3D Temperature and Soot Loading Measurement in a Diffusion Flame Burner Using Tomographic Three Colour Spectrometry

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Colour pyrometry has been widely applied to measurement of the temperature and soot loading in combustion science. However, the spatial property field information is lost when using traditional colour pyrometry because it is used to measure the line-of-sight integral radiation from the soot particles. Laser techniques can be used to measure the 3D property field with high temporal and spatial resolution, but at the cost of a complicated optical setup and repeated measurements in different portions of the flame.

A three-colour pyrometry technique based on 3D tomography has been developed to measure the three-dimensional temperature and soot loadings in an axisymmetric laminar diffusion flame by using a simple optical system. First, an image of the flame was taken by a spectrally calibrated colour camera. Cone-beam tomographic reconstruction, using the filtered back projection algorithm, was then employed to create a 3D map of colour values. Finally, colour ratio pyrometry was applied, in order to generate the soot volume fraction, soot diameter distribution and the temperature field. Four different scattering models, including the Hottel and Broughton empirical correlation, the Rayleigh-Gans scattering theory, the Rayleigh-Gans scattering theory with Penndorf extension, and the Mie scattering theory, were used to calculate the emissivity of the particles. The effects of various optical and mathematical parameters will be discussed briefly, such as the field of view of the optical system, the addition of a spectral filter to utilize the full dynamic range of each colour site on the camera and the parameters in the tomography algorithm. Also to be discussed briefly will be some noise reduction methods, such as the 3D median filtering and downsampling.

This technique has been applied to the pure and diluted ethylene flames produced by a Santoro burner. The air flow rate, the fuel flow rate and the diluent (N_2) flow rate were controlled by independent mass flow controllers. Both the remote control voltage signals and the set point voltage signals of the mass flow controllers were connected to data acquisition cards with a Labview interface control program to form a control system. The results showed consistent temperature profiles when using different scattering models. Fig. 1 shows the temperature, soot diameter and soot volume fraction distributions in the central plane of the flame for a pure ethylene flame obtained by using the Mie scattering theory. The diluted ethylene flame showed a slightly higher temperature profile, and smaller soot volume fraction.

