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CBT-TCS: the New Temperature and Soot Loading Measurement Technique in a Laminar Diffusion Flame

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Outline

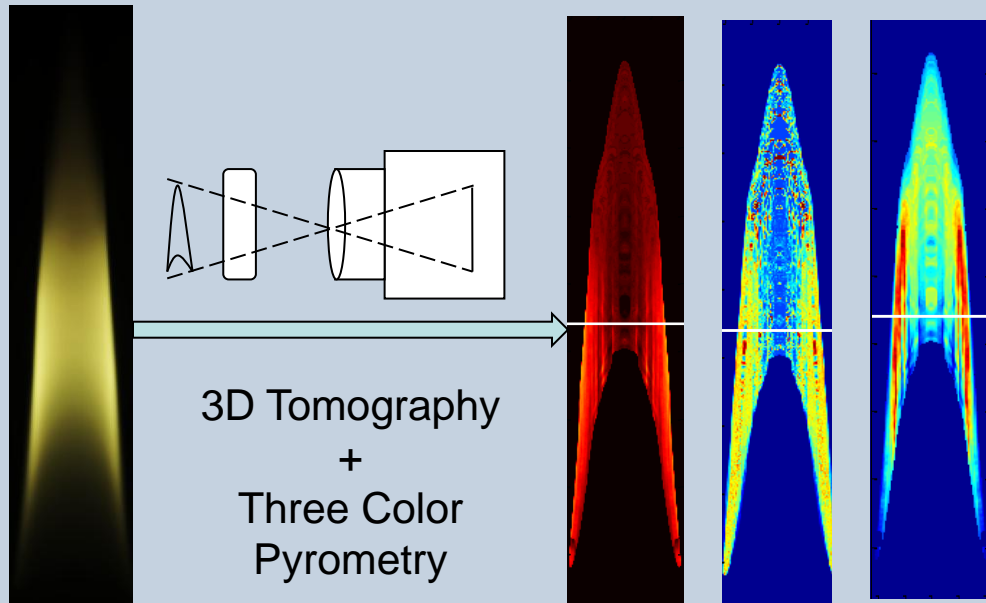
- Introduction
- Experiment Setup and Software Packages
- Accuracy Improvement Techniques
- Sample Data and Assumptions
- Conclusions

Motivation

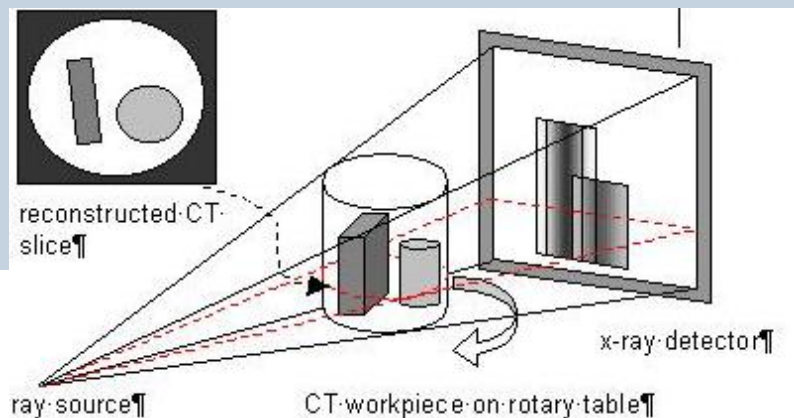
- Sub-micron particulate matter is of concern to human health
- Legislation places limits on the particulate emissions
- For model validation, a simple flame is needed
- Spatially resolved non-intrusive measurement is needed of:
 - Flame temperature
 - Soot volume fraction
 - Soot particle diameter

Introductions to CBT-TCS

(Cone Beam Tomographic Three Colour Spectrometry)



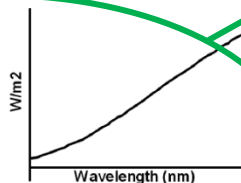
- Optical diagnostic techniques used to measure the 3D temperature, soot diameter and soot volume fraction distributions
- Combination of three colour pyrometry and 3D tomography technique



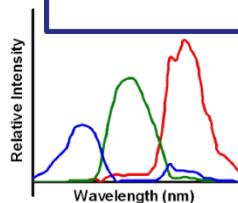
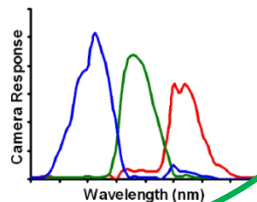
Three Colour Pyrometry - Strategy

$$I_{\lambda} = \epsilon_{\lambda} \frac{2\pi hc^2}{\lambda^5 [\exp(hc/\lambda kT)]}$$

Calculated spectral intensity of glowing soot at Ts & KLs



Spectral response of CCD camera from R, G, B channels



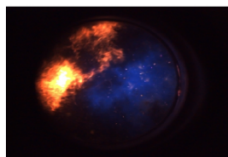
X

Spectral intensity filtered by camera and optics, R, G, B

Integrals over wavelength, R, G, B

Double-entry (R/G & R/B), double-output (T & KL) look-up tables

2-D T & KL (false colour images)



R/G & R/B values from pixels

Calibration of the spectral response of the Camera Sensor

Three Colour Pyrometry

- emissivity & scattering models (1/2)

- Energy balance (Kirchhoff's Law)



Emissivity (ε) = Absorption efficiency (Q_{abs})

- Different Scattering Models

- Rayleigh-Gans Theory ($X [x = \pi d/\lambda] < 0.3$);

d - diameter; T and fv - Soot volume Fraction

$$\varepsilon = Q_{abs}^R = 4x \operatorname{Im} \left\{ \frac{m^2 - 1}{m^2 + 2} \right\}$$

Where $m = n - ik$ is the complex refractive index

- Rayleigh-Gans Theory with Penndorf extension ($x < 0.8$; T , D and fv)

$$\varepsilon = Q_{abs}^P$$

$$= Q_{abs}^R + 2x^2 \left[N_1 \left(\frac{1}{15} + \frac{5}{3} \frac{1}{M_4} + \frac{6}{5} \frac{M_5}{M_1^2} \right) + \frac{4}{3} \frac{M_6}{M_1^2} x \right] - Q_{sca}^R \left[1 + 2 \frac{x^2}{M_1} \left(\frac{3}{5} M_3 - 2N_1 x \right) \right]$$

Three Colour Pyrometry

- emissivity & scattering models (2/2)

- Mie Scattering Theory (analytical solution; T , D and fv)

$$\varepsilon = Q_{abs}^M = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) \operatorname{Re}(a_n + b_n) - \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) (|a_n|^2 + |b_n|^2)$$

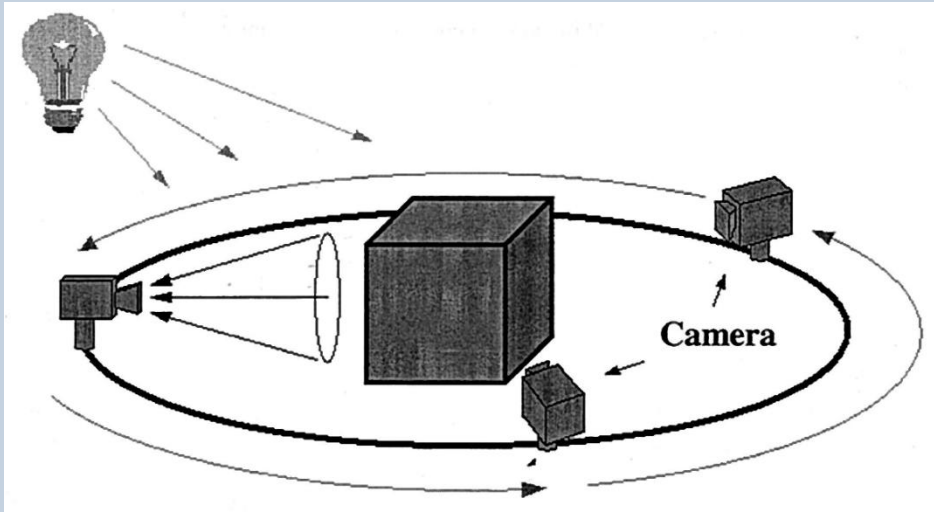
where a_n and b_n are scattering coefficients and are functions of x and m

