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Measurement of the spatially distributed temperature and soot loadings in a laminar diffusion flame using a Cone-Beam Tomography technique

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ABSTRACT

A new low-cost optical diagnostic technique, called Cone Beam Tomographic Three Colour Spectrometry (CBT-TCS), has been developed to measure the planar distributions of temperature, soot particle size, and soot volume fraction in a co-flow axi-symmetric laminar diffusion flame. The image of a flame is recorded by a colour camera, and then by using colour interpolation and applying a cone beam tomography algorithm, a colour map can be reconstructed that corresponds to a diametral plane. Look-up tables calculated using Planck's law and different scattering models are then employed to deduce the temperature, approximate average soot particle size and soot volume fraction in each voxel (volumetric pixel). A sensitivity analysis of the look-up tables shows that the results have a high temperature resolution but a relatively low soot particle size resolution. The assumptions underlying the technique are discussed in detail. Sample data from an ethylene laminar diffusion flame are compared with data in the literature for similar flames. The comparison shows very consistent temperature and soot volume fraction profiles. Further analysis indicates that the difference seen in comparison with published results are within the measurement uncertainties. This methodology is ready to be applied to measure 3D data by capturing multiple flame images from different angles for non-axisymmetric flame.

1. Introduction

As more and more concerns have been raised about the negative impact of particulate emissions from the combustion of hydrocarbons to human health and the environment, much research has been carried out to investigate the formation mechanisms of the particulates and possible abatement methods. This research is based on the measurement of the combustion environment, especially temperature, and the corresponding soot loadings, including their size and concentration. Amongst different measurement techniques, optical diagnostics have many advantages, including their non-intrusive characteristics and good spatial and temporal resolution.

Non-laser based optical diagnostics of soot can be broadly divided into two groups: emission based measurements and extinction based measurements. The former do not need a light source so are less complicated in their experimental setup and are easy to apply. The emission based measurement techniques are usually based on thermal radiation from the soot particles. The emissivity of such particles can be calculated from a scattering model. Typical scattering models using the assumption of spherical soot particles include the Hottel and Broughton empirical correlation [1] (used in two-colour or three-colour pyrometry), the Rayleigh–Gans (RG) theory (used in

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most single or multiple wavelength soot spectrometry applications) [2], and the Mie scattering theory, which is the analytical solution of Maxwell's equations for scattering by spherical particles [3].

Meanwhile, tomography, which is used to reconstruct a higher dimensional property field based on projections in a lower dimension, has been applied to line-of-sight measurements to obtain spatial resolution along the optical path. Hall and Boncyzk [4] used single wavelength emission-absorption spectrometry to reconstruct the 2D soot concentration and temperature fields in ethylene and iso-octane diffusion flames at specific heights. Snelling et al. [5] extended this work by applying multi-wavelength emission spectrometry to measure the 2D temperature and soot concentration fields and they also discussed the influence of various optical parameters on the accuracy of the experiment. Ayranci et al. [6] proposed a new approach to correct the assumption of a constant refractive index for soot over a certain range of wavelengths when using the RG theory. Lu et al. [7] introduced an iterative method to diminish the error caused by the optically-thin assumption. These researchers have greatly improved the spatial resolution and accuracy of two-dimensional emission spectrometry. Their experiments are all based on the measurement of absolute light intensity, which can be difficult because of the need for a source with an absolute calibration, such as a black body at a known temperature. These experiments also rely on the assumption that the RG theory is valid throughout the whole spectrum, which is not necessarily the case, especially in the visible light region. In addition, two-dimensional tomographic emission spectrometry only gives the temperatures and soot concentration distributions at a specific height in one measurement. Moreover, their measurements do not include any information about the soot particle size.

The technique introduced in this paper, called Cone Beam Tomographic Three Colour Spectrometry (CBT-TCS), is a relatively inexpensive analysis method based on a modified three colour pyrometry approach combined with a 3D cone beam tomography technique. CBT-TCS can be used to measure the temperature and soot diameter distributions without needing an absolute calibration, but the measurement of soot volume fraction does need an absolute intensity calibration. In general this will require multiple views, but in the case of an axi-symmetric flame only one image is needed.

This paper will begin by reviewing selected thermal radiation and scattering theory along with introducing how this is relevant to the CBT-TCS technique. The sensitivity of the technique to changes in temperature and particle size is then assessed numerically. The paper continues by explaining how CBT-TCS is realised, both in terms of apparatus and going into some detail regarding the computer algorithm. Following this is a discussion of any further assumptions related to the technique. Finally, this paper shows results from applying CBT-TCS to a laminar diffusion flame (the Gülder burner [8]), before closing with some conclusions that discuss the strengths and weaknesses of this measurement approach.

2. Theory

The physics of thermal radiation and light scattering by particles are introduced in this section and used as background in the selection of a scattering model to use in CBT-TCS.

2.1. Thermal radiation

The thermal radiation at specific wavelength (I_λ) from a surface as a function of temperature (T) can be calculated from Planck's law, by employing a dimensionless material parameter called emissivity (ε_λ), which is simply the ratio of the emitted radiation to that of a perfect black body source.

Assuming a soot particle is in local thermal equilibrium, Kirchhoff's Law explains that the absorption of the particle must balance its emission, for all wavelengths. In the case that the soot particles' refractive index is known, scattering theory may be used to determine the interaction of radiation with the particle. Scattering theory provides values for the efficiency with which radiation is absorbed, Q_{abs}, and scattered, Q_{scatt}. These contributions are also often summed to form the overall extinction efficiency, Q_{ext}. In order for thermal balance to hold, the emissivity ε_λ of a soot particle can therefore be determined by calculating Q_{abs} since the scattering does not involve any energy transfer [9]. Q_{abs} is generally a function of wavelength, λ, and can be calculated by using different scattering models, which will be discussed in Section 2.2.

Assuming a mono-disperse distribution of independent particles, the spectral radiance of the spherical soot particles (I'_λ, measured in J s^{-1} sr^{-1} m^{-1}) of diameter (d) within a voxel (volumetric pixel) with volume V can be calculated by adopting the following equation:

$$I'_\lambda = \frac{6 f_v V}{d} Q_{abs} I_\lambda(T) \tag{1}$$

where f_v is the soot volume fraction. This mono-disperse assumption (that the soot particles within an individual voxel have the same shape, size and mass) will introduce some errors into the measurements produced by CBT-TCS, depending on the homogeneity of the thermal radiation properties of the soot particles. However, since the voxel size is small (a cube with 46 μm side length), the technique may still track ensemble-averaged properties with good spatial resolution.

2.2. Scattering models

This sub-section discusses scattering models and particle characteristics.

2.2.1. Spherical particles

A solution of Maxwell's equations for scattering from spherical particles was first derived by Mie in 1908 [3]. The mathematical description of absorption efficiency as predicted by Mie theory can be written as

$$Q^M_{abs} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1)(\mathrm{Re}(a_n + b_n) - (|a_n|^2 + |b_n|^2)) \tag{2}$$

where x is the size parameter which is defined as $x = \pi d/\lambda$ (d is the diameter of the particle) and a_n and b_n are scattering coefficients which are functions of the complex refractive index ($m = n - ik$) and the size parameter. Further details such as expansions of a_n and b_n can be found in