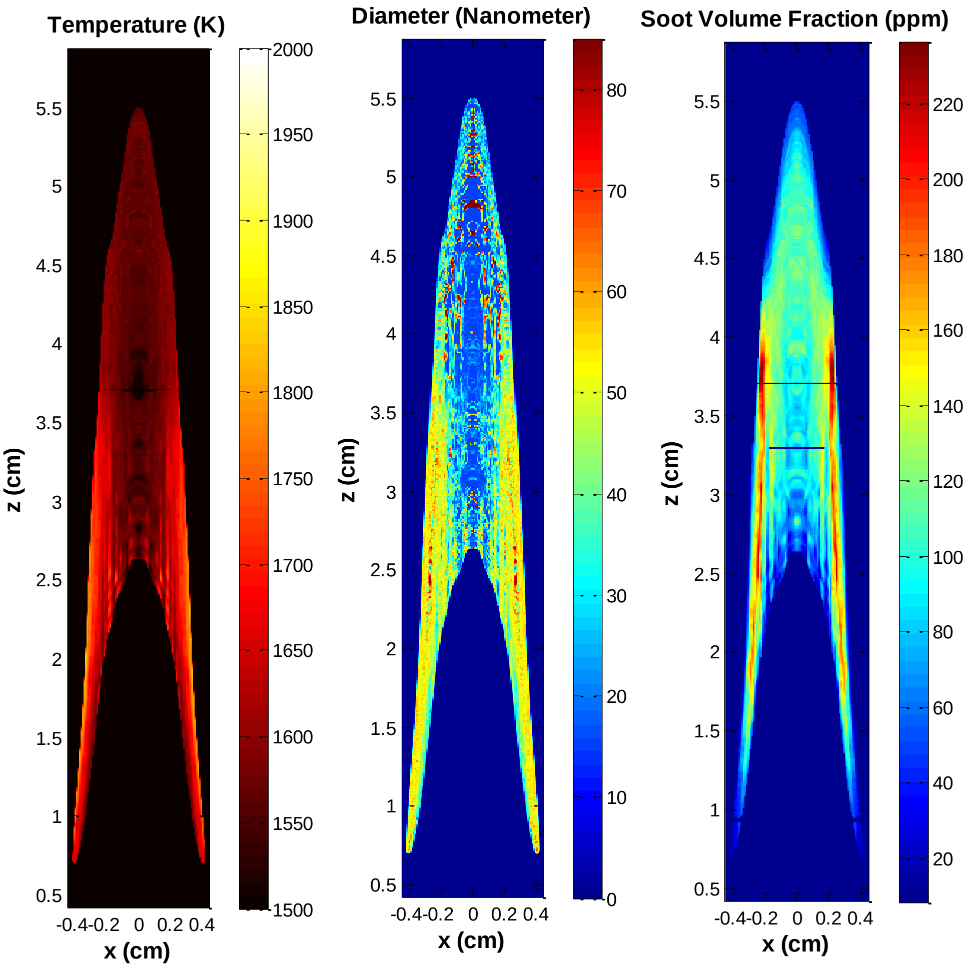

Fig. 1 Temperature, soot diameter and soot volume fraction distributions in the central plane of a pure ethylene flame obtained by using the Mie scattering thoery

Publications:

- H. Zhao, R. Stone, L. Zhou, *International Journal of Hydrogen Energy*, 35 (2010) 4676-4686.

- R. Stone, H. Zhao, L. Zhou, *2010 SAE International Conference*, Detroit, USA (2010), 2010-01-0580.

Summary of poster content

Title: Cone Beam Tomographic Three Colour Spectrometry --- a New 3D Temperature and Soot Loading Optic Diagnostic Technique

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- **Introduction**

Cone Beam Tomographic Three Colour Spectrometry (CBT-TCS) is a new optic diagnostic technique which can be used to measure 3D distributed temperatures and soot loadings in a flame. It is based on the principle of three colour pyrometry and cone-beam tomography.

- **Theory -** Radiation and scattering models

The light intensity recorded by the camera is from the radiation of soot particles, which can be calculated by using Planck's law. Because the soot particles are not black bodies, their emissivity must be taken into account when calculating their radiation. The energy balance shows that the emissivity of the soot particle equals its light absorption efficiency. Different scattering models will give different correlations to calculate the absorption efficiency. The most accurate model is from using Mie scattering theory, which is the analytical solution to the Maxwell equations for spherical particles. However, Mie scattering theory is in famous for its demand on computational power. Therefore, when the particle is small enough, simpler scattering models can be used. When the size parameter (pi*diameter of the particle/incident light wavelength) is less than 0.8, the Rayleigh-Gans theory with the Penndorf extension can be used; when the size parameter is less than 0.3, the Rayleigh-Gans theory can be used alone. The Mie theory and Penndorf extension can be used to calculate the temperature, soot diameter and soot volume fraction, but the Rayleigh-Gans theory can only be used to calculate the temperature and soot volume fraction (so it is necessary to guess the mean particle diameter size). There is another empirical correlation developed by Hottel and Broughton to calculate the temperature and *KL*. The *KL* can be used to estimate the soot loading qualitatively.

- **Three Colour Pyrometry (TCP)**

Two different strategies used in three colour pyrometry are introduced. The first is uses the Hottel and Broughton correlation (or Rayleigh-Gans theory) to calculate the temperature and *KL* (or diameter if using Rayleigh-Gans theory), which does not need an absolute calibration of the camera sensor. The second approach uses the Rayleigh-Gans theory with the Penndorf extension or the Mie theory to determine the temperature, soot diameter and soot volume fraction. This strategy requires the absolute calibration of the camera sensor.

- **Cone Beam Tomography** – Filtered Backprojection algorithm

The procedure to implement the Filtered Backprojection (FBP) algorithm to reconstruct the 3D colour maps is as follows.

- **CBT-TCS** – Strategy

The overall strategy is to use CBT-TCS to measure the 3D temperature, soot diameter and soot loadings (*KL* or soot volume fraction).

- **CBT-TCS** – Experiment setup

The experimental setup used to do the CBT-TCS is shown in this section. The figures also show the half-cone pointer used to focus the camera and a snapshot of the focusing process.