- Hottel and Broughton Correlation (Empirical correlation; T , KL)

$$\varepsilon = 1 - \exp\left(-\frac{KL(s)}{\lambda^\alpha}\right)$$

where KL is proportional to the soot volume fraction and α is a constant

Cone-Beam Tomography – Cone-Beam System



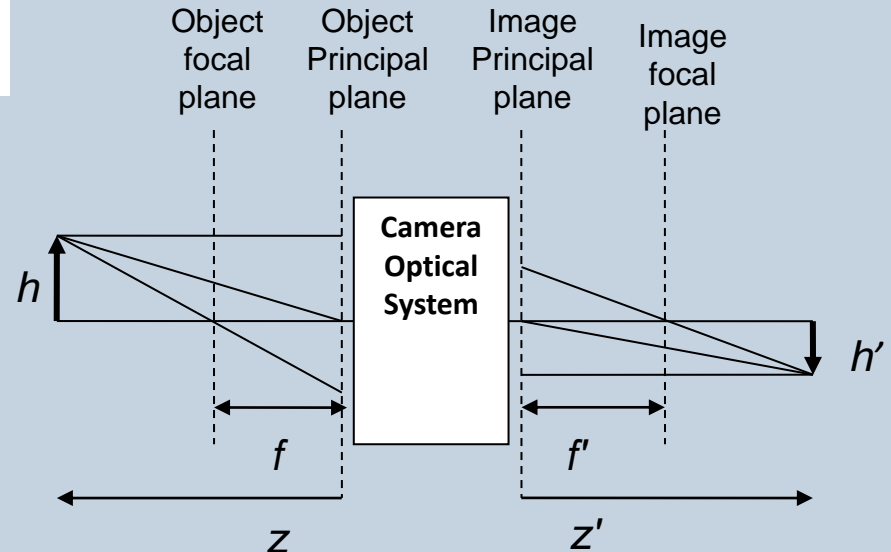
- Need only one projection for axis-symmetric object (e.g. laminar diffusion flame)

Newton's Lens Formula:

$$h'/h = f/(z + f) = (z' + f')/f'$$

\Rightarrow

$$h'/z' = -\left(\frac{f}{f'}\right)\left(\frac{h}{z}\right)$$
 Constant



Cone-Beam Tomography

– Filtered Backprojection Algorithm

Fourier Slice Theory: FT of Projection = FT of the Field

Step 1 Filtered Projection

$$R_{\beta}'(p, \zeta) = R_{\beta}(p, \zeta) \frac{D_{SO}}{\sqrt{D_{SO}^2 + \zeta^2 + p^2}}$$

$R_{\beta}(p, \zeta)$: Projection Data

$$Q_{\beta}(p, \zeta) = \text{IFFT}(\text{FFT}(R_{\beta}'(p, \zeta) \text{ with ZP}) \\ \times H(p, \zeta))$$

$H(p, \zeta)$: Window Function

IFFT: Inverse Fast FT; and FFT: Fast FT; ZP: Zero Padding

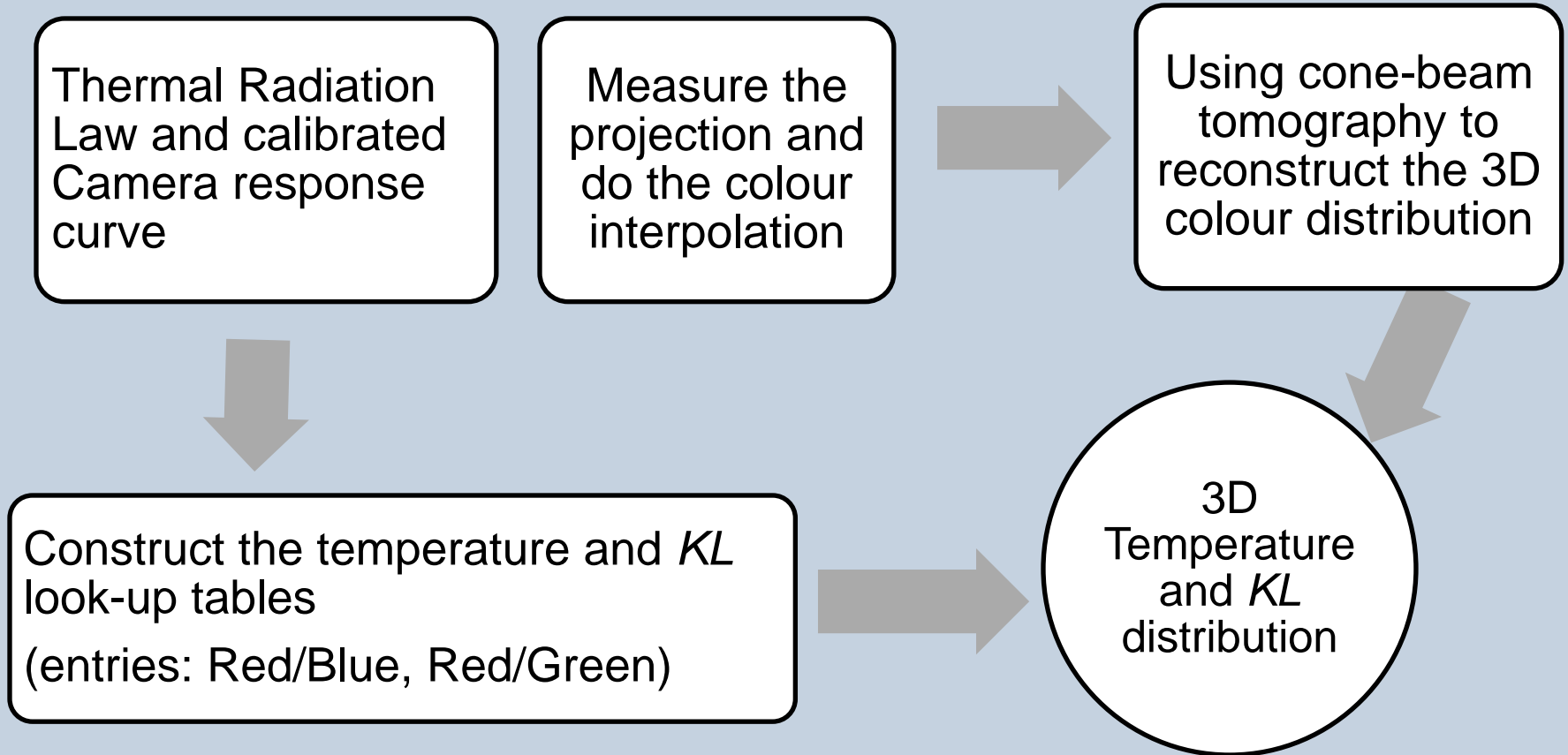
Step 2 Backprojection

$$g(t, s, z) \\ = \int_0^{2\pi} \frac{D_{SO}'^2}{(D_{SO}' - s')^2} Q_{\beta} \left(\frac{D_{SO}t}{D_{SO} - s'}, \frac{D_{SO}z}{D_{SO} - s'} \right) d\beta$$

