction at 632 nm



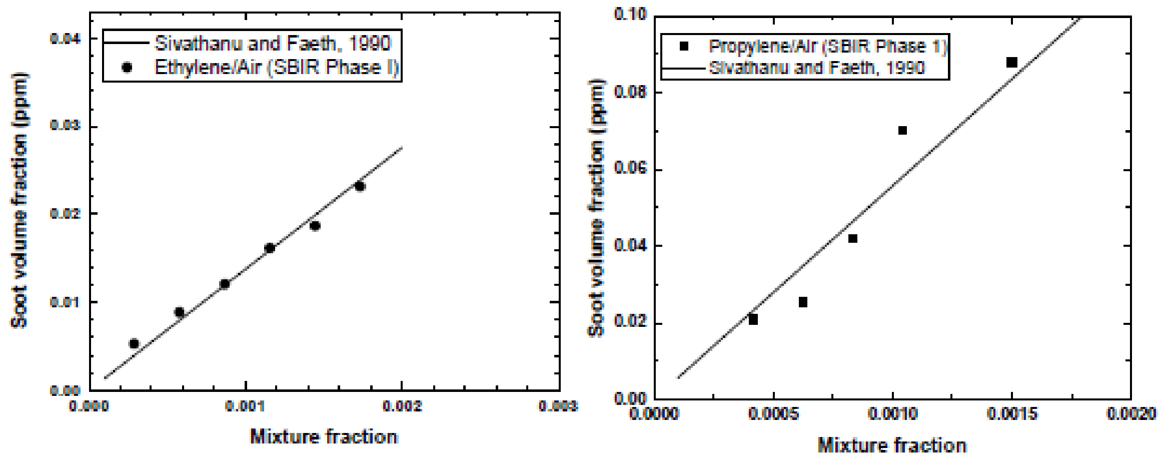
Sensor suite ~ 2 meters above the flame

Turbulent propylene/air and ethylene/air diffusion flames

Results from over-fire experiments



Radial profiles of soot volume fraction estimated from the sensor suite.



Soot volume fraction state relationship in sooting diffusion flames.

Good agreement with literature values (Sivathanu and Faeth, 1990)

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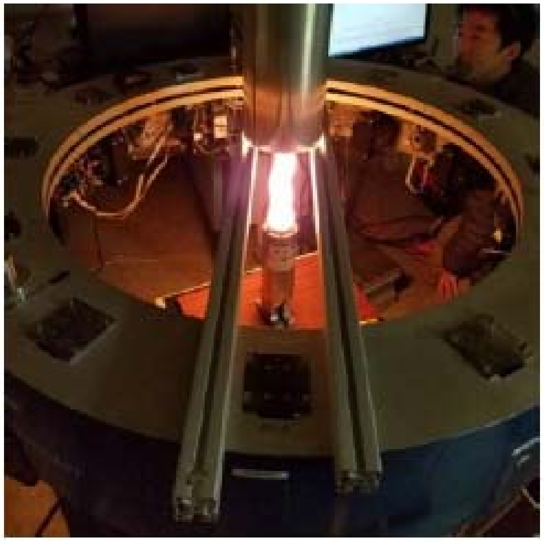
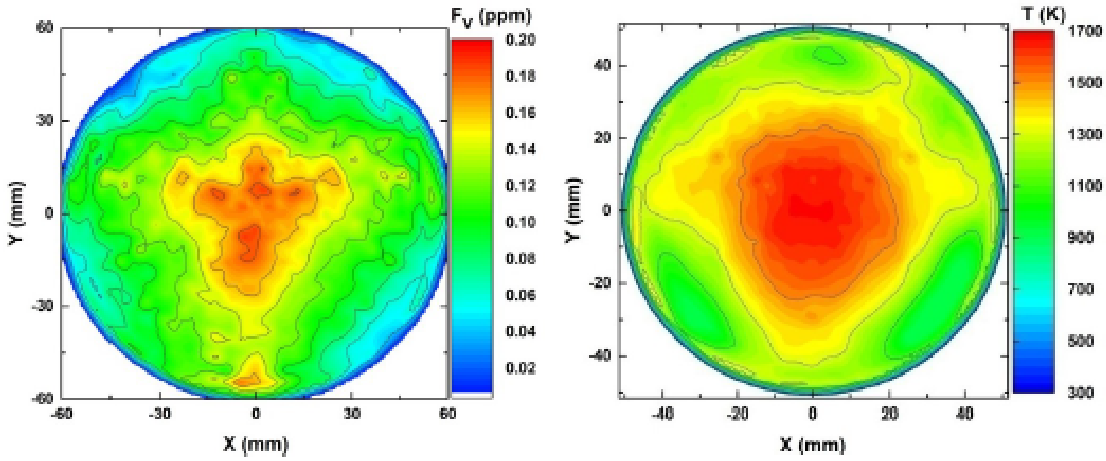
Innovations in Quality Control