- **CBT-TCS** – Sample data

Some sample results from an ethylene diffusion flame burner tests are shown in this section. The results include 2D plots of the field properties in central axis plane and 1D plot of radial distributed field properties (at a height specified by the white horizontal line in the 2D plot) when using different scattering models. These plots show that the temperature distributions measured by using different scattering models have very consistent structures. But the Hottel and Broughton correlation and Rayleigh-Gans theory tend to overestimate the temperature slightly. The soot volume fractions found by using the different scattering models agree with each other very well, which indicates that the effect of soot diameter on the soot volume fraction is very small. The soot diameter results by using the Penndorf extension and the Mie theory show very similar structures but the Penndorf extension tends to overestimate the particle size.

- **Conclusions**

The CBT-TCS has been successfully applied to a diffusion flame to measure the spatially distributed temperatures, soot diameters and soot volume fractions. Various noise suppression techniques have been used to increase the accuracy of the results. To further improve the accuracy, the optical thin approximation should be corrected carefully. The CBT-TCS can also be used to measure the field properties in asymmetric flames if using multiple projections at different gantry angles.

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Cone Beam Tomographic Three Colour Spectrometry --- A New 3D Temperature and Soot Loading Optic Diagnostic technique

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Introduction

Cone Beam Tomographic Three Colour Spectrometry (CBT-TCS) ---- 3D temperature and soot loading optic diagnostic techniques based on:

- Three Colour Pyrometry (TCP): particulate radiation and scattering models
- Cone Beam Tomography (CBT): Filtered Backprojection (FBP) algorithm

Theory --- Radiation and scattering models

- **Planck's radiation law for grey body:**

$$I_{\lambda b} = \varepsilon_\lambda \frac{2\pi hc^2}{\lambda^5[exp(hc/\lambda kT) - 1]}$$

where ε is the emissivity, λ is the wavelength, T is the temperature, h is Planck constant ($6.626*10^{-34}$ Js), c is the speed of light in vacuum ($2.998*10^{8}$ m/s), and k is the Boltzmann constant ($1.38*10^{-23}$ J/K)

- **Hottel and Broughton Empirical correlation:** $\varepsilon_\lambda = 1 - exp(-KL/\lambda^\alpha)$

where K is a function of soot loading, L is the optical path thickness, α is a constant (1.39 for amyl acetate flames within visible spectrum)

- **Kirchhoff's law for spherical particles (Energy Balance):** $Q_{abs} = \varepsilon$

where Q_{abs} is the absorption efficiency

- **Rayleigh-Gans Scattering Model:**

$$Q_{abs}^R = 4xIm\left\{\frac{m^2-1}{m^2+2}\right\};\ x = \pi D/\lambda$$

where x is the size parameter, m is the complex refractive index (close to 1.57 – 0.56i for soots), D is the particle diameter
Note: this model is valid when x is smaller than 0.3 (error < 10%) when m is chosen as 1.57 – 0.56i

- **Rayleigh-Gans Scattering Model with Penndorf extension [1]:**

$$Q_{abs}^P = Q_{abs}^R + 2x^2[N_1\left(\frac{1}{15}+\frac{5}{3}\frac{1}{M_4}+\frac{6}{5}\frac{M_5}{M_1^2}\right)+\frac{4}{3}\frac{M_6}{M_1^2}x] - Q_{sca}^R[1+2\frac{x^2}{M1}\left(\frac{3}{5}M_3 - 2N_1 x\right)]$$

where N_n and M_n are functions of m.
Note: this model is valid when x is smaller than 0.8 (error < 10%) when m is chosen as 1.57 – 0.56i

- **Mie Scattering Model (Analytical solution of Maxwell equations):**

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

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

Three Colour Pyrometry (TCP)