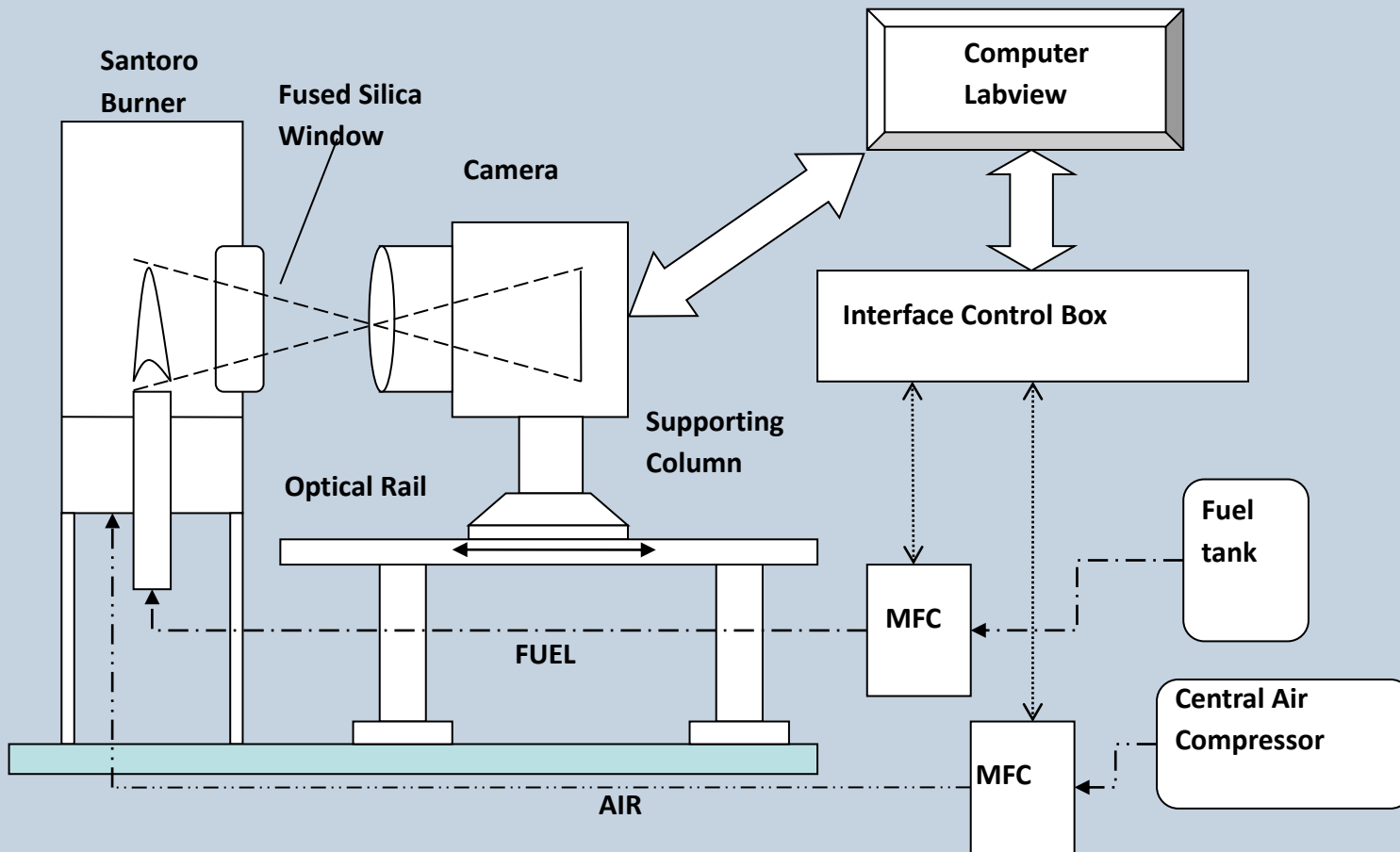
$g(t, s, z)$: the property field in Cartesian coordinate

References: Kak, A. C., Slaney, M. (1999), Principles of Computerized Tomographic Imaging, IEEE press, New York

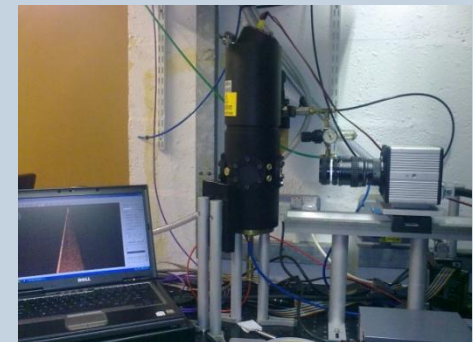
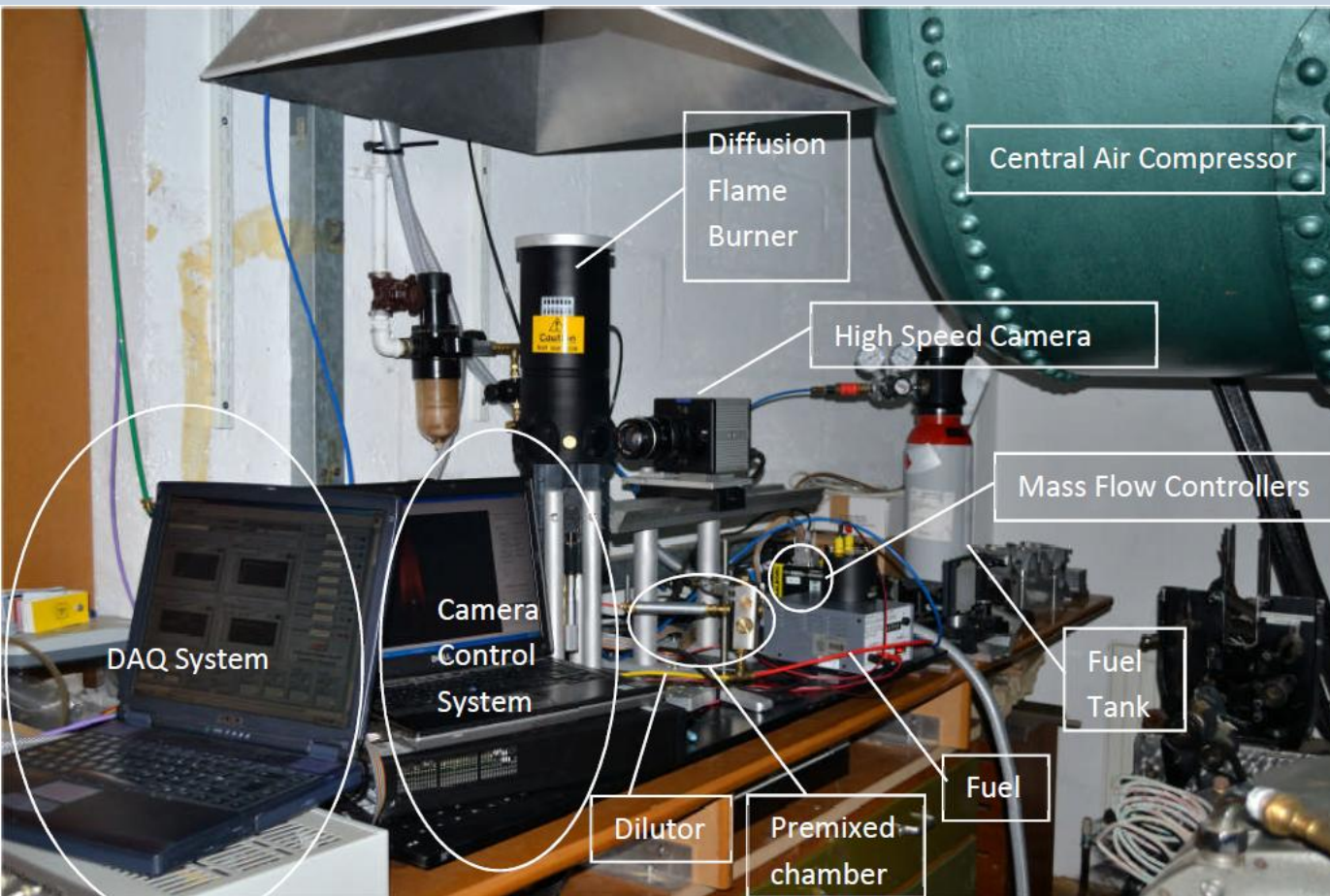
Cone-Beam Tomographic Three Colour Spectrometry (CBT-TCS) - Strategy



Experiment Setup - Diagram



Experiment Setup - Photos



Software Package – Original OSCaR

- Open source tomography code

OSCaR source code URL: www.cs.toronto.edu/~urezvani/OSCaR.html

- Three MATLAB GUIs

- Functions of original code:

- Predefine parameters to do the tomography
- Implementing the 3D filtered backprojection algorithm to X-ray images from different gantry angles by using different window functions

Software Package – Original OSCaR

- Open source tomography code

The screenshot displays the OSCaR software interface, which is divided into three main windows:

- OSCaRMain:** The main window, titled "OSCaR-02 An Open Source Cone-Beam CT Reconstruction Tool for Imaging Research". It contains three main sections:
 - Preprocess:** "Input 3D sinogram data for processing prior to reconstruction". Includes a "Load Projections" button.
 - Reconstruct:** "Image reconstruction using Feldkamm-Kress-Davis algorithm". Includes a "Reconstruct" button.
 - Quit:** A "Quit" button.
- OSCaRPreprocess:** Titled "OSCaR-02 Preprocess An Open Source Cone-Beam CT Reconstruction Tool for Imaging Research". It features:
 - Binary File Info:** Fields for Row No., Column No., Projection #, Machine, and Pixel Type.
 - Projection Information:** Fields for u_off (pixels), v_off (pixels), Weight, Air Normalization, and Projection Angle.
 - Projections:** A grid of plots showing projection data.
 - Orientation:** Buttons for "Flip Horizontally", "Flip Vertically", and "Transpose".
 - Parameters:** Input fields for du (cm), dv (cm), SAD (cm), and SDD (cm).
 - Buttons:** "Load Data", "Export", and "Cancel".
- OSCaRReconstruct:** Titled "OSCaR-02 Reconstruct An Open Source Cone-Beam CT Reconstruction Tool for Imaging Research". It features:
 - Reconstruction Size (cm):** Input fields for x_min, x_max, y_min, y_max, z_min, and z_max.
 - Voxel Size (cm):** Input fields for dx, dy, and dz.
 - Voxel Numbers:** Input fields for Nx, Ny, and Nz.
 - Reconstruction Status:** Fields for Proj # and Angle, with a "Stop" button.
 - Buttons:** "Execute" and "Close".
 - File Formats:** A dropdown menu for "File Formats" and a "Save Reconstruct..." button.
 - Viewers:** Two side-by-side projection viewers showing "Projection #1 - 0 degrees" and "Projection #81 - 90.0291 degrees".
 - Memory:** A bar indicating "Approximate Required Memory (RAM)" of "2 MB".
 - Toggle Axes:** Buttons for "Axial (toggle axes)", "Coronal (toggle axes)", and "Sagittal (toggle axes)".

Software Package – Modified OSCaR

- Including one main panel and four sub-panels
- Extended functions:
 - Read projection images, do the colour demosaicing and the downsampling
 - Modified the 3D filtered backprojection algorithm to make it applicable to current optical setup and apply this algorithm to individual colour channels by using different window functions with different zero-padding lengths
 - Applying 3D median filter, construct the look-up table and do the mapping to find T , D and f_v according to the selected optical components and scattering model
 - Apply a circumferential average and export the final data matrix

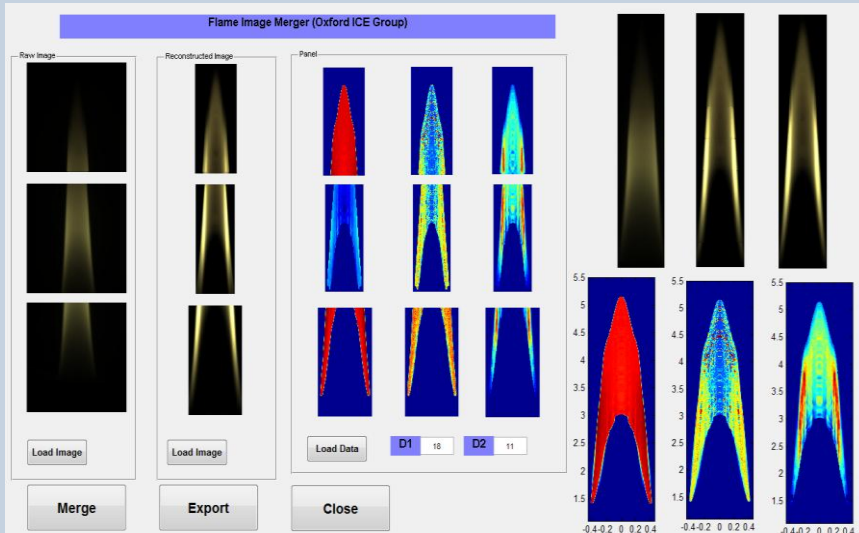
Software Package – Modified OSCaR

panel and four sub-panels

The software package consists of several main components and steps:

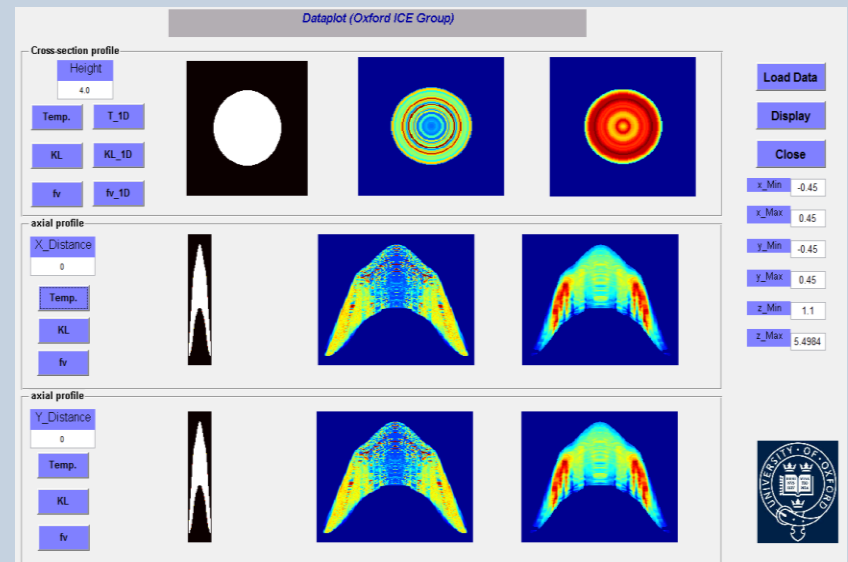
- OSCaRMain (Spectrometry):** An Open Source Cone-Beam CT Reconstruction Tool for Image Reconstruction (Oxford Edition - Modified by IC Engine Group for Application in Color Ratio Pyrometry). It includes four main steps:
 - Step 1 Create Data File:** Import projection pictures and related sampling properties to construct the projection data file in binary format.
 - Step 2 Load Projections:** Input Projection Data File for processing prior to reconstruction.
 - Step 3 Reconstruct:** Image reconstruction using Feldkam-Kress-Davis algorithm.
 - Step 4 Color Ratio Mapping:** Construct Color Ratio map and find the T and KL value by mapping into the pre-constructed table.
- OSCaRCreate:** Interface for creating the reconstruction. It shows a 'Raw Image' and a 'Reconstructed Image'. A 'Next Stage' dialog box indicates 'Data Saving Finished. Now proceed to next stage!'. Parameters include:
 - Approximate Required Memory (RAM): 4 GB
 - Downsampling Box: Mean, Median, Rate (2)
- OSCaRPreprocess:** Interface for preprocessing the data. It shows a central image and various parameters like 'Approximate Required Memory (RAM): 1024 MB'.
- OSCaRMapping:** Interface for color ratio mapping. It displays cross-section profiles and axial profiles for Temperature (K), KL, and Soot volume fraction (ppm). Parameters include:
 - Height: 0.1
 - Temp, KL, Iv
 - X_Distance: 0
 - Temp, KL, Iv
- OSCaRReconstruct:** Interface for the reconstruction process. It shows projection views (e.g., Projection #1 - 4 degrees, Projection #23 - 90 degrees) and filtering options. Parameters include:
 - Reconstruction Size (cm): X_min: -0.4, X_max: 0.4, Y_min: -0.4, Y_max: 0.4, Z_min: -1, Z_max: 1.1
 - Voxel Size (cm): dx, dy, dz (all 0.004)
 - Filter: Hamming
 - Approximate Required Memory (RAM): 6 GB