Experimental configuration 2: under-fire region

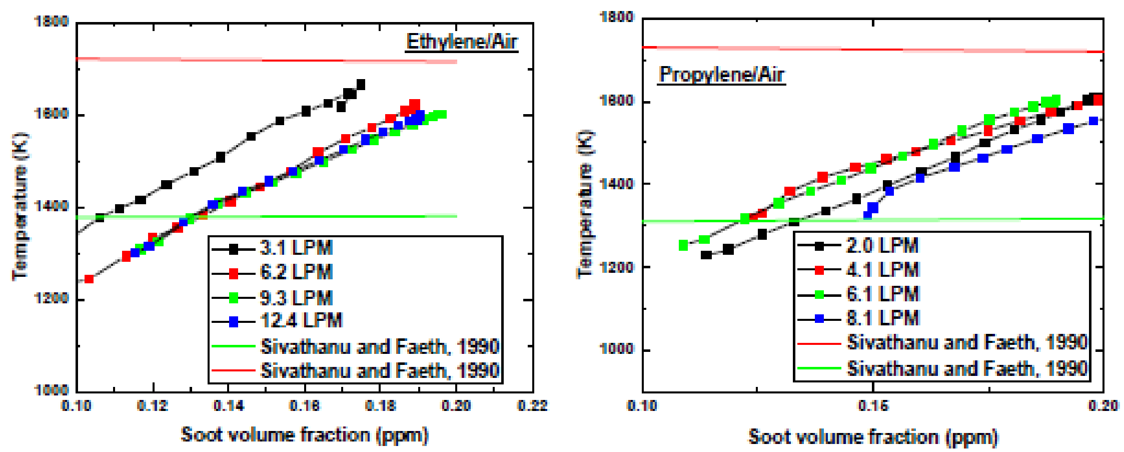


- Emission at two wavelength data (800 nm and 900 nm) from ethylene and propylene
- Deconvolute data for instantaneous planar temperature and soot volume fractions
- Validate soot-temperature correlations
- 100 mm above the burner exit

Results from under-fire experiments



Planar soot volume fractions and temperatures in ethylene/air diffusion flame.