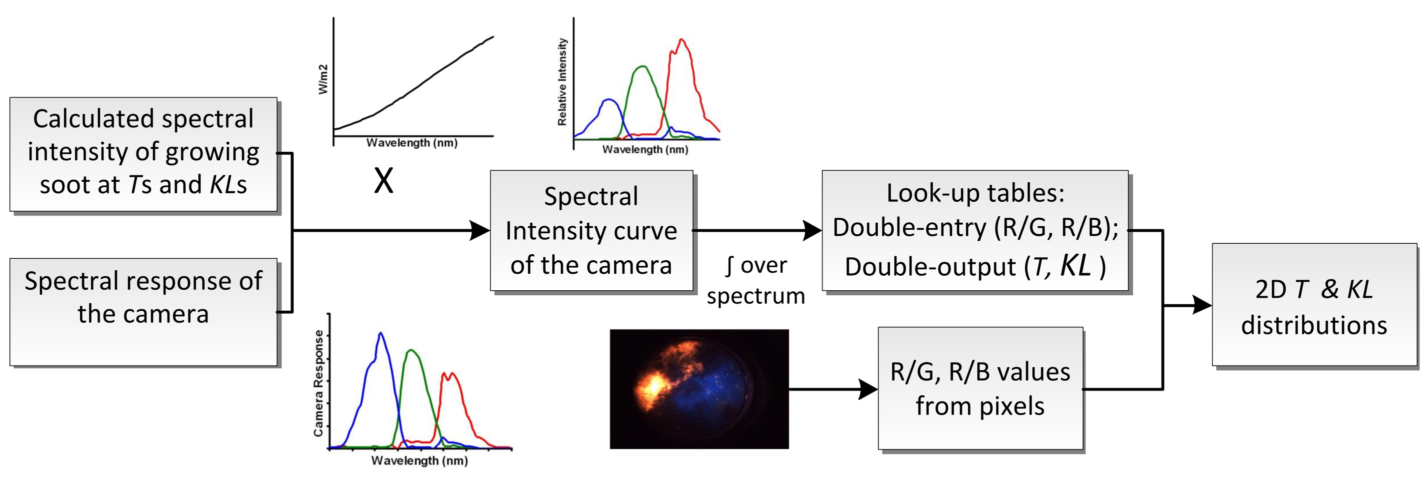


Fig. 1 The strategy for the determination of temperature and soot loading (*KL*) in Three Colour Pyrometry (TCP) by using the Hottel and Brought correlation