Software Package – Post-processing

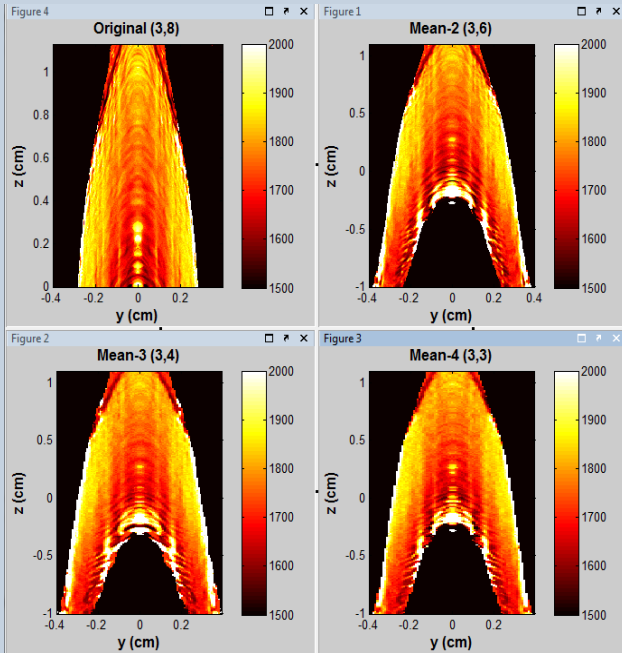


- Merging data from different portions of the flame

- Display and save the selected data

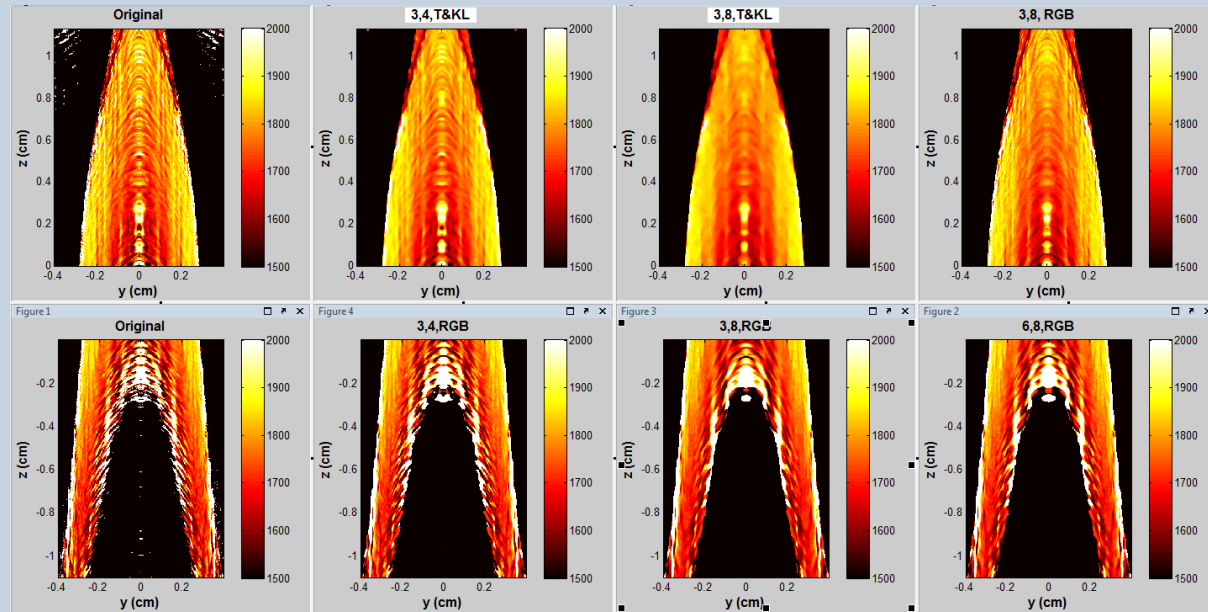


Accuracy Improvement Techniques (1/2)

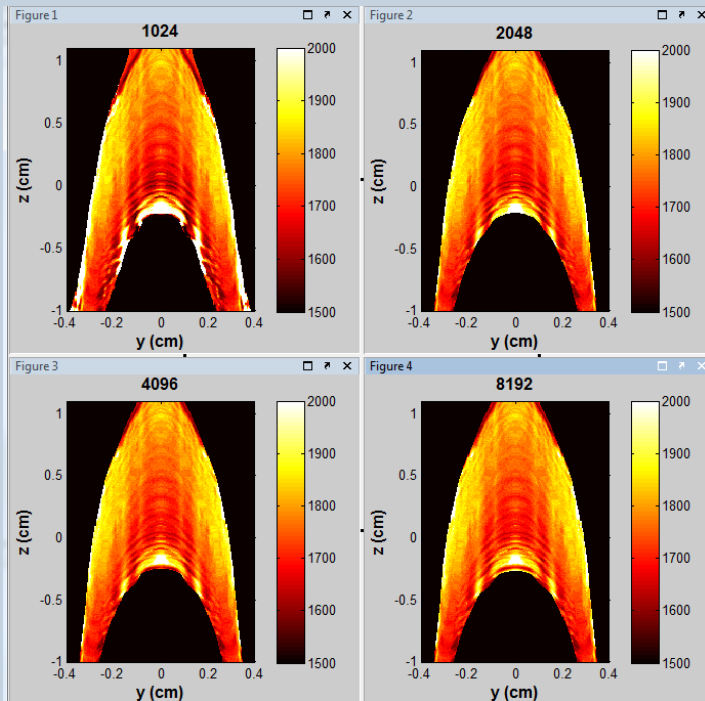


- 3D Median Filter
 - apply to the T , D , or KL data
 - Blur the image
 - apply to the reconstructed RGB colour map
 - Enhance the smoothness

- Downsampling
 - Trade-off between accuracy and spatial resolution:
 - smaller pixel width \Rightarrow smaller difference between two adjacent projections, if the difference is comparable to the background
 - noise poor accuracy but good spatial resolution



Accuracy Improvement Techniques (2/2)



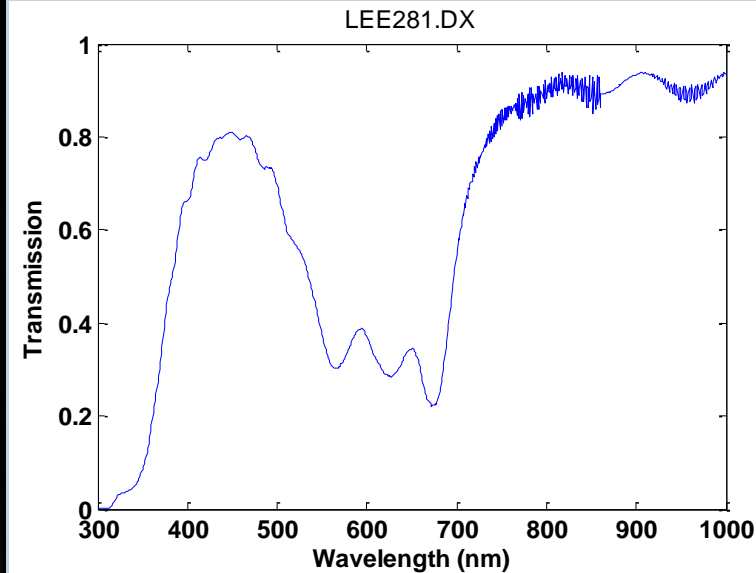
- Increase the zero-padding length when using the fast Fourier transform so as to increase the resolution in the frequency domain

- Other techniques
 - Circumferential averaging for axis-symmetric flame
 - Using optical filters to make more use of the dynamic range of different colour channels (especially the blue)

