Recent Achievements in Measurements of Soot Volume Fraction and Temperatures in a Coflow, Diffuse Ethylene-air Flame by Visible Image Processing

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Abstract. In this review paper, the recent achievements in measurements of soot volume fraction and temperatures in a coflow, diffuse Ethylene-air flame by visible image processing are briefly outlined. For the inverse analysis of the radiative properties and temperatures, different methods show different features. The least-squares method, a regularization method and a linear programming method are all suitable for this problem, and a linear programming method can give more reasonable results. The red, green and blue flame images, which can be captured by some colour CCD camera, can be taken approximately as monochromatic images, and can be used to reconstruct temperature and soot volume fraction. But more ideal is the true monochromatic images filtered by filters at certain wavelengths. Finally, the optically-thin assumption, which is adopted widely, will cause large errors, about 100 K for temperature and 50% for soot volume fraction, as the absorption of the flame medium is neglected.

1. INTRODUCTION
Soot emission from hydrocarbon flames plays an important role in relation to both heat transfer by radiation and air pollution (Haroun et al., 2000). Knowledge about temperature and soot distribution in a flame is essential for gaining fundamental insight into the combustion process. Numerical simulation, capable of predicting the field variables, still requires extensive validation using experimental data. The experimental approach can be divided into two categories (Bhattacharjee, 2000): intrusive probe methods and non-intrusive optical or acoustic methods. The former methods suffer from a relatively large time response in addition to disturbing the combustion reaction. Optical methods utilize emission, absorption, or refraction of light by the burnt gases, or laser interaction such as coherent anti-Stokes Raman scattering (CARS) (Robert et al., 1997) or laser-induced fluorescence (LIF) (Bengtsson, 1996), while the acoustic method exploits the transit time of sound (Passechnik et al., 1996).

Lasor Induced Incandescence (LII) is a newly developing method to measure the soot volume fraction and its size distributions in flames by more and more researchers and institutes (Schulz et al., 2006). Schulz et al. (2006) presents controversial topics and areas of disagreement identified in the comparison of different models and measurement approaches. Despite extensive application of LII to many practical diagnostics problems and development of commercial instruments for routine implementation of LII, these comparisons demonstrate significant shortcomings in the fundamental understanding of LII and, hence, in the interpretation of measurement results (Schulz et al., 2006).

Most of these methods, however, require radiation sources, which restricts the measurement environment (Bhattacharjee, 2000). They are also subject to interference from background radiation.
Two-color emission pyrometry (di Stasio et al., 1994; Iuliis et al., 1998; Panagiotpu et al., 1996) is widely used in practical situations, especially for studies in internal combustion engines. It readily allows the estimation of averaged values of soot volume fraction and temperature. The reliability of the data depends on the calibration procedure and knowledge of the index of refraction. But this method is mostly used in strictly controlled flames with uniform flames.

For non-uniform flames, Liu et al (2003) presented a multi-wavelength inversion method to reconstruct the temperature distribution in non-axisymmetric turbulent unconfined sooting flame by the multi-wavelength measured data of outgoing emission and transmission radiation intensities. Since the additional laser light should be adopted in this method, it is undesirable for practical applications, such as large-scale furnaces, diesel engines.

An improved Tikhonov regularization method with radiation energy images detected from the boundary of the furnace to reconstruct the temperature distribution, absorptivity of wall surface and absorption coefficient of medium in a 2-D furnace system with a gray medium has been simulated (Zhou et al., 2000; Zhou et al., 2002; Zhou et al., 2003). The combustion monitoring technologies based on flame image processing are now showing more and more attractive potential for on-line monitoring of combustion in large-scale furnaces. Recently, much work has been made in this filed by the authors (Zhou, 2005; Zhou et al., 2005; Lou et al., 2007), including two papers presented in the recent International Symposiums on Combustion (Zhou et al., 2005; Lou et al., 2007). The issues related to the online visualization of 2-D/3-D temperature distributions in large-scale furnaces by flame image processing, including radiative image formation models and reconstruction methods of temperature distributions, the experiments of visualization of 2-D/3-D temperature distributions in coal-fired boiler furnaces in several power plants, and the application of the radiative energy information got from the monitoring system into the combustion and load control of boiler-turbine unit, was reviewed in detail (Zhou et al., 2007).

In this paper, the theories for the flame image processing and the reconstruction of the temperature and soot volume fraction distributions in a coflow, diffuse Ethylene-air flame will be briefly introduced. Then, experiments carried out to get the radiative properties, temperatures and soot volume fraction of the flame will be outlined. Finally, some concluding remarks will be given.

2. THEORIES AND SIMULATION

For the reconstruction of temperature and soot volume fraction distributions inside a non-uniform sooting flame, good selection of inverse algorithms is a key step to get desirable results. Different inverse algorithms and their features in reconstruction of temperatures and soot volume fraction have been studied by simulations (Ai et al., 2005; Zhou et al., 2007). This is a fundamental work for analysis of experimental images and data.