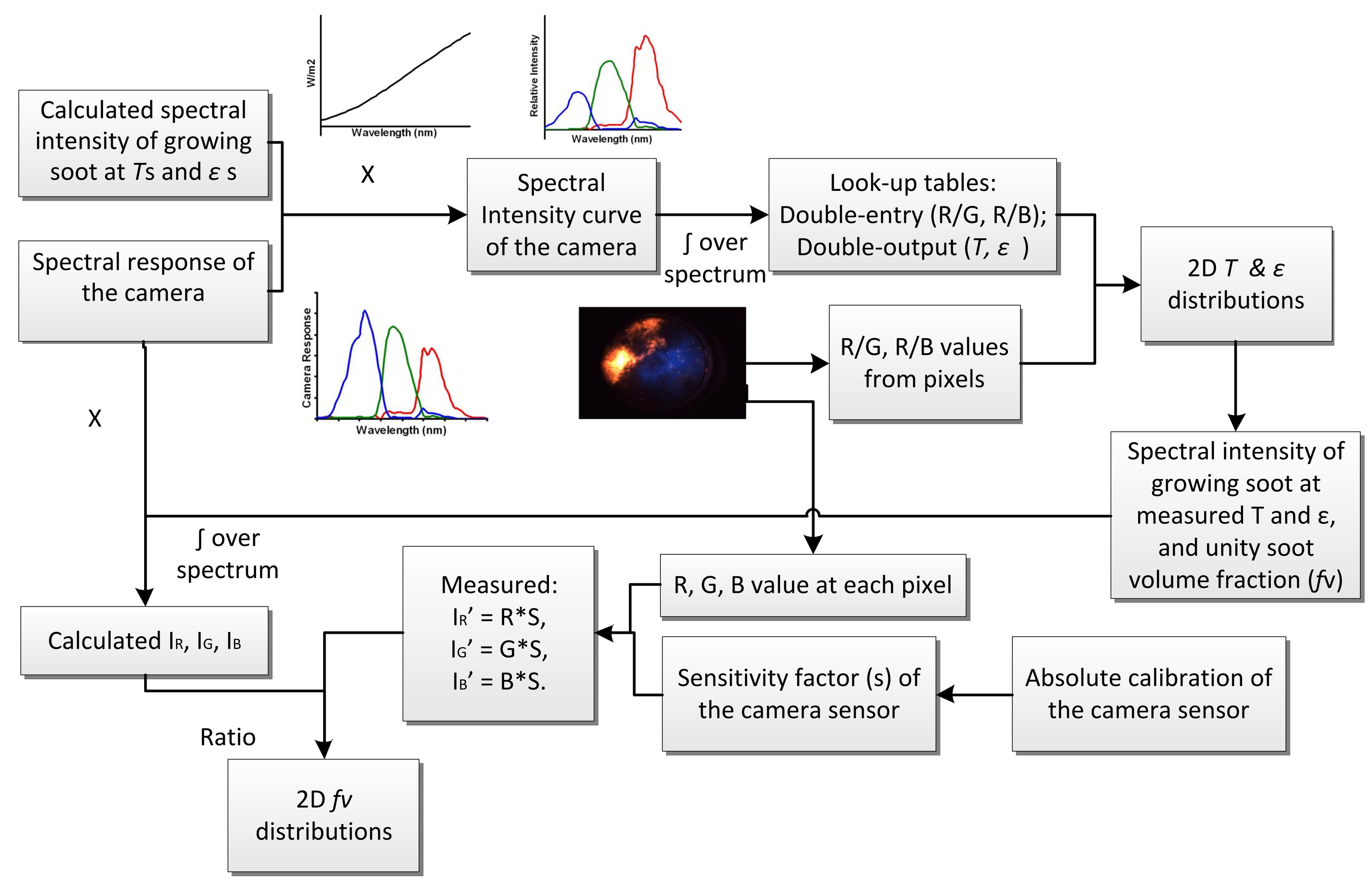


Fig. 2 The strategy for the determination of temperature, soot diameter and soot volume fraction in Three Colour Pyrometry (TCP) by using other scattering models

Cone Beam Tomography – Filtered Backprojection (FBP) alglorithm [2]

Based on Fourier Slice Theory: Fourier Transform (FT) of projections = FT of the field property

Step 1 (projection): Measure the projection data (R_β) and calculate weighted projection (R_β') :

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

Step 2 (Filtering and backprojection): Filtering and backprojecting the calculated projection data from a specific angle:

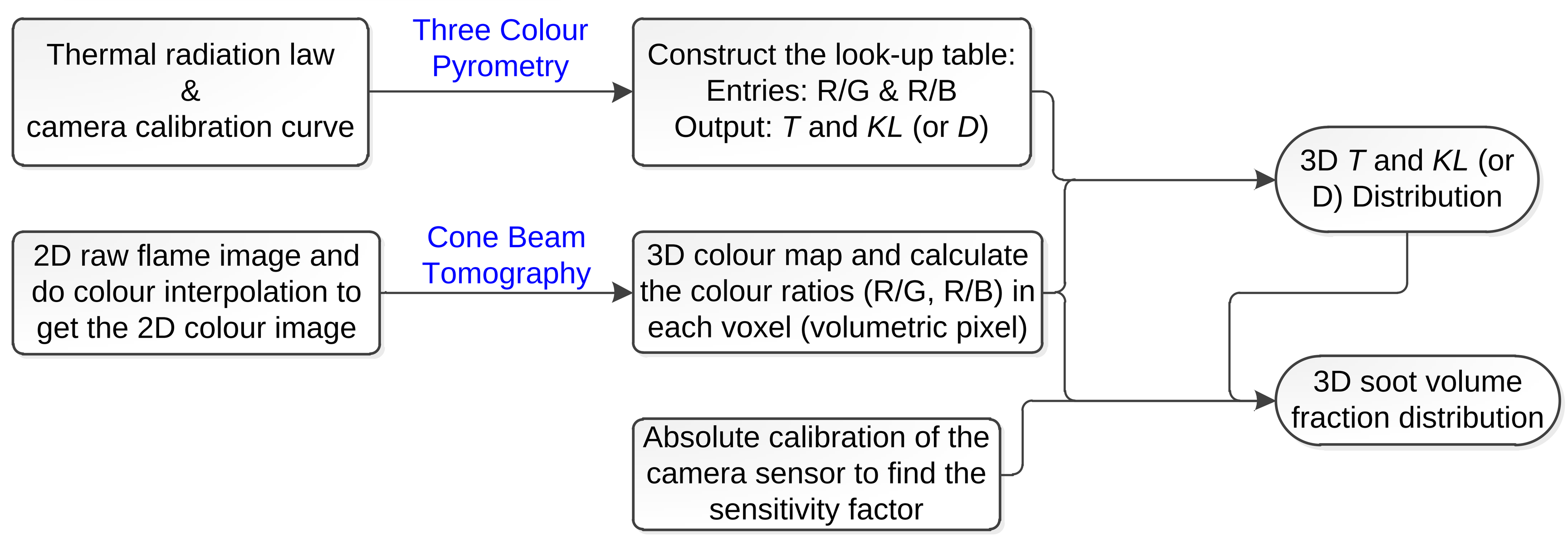
$$Q_\beta(p,\zeta) = \mathrm{IFFT}(\mathrm{FFT}(R'_\beta(p,\zeta)\mathrm{with\ ZP}) \times H(p,\zeta))$$