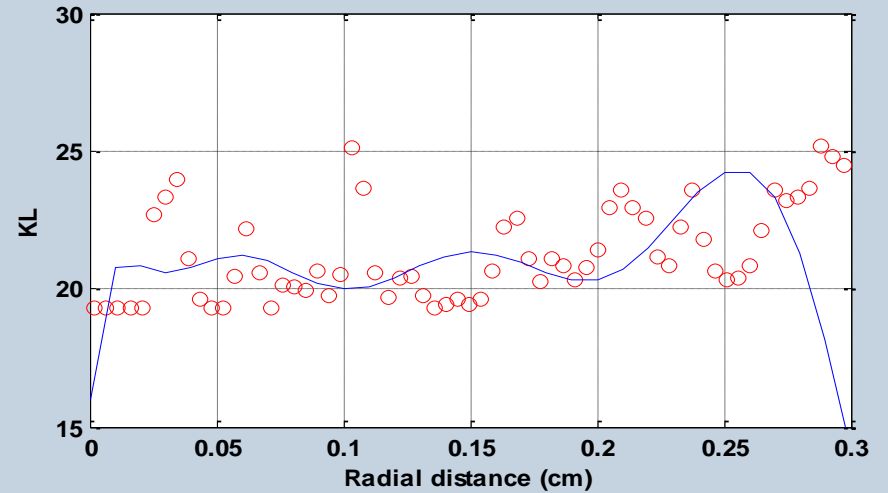
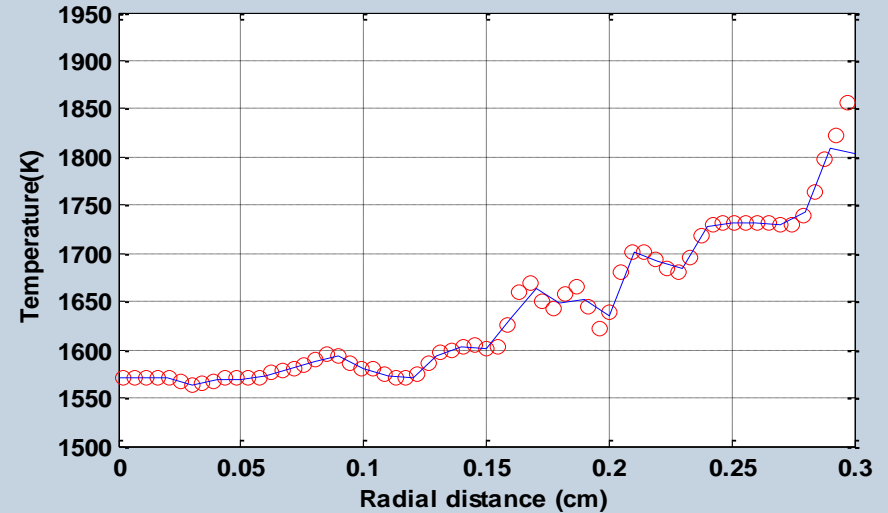
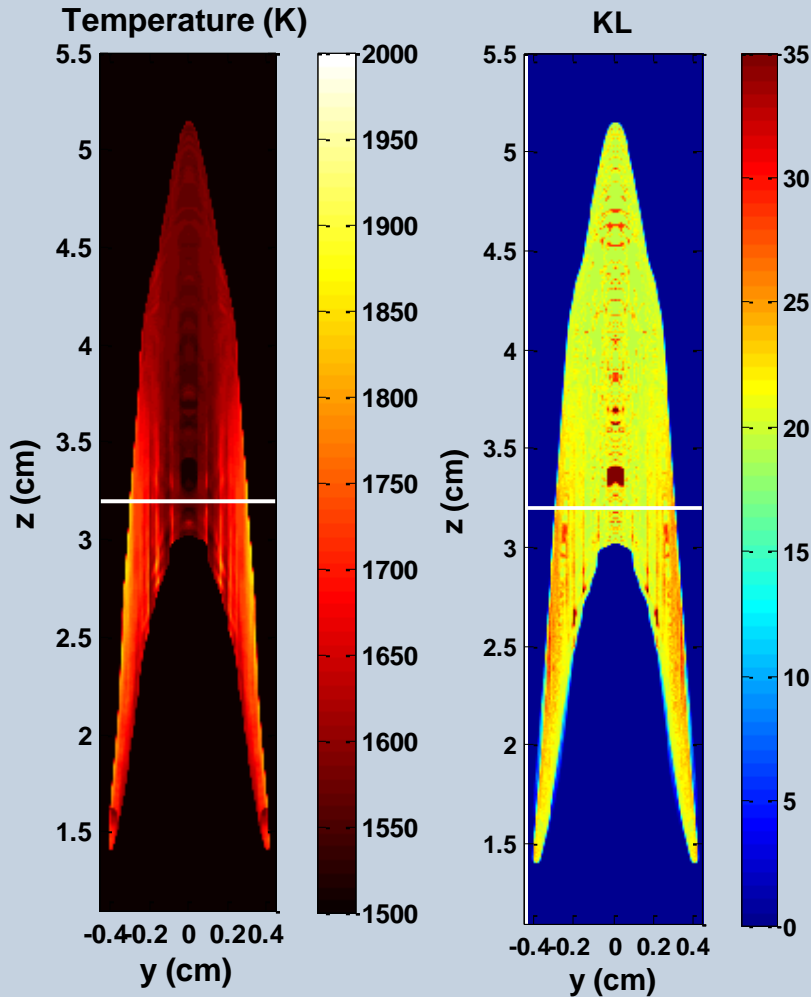
Sample data – ethylene co-flow laminar diffusion flame