2.1 Simulation on Simultaneous Reconstruction

An absorbing, emitting, non-scattering, axisymmetric sooting flame was studied (Ai et al., 2005). As shown in Fig. 1, the radiation intensities received by CCD camera were simulated for the inverse analysis. The radiation intensity of flame received by the line of sight can be expressed as:

\[ I_\lambda (j) = \int_{l_{\lambda}(j)}^{l_{\lambda}(j)} \kappa_\lambda (l) I_{\text{bd}} (l) \exp \left[ -\int_{l}^{l_{\lambda}(j)} \kappa_\lambda (l') dl' \right] dl \] (1)

where \( \kappa_\lambda \) is the spectral absorption coefficient, given by Rayleigh limit of the Mie theory:

\[ \kappa_\lambda (l) = \frac{36\pi F (\lambda)}{\lambda} f_{\text{r}} (l) \] (2)

where \( F (\lambda) \) is a function of the real and imaginary parts of the refractive index:

\[ F (\lambda) = \frac{1}{6} \text{Im} \left[ \frac{m^2 - 1}{m^2 + 2} \right] = \frac{nk}{(n^2 - k^2 + 2)^2 + 4n^2k^2} \] (3)
Fig. 1 Geometry in a cross section of the axisymmetric flame

Fig. 2 The temperatures estimated from noised measurement of intensity compared with the preset temperatures.

$I_{b\lambda}$ is the spectral radiation intensity of blackbody, given by Planck’s formula:

$$I_{b\lambda}(l) = \frac{C_1 \lambda^{-5}}{\pi \left( e^{C_2/(\lambda l(l))} - 1 \right)}$$  \hspace{1cm} (4)

where $C_1$ and $C_2$ are blackbody radiation constants, $\lambda$ is the wavelength.

According to the radiation energy image received by CCD, we could obtain three monochromatic intensity at three wavelengths, $R$(red), $G$(green), $B$(Blue). When the profiles of soot temperature and volume fraction were known, they could be estimated by Eq. (1). Using a Newton-type iteration algorithm and the least-squares method, simultaneous estimation of temperature and soot volume fraction in the flame was conducted. A factor is introduced to balance the magnitude difference between the radiation intensities received by different region of CCD. The effects of different temperature and soot concentration distributions and measurement errors were investigated. The result shown in Fig. 2 shows that the simultaneous estimation method have enough accuracy with various distributions and different measurement error. As shown in Fig. 2, the large deviation in the flame center is caused by the non-invasive detect technique which only provides accumulation intensity data in the measured lines. If the low temperature zone locates inside the center of the flame, which emits low radiation, it is hard to detect the temperature from the accumulation radiation measured from outside.

2.2 Inverse Methods for Optically-thin Flame Medium

In most studies of flame emission tomography, the diffuse Ethylene-air flame is taken as optically-thin medium (Ayranci, 2008). In this case, the intensity in Eq. (1) is simplified as

$$I_{\lambda,\lambda}(l) \approx \int_{l_\lambda(l)}^{l_\lambda(l)} H_{\lambda}(l) d\lambda$$  \hspace{1cm} (5)

After being discretized, the equation above is transformed into a matrix equation as (Zhou et al., 2007)

$$AH = I$$  \hspace{1cm} (6)

Basing on the monochromatic radiation intensity images, a least-squares method, a regularization method (Zhou et al., 2002) and a linear programming method (Zhou et al., 2000b) were separately used to solve the inverse problem of radiative transfer equation for the axisymmetric optically-thin flame (Zhou et al., 2007). In this study, the central wavelength of the filter is 690 $\lambda m$, the mass flow rates of Ethylene and air are 100 (ml/min), and 112 (l/min), respectively. The diameter of the flame is about 1 cm, and its height is about 2.3 cm. Three typical cross sections at different heights of the flame are measured, which locate in the bottom, the center and the top parts of the flame. The results are
shown in Fig. 3. From the results it can be seen that all the three methods can reveal the main features of the flame.

![Graph](a)

![Graph](b)

**Fig. 3** Reconstruction of $H$ profiles by the three methods (a) and enlarged display in the local area of the flame center (b). C: least-squares method; A: regularization method; B: linear programming method.

From Fig. 3b it is also very obvious that significant errors occur at the center part of the flame, where the emittance is relatively low in this case. Among these three methods, the linear programming method both having the characteristics of lubricity and restriction and is the best appropriate method compared with the other two methods for the region of axisymmetric flame where has a relatively low temperature core. For the least square method, the intensity will be negative at some points, which is not reasonable. For the regularization method, the smoothness is better than that by the least square method, but the negative data still occur.