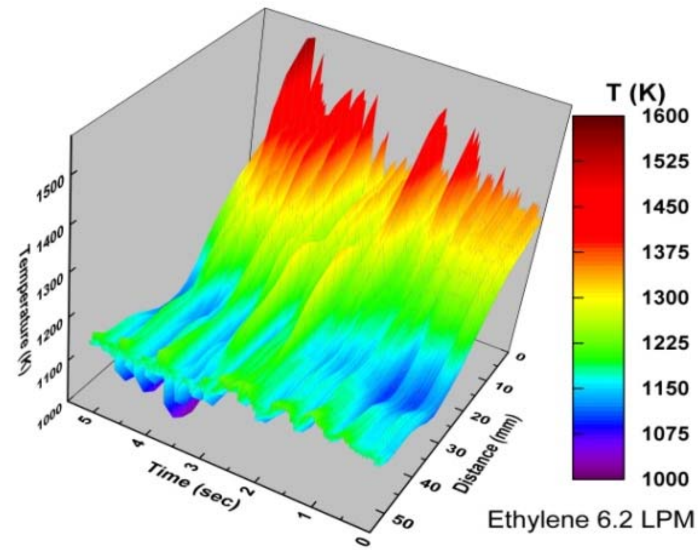


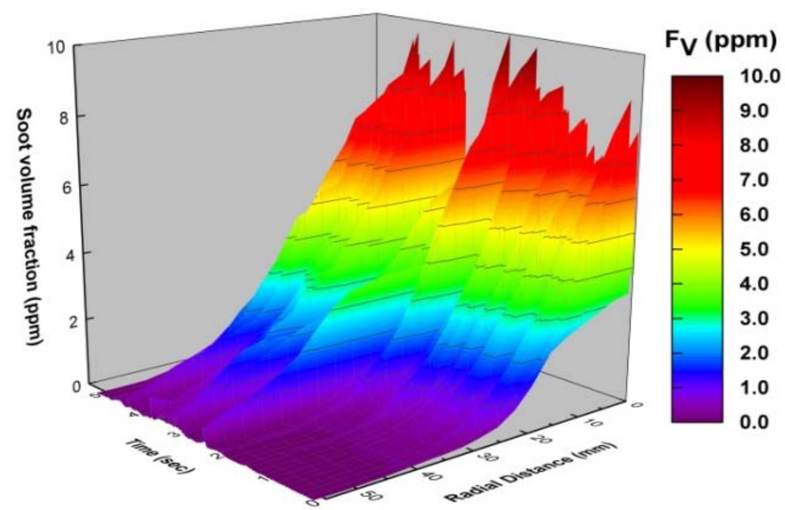
Soot volume fraction/temperature correlations in hydrocarbon flames.

Soot volume fraction and temperature are linearly correlated in the underfire region.