- Test Condition

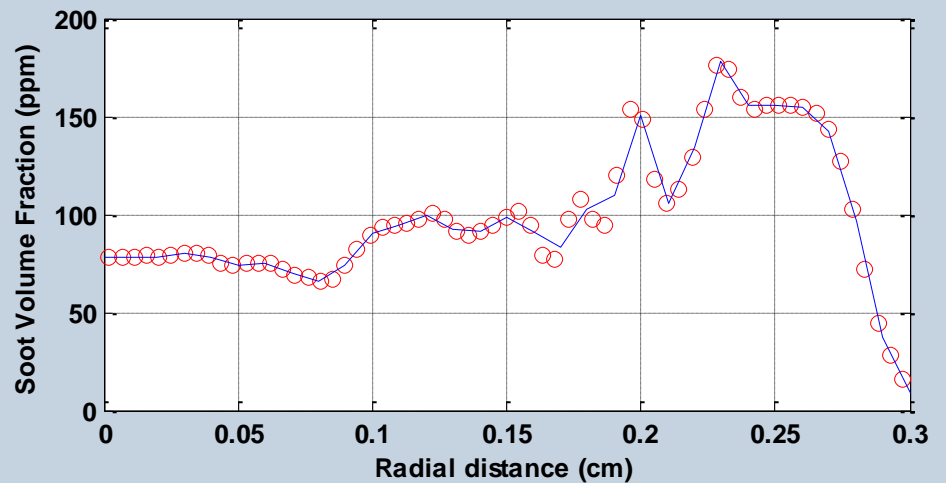
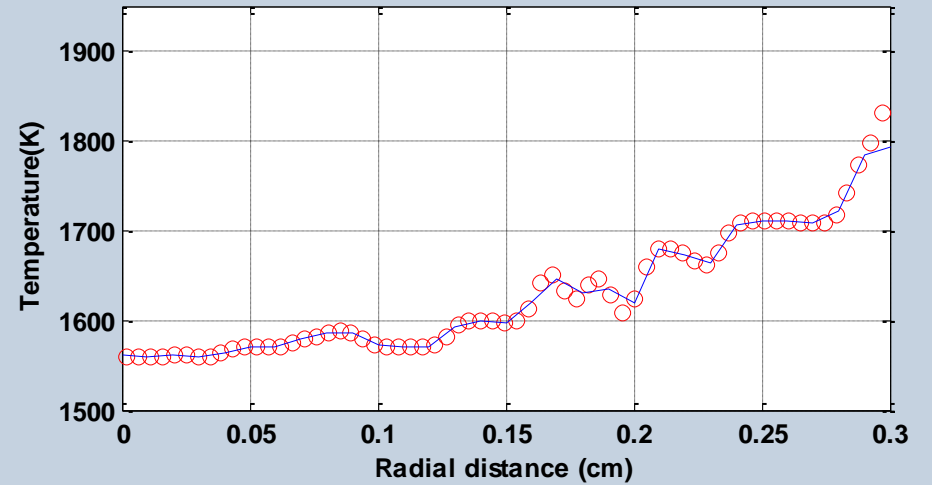
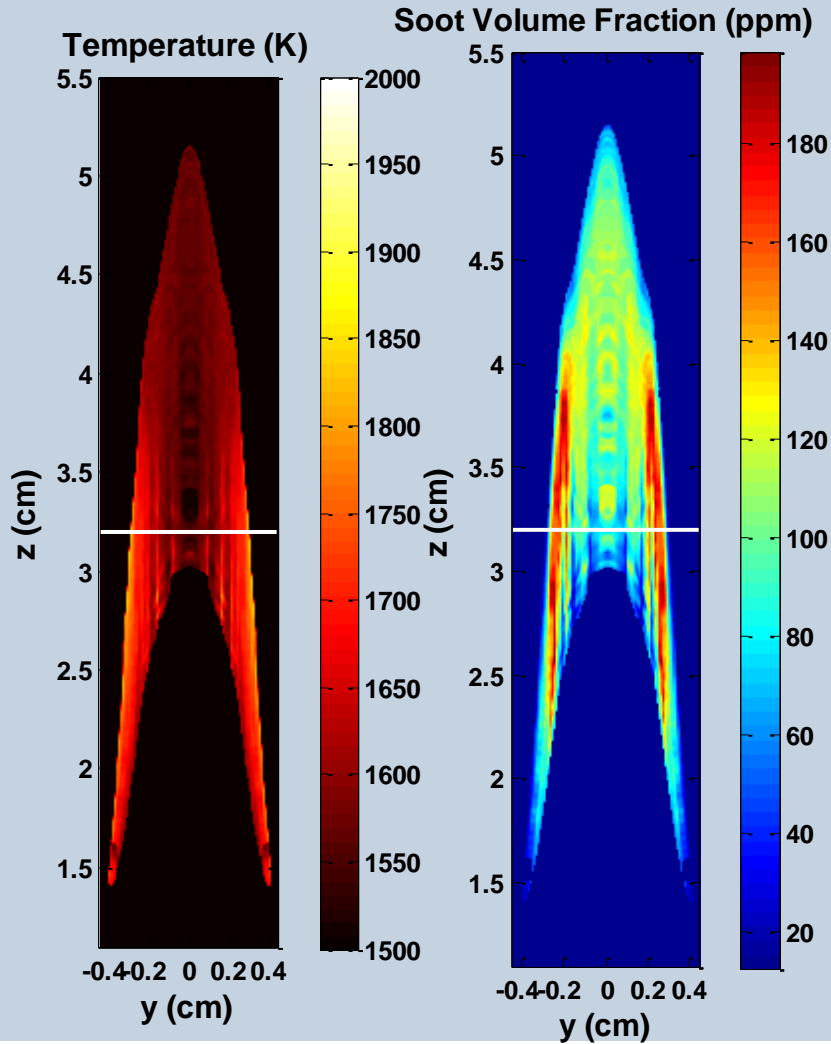
- Fuel flow rate: 143 mL/min;
Air flow rate: 45 L/min
- Camera setup:
Frame rate: 60 frames/sec
Aperture size: $f/32$ (with 2* convertor)
Focus length: 100mm
Object to lens distance: 23.6 cm
Lens to detector distance: 17.4 cm
- Optical component
Lens: Nikon 50mm lens with 2* convertor
Filter: LEE E281 filter (around 0.4 transmission efficiency for red and green light and 0.8 for blue light)



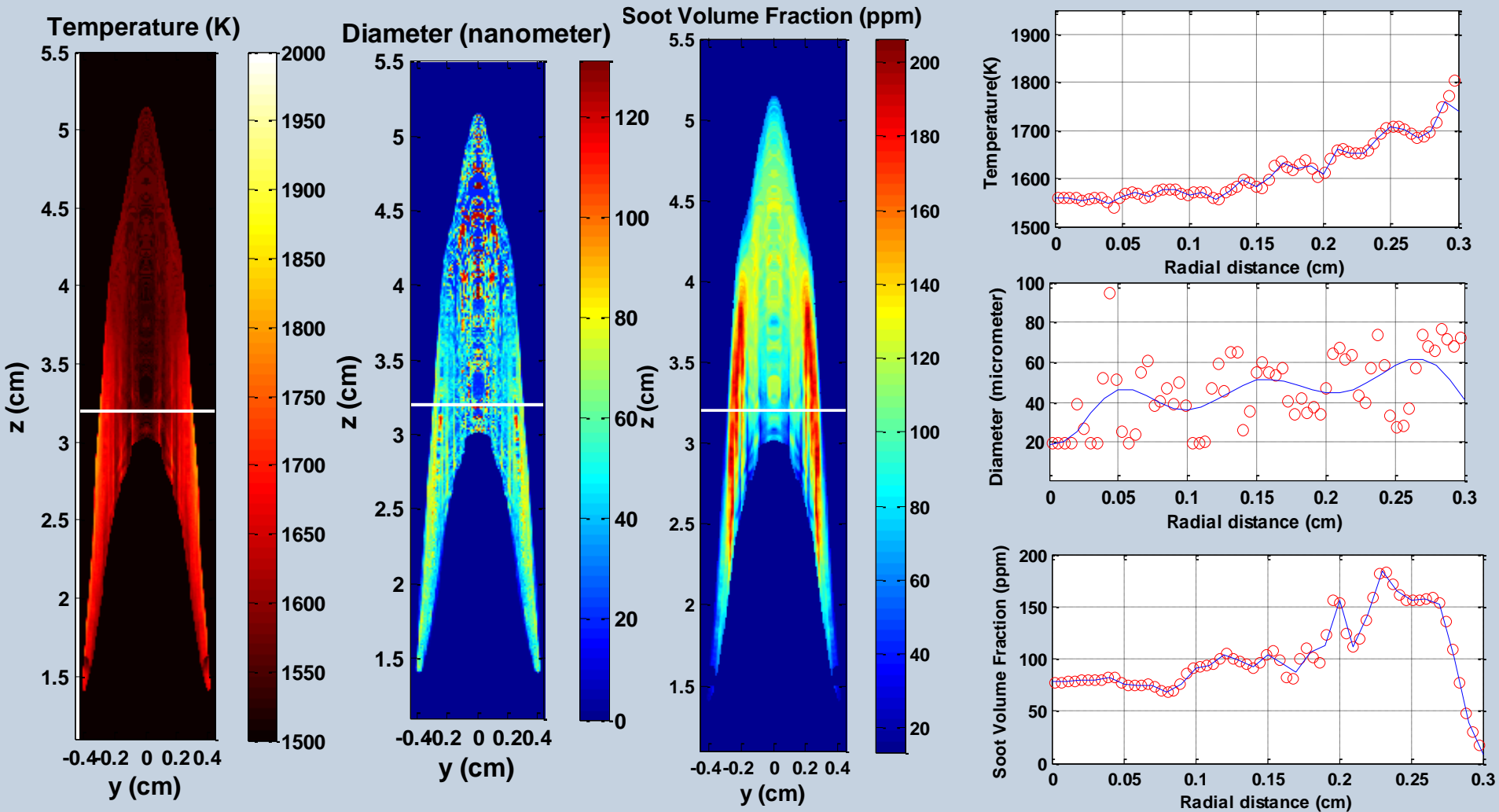
Sample Data (1/4) – Hottel and Broughton