Where $H(p,\zeta)$ is the product of the weighting function and the window function; IFFT: Inverse Fast FT; and FFT: Fast FT; ZP: Zero Padding

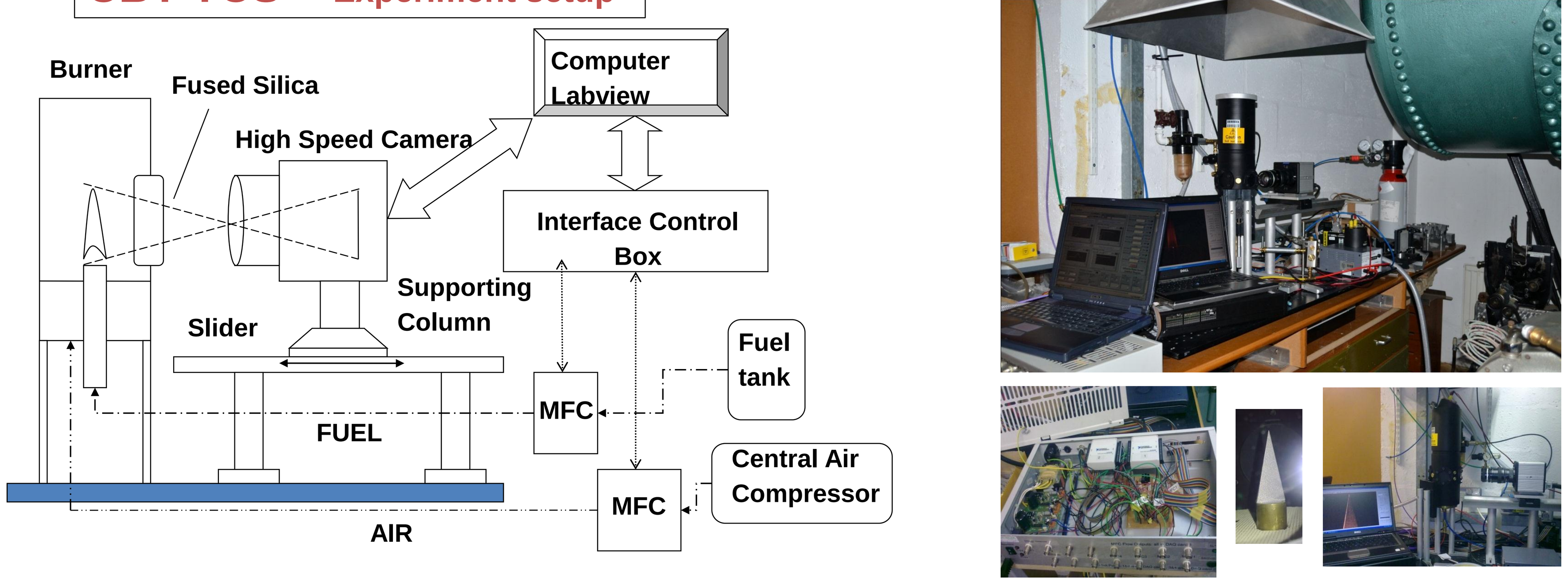
Step 3: Each weighted projection is mapped back to the global coordinates:

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

CBT-TCS --- Strategy

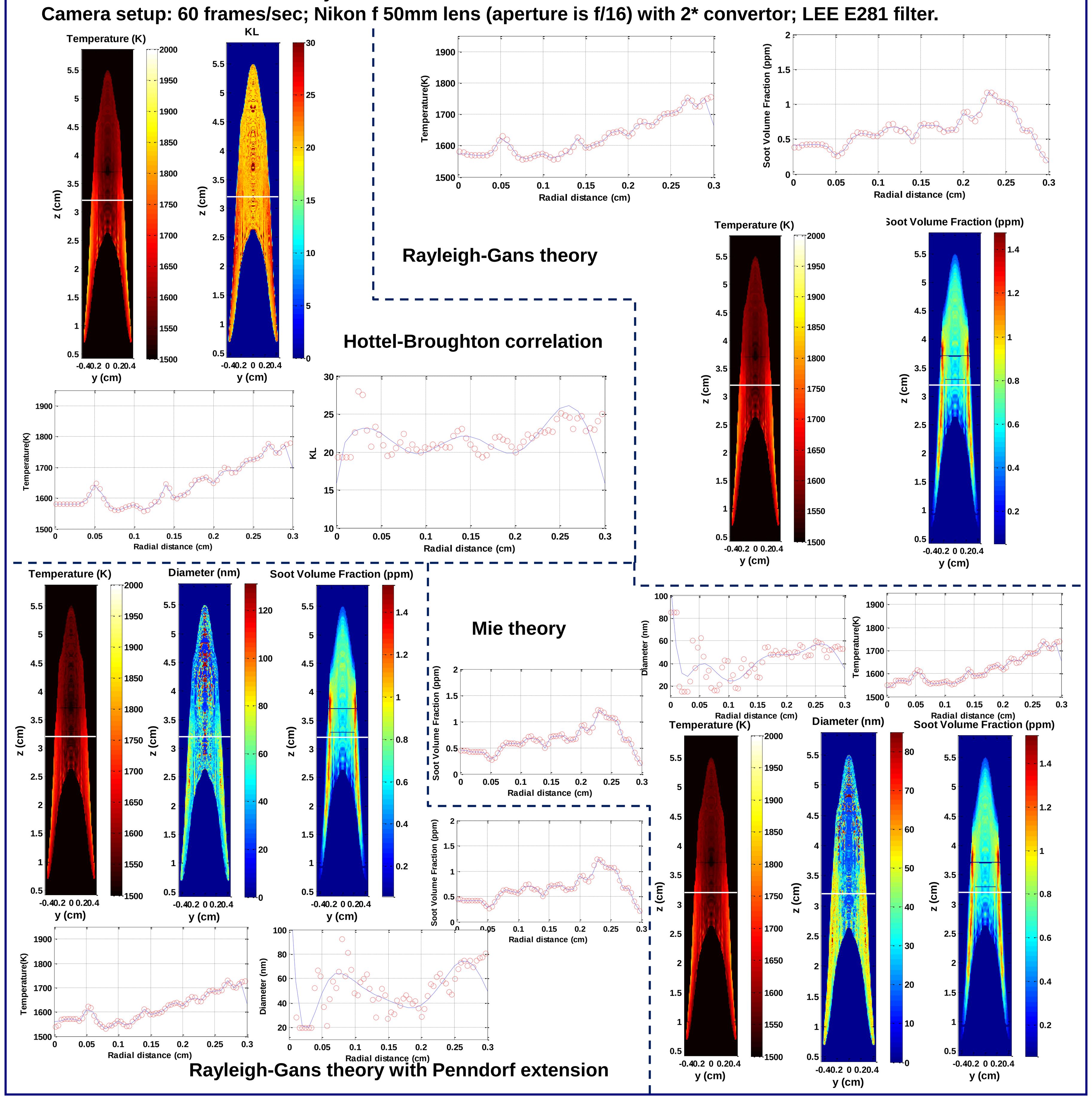


CBT-TCS --- Experiment setup



CBT-TCS --- Sample data

Flow condition: 143 mL/min ethylene + 45 L/min air
Camera setup: 60 frames/sec; Nikon f 50mm lens (aperture is f/16) with 2* convertor; LEE E281 filter.



Conclusions

- Cone beam tomographic three colour spectrometry (CBT-TCS) has been successfully used to measure the spatially distributed temperature, soot diameter and soot volume fraction of an axisymmetric diffusion flame.
- Various techniques, including using a blue filter, downsampling, applying a 3D median filter, and circumferential averaging, can be used to increase the signal to noise ratio and produce a smoother temperature profile.
- To increase the accuracy of the measured data, the optical-thin approximation needs to be addressed more carefully. Moreover, the CBT-CRS technique can also be used to measure the temperature profile within non-axisymmetric flames by recording multiple projections from different angles.

References

[1] R. B. Penndorf, *J. Opt. Soc. Am. A., 52* (1962) 896-902.

[2] L. A. Feldkamp, L. C. Davis, and J. W. Kress, *J. Opt. Soc. Am. A.,* 6 (1984) 612-619.

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