Estimated values agree with past measurements

Transient underfire results



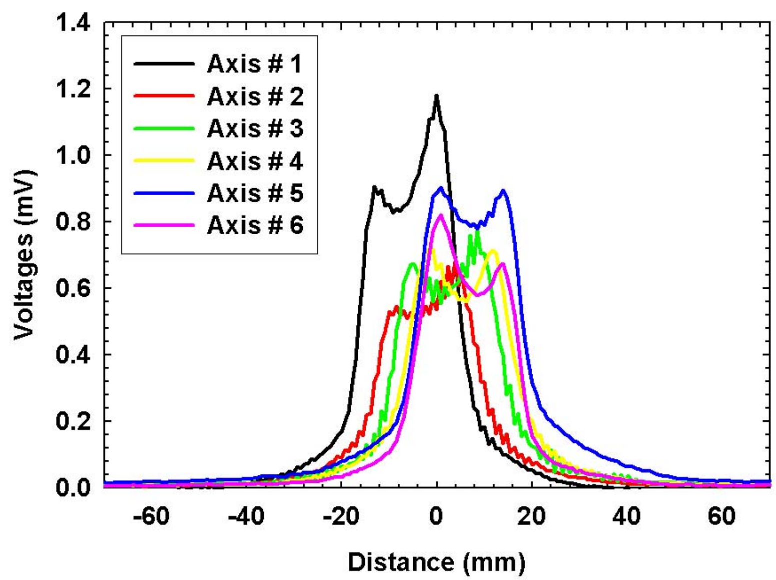


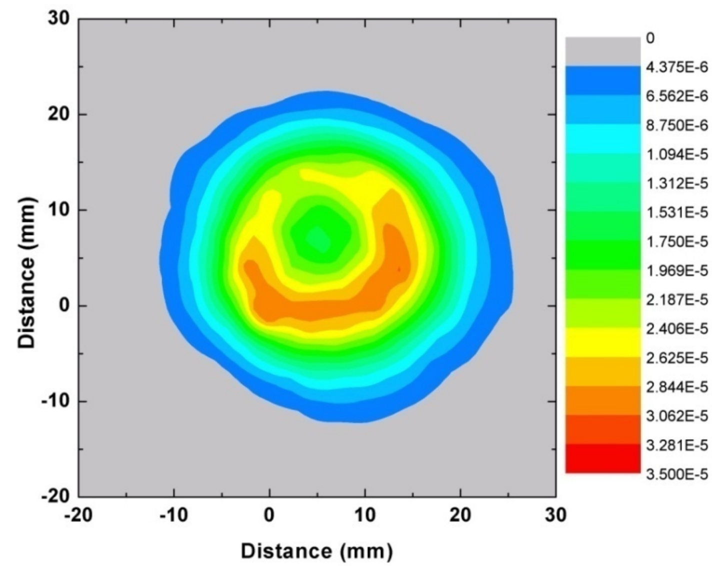
- Transient data at 1,000 Hz
- Temperature ranges from 1,000 to 1,600 K
- Soot volume fraction ranges from 1 to 10 ppm

Experimental configuration 3: Hydrogen/air flame

- Turbulent H_2 diffusion flame
- 10 mm diameter burner
- Emission measured using 310 nm (from OH) filters in front of receiver modules
- 25 mm above burner exit

Results from Hydrogen/Air Flames



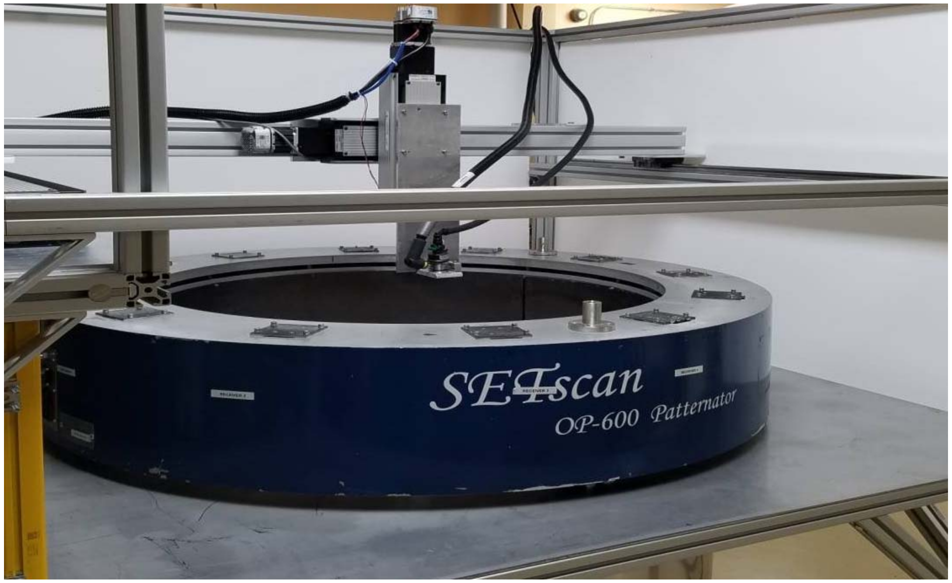


Very good convergence between the measured and deconvoluted intensities

Asymmetry in the reaction zone observed

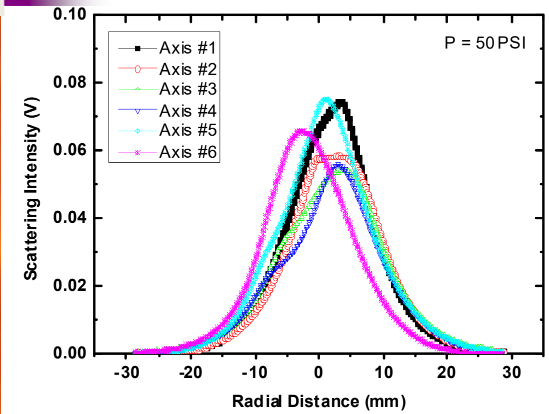
Values of OH consistent with literature (Zhao et al., 2018)