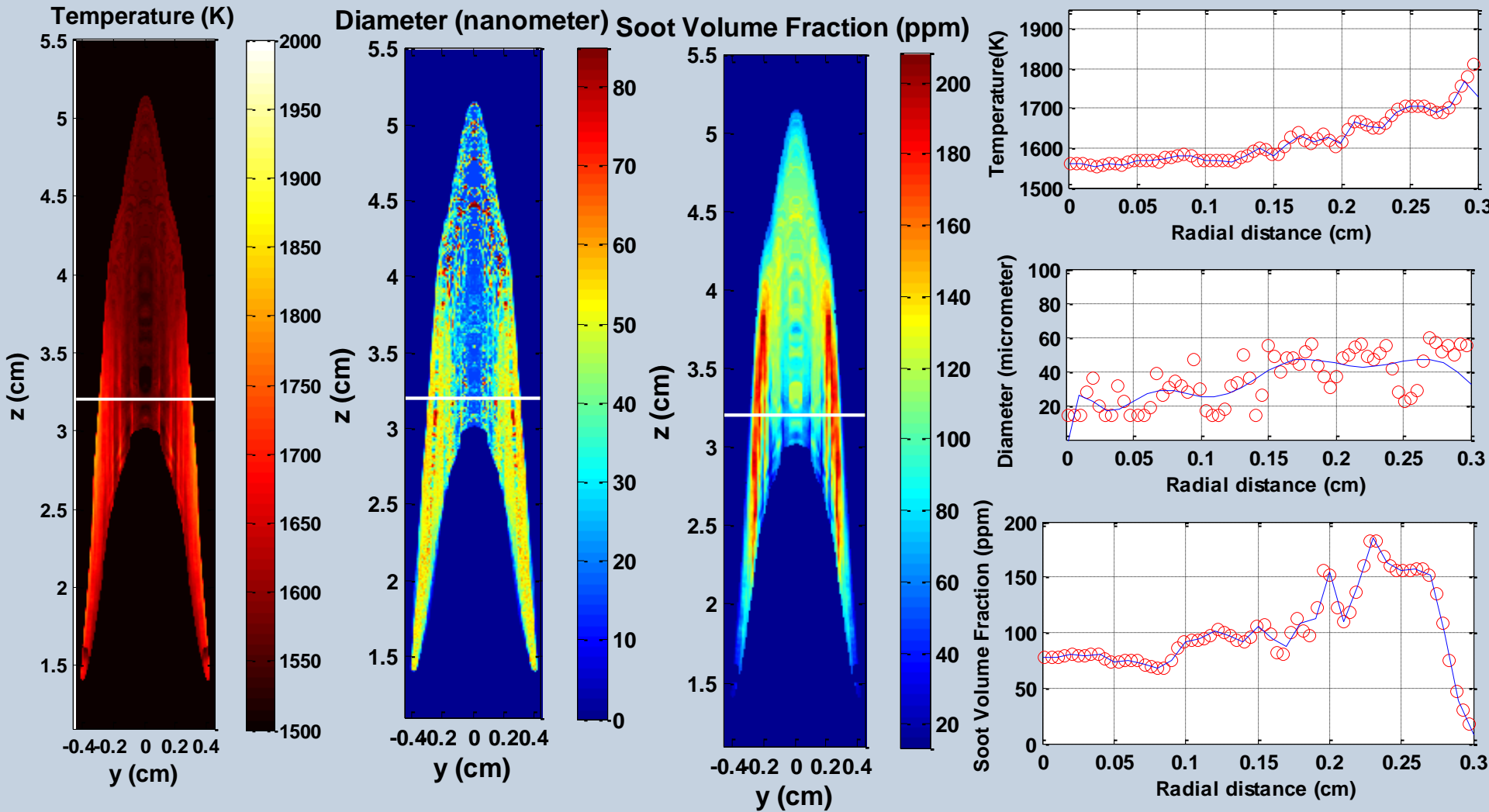
Sample Data (2/4) – Rayleigh-Gans Theory



Sample Data (3/4) – Rayleigh-Gans-Penndorf



Sample Data (4/4) – Mie Scattering



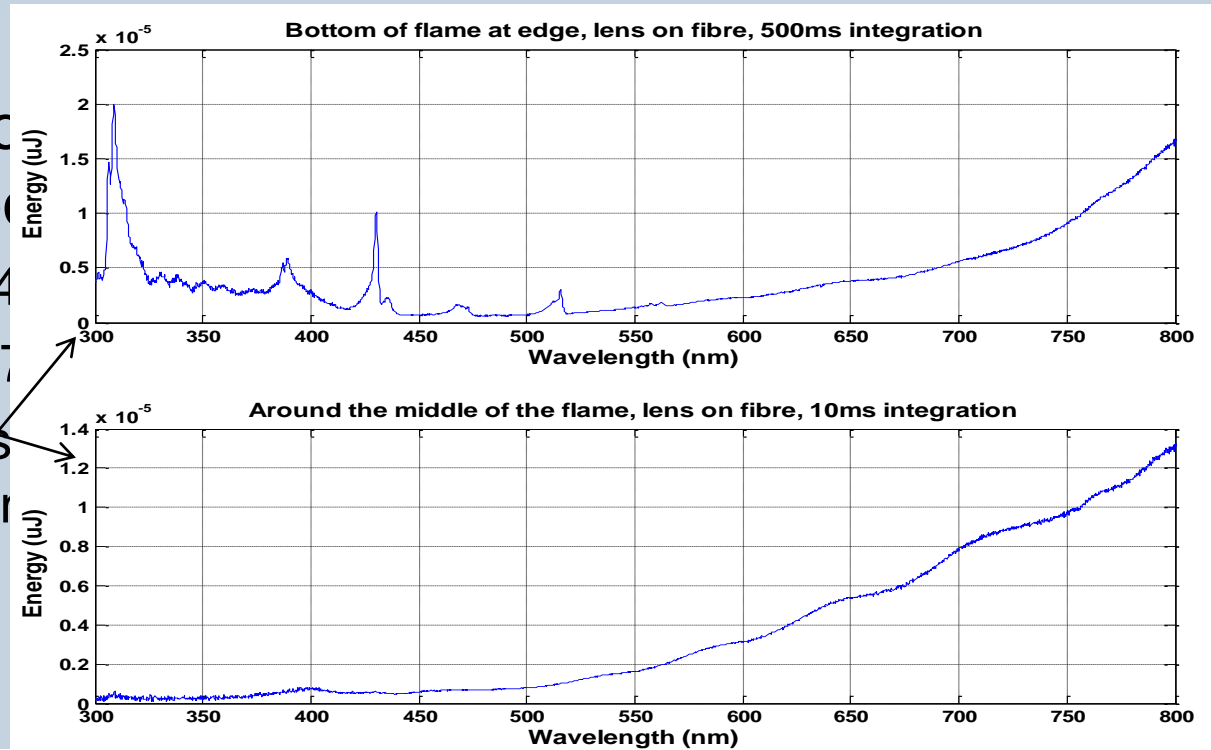
Assumptions (1/2)

- Particulate temperature is the same as local flame temperature
- Thermal radiation from other species are negligible compared to soot particles
 - CO₂: 2.0, 2.7, 4.3, 9.4, 10.4 and 15 μm
 - H₂O: 1.38, 1.87, 2.7, and 6.3 μm
 - Chemilluminescence from radicals is negligible except from the circumferential base of the flame

Assumptions (1/2)

- Particulate temperature is the same as local flame temperature

- Thermal radiative component to soot
 - Carbon, 2.7, 4
 - Hydrogen, 1.87
 - Carbon monoxide, 1.87



Assumptions (2/2)

- The radiation attenuation along the optical path is negligible (optical-thin approximation)
 - Not clear at this point
 - Can be partially corrected by using an iterative method suggested by Lu et al. (2009)
 - Need to be corrected by introducing certain scattering models in the future

Conclusions

- The CBT-TCS technique is an effective and convenient optical diagnostic method to measure the spatially distributed temperature, soot diameters and soot volume fraction for an axi-symmetric flame
- The optical-thin assumption may need to be addressed in the future to increase its accuracy
- CBT-TCS can be applied to asymmetric flames by using multiple images

Thanks for Your Attention ~~

Q & A