3. EXPERIMENTS AND ANALYSIS

Generally, there are two main methods to conduct measurements of temperature and soot volume fraction inside a flame using visible radiation image processing, one using directly the colour images (Ai et al., 2006), and the other using monochromatic radiation images. For the first method, the colour images are always taken as approximately monochromatic images with representative wavelengths for Red (R), Green (G) and Blue (B) images. In this case, the bands of the image sensors (generally with CCD cameras) for the different monochromatic images are not so narrow in order to get strictly monochromatic images, and errors will be included.

3.1 Measurements by Colour Flame Image Processing

A new emission CT method was used to estimate temperatures and soot volume fractions simultaneously in laminar ethylene flames from the monochromatic radiation intensity images captured by a colour flame image detector (Ai et al., 2006). Fig. 4 shows the four flame images captured in different conditions. For the first flame image which was captured at the smallest mass flow rate of ethylene, the intensity images from red and green monochromatic images, and the temperature and the soot volume fraction images are all shown in Fig. 5. It can be seen that the zone with the greater soot concentration lies inside the higher flame temperature zones in the flame, both inside the flame front and outside the flame axis. In addition, with the fuel flow rate increasing, the amount of soot in the flame increases, thus increasing radiation losses. This, in turn, causes a lower flame temperature.
3.2 Measurements by Monochromatic Flame Image Processing

As radiative flame images from soot in the laminar diffusion flame were captured by the Samsung SCC-833P CCD camera, a red interferometric filter (10 nm FWHM, 20% transmissivity) was placed between the lens and CCD sensor in order to capture monochromatic radiative images (Lou et al., 2008). In the experiment, two kinds of filter with different wavelength of 600 nm and 618 nm were used. The camera had a 1/3" interline-transfer CCD sensor (type S-HAD) with a resolution of 752(H) × 582(V) pixel elements. The electronic shutter of the camera is set as 1/5000 s⁻¹. Dedicated application software developed by the authors was used to process monochromatic flame images and to calculate the distributions of soot temperature and volume fraction.

Three different cases of the diffusion flame were generated with air and fuel (ethylene) flow rates of 94 l/min and 64 ml/min (case 1), 142 l/min and 97 ml/min (case 2), and 189 l/min and 129 ml/min (case 3), respectively.

Fig. 6 shows the monochromatic flame images captured by the CCD camera in the three cases at the wavelengths of 600 nm (a) and 618 nm (b), respectively. The corresponding monochromatic radiative intensity images of 600 nm and 618 nm calculated by image processing are given in Fig. 7. The flame
temperature images and emissivity images calculated by image processing in the three cases are given in Fig. 8.

![Representative flame images at the wavelength of 600 nm (a) and 618 nm (b), respectively.](image)

Fig. 6

The distributions of soot temperature and volume fraction in three cases have been reconstructed simultaneously, and the results are shown in Fig. 9. It should be mentioned that, at the bottom of the flame (5 mm above the burner), there is no radiation received from center region of flame and it is hard for the reconstruction of soot temperature. The radiation imaging model will be improved in the near future. The maximum soot volume fraction shown in Fig. 7(b) is nearly 5 ppm, which is similar to that given in [Iuliis, S. D. et al (1998)]. The maximum temperature in the flame is about 2000 K, which has been reported in literature. From Fig. 9, it can also be seen that, with the increase of the fuel flow rate the soot volume fraction in the flame also increases. In addition, as the fuel mole fraction increases, the location of peak soot shifts from the center of the flame to the edge of the flame. This movement of location of the peak soot is like that mentioned in [M.D. Smooke, M. D. et al (2005)]. Besides that, the experimental results indicated that much more soot lies inside the flame zone with higher temperatures, which was also measured in [Snelling, 2002].

![Monochromatic radiative intensity images (W/m²/sr) in the three cases at the wavelength of 600 nm (a) and 618 nm (b), respectively.](image)

Fig. 7
3.3 Effects of Absorption of Medium on Reconstruction

With the reconstruction results for temperature and soot volume fraction with the optically-thin assumption of the medium as a initial guess, the absorption of the medium on the reconstruction can be considered in the inverse analysis procedure. Without optically-thin assumption, 

\[ I_\lambda(j) = \int_{l_\lambda(j)}^{l_{\lambda(j)}} H_\lambda(l) \cdot \exp[-\int_{l'}^{l_{\lambda(j)}} \kappa_\lambda(l')dl'] dl' \]  

(7)

Compared with Eq. (5), the term \( \exp[-\int_{l'}^{l_{\lambda(j)}} \kappa_\lambda(l')dl'] \) in Eq. (7) can be taken as a compensation factor term, which can be updated from the initial guess of soot volume fraction. Then, Eq. (7) can be solved by the same method, and an updated results for the