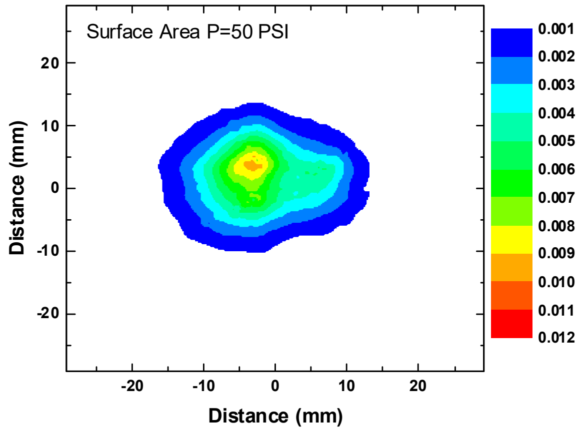
Configuration 4 – Non-reacting sprays

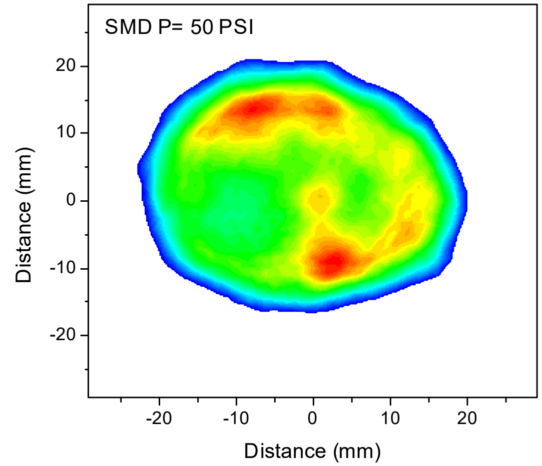


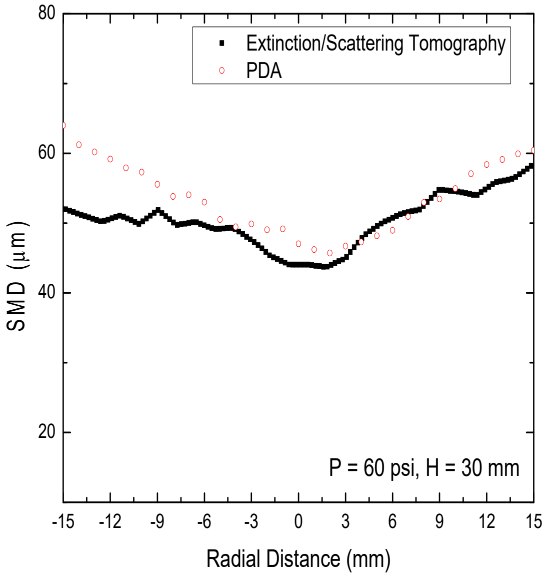
- Water spray from a nozzle
- Extinction and scattering at 0.5 degrees measured using a 2-D array (2 x 512 elements)
- Laser wavelength at 635 nm
- Mie theory to obtain drop sizes and surface area densities

Cold spray results









- Scattering signal not symmetric
- Surface area density highest near the center of the spray
- SMD is higher closer to the edge
- Measurements are in agreement with those obtained by PDA

Conclusions

- Planar soot volume fractions estimated in the overfire region of turbulent flames were in very good agreement with the values reported in literature.
- The estimated planar temperatures and soot volume fractions were consistent with past measurements.
- OH estimates in a hydrogen diffusion flames were in qualitative agreement with reported values.
- Estimated drop size measurements were confirmed with PDPA measurements.
- The sensor suite has been completely validated and provides a useful diagnostic to study turbulent flames and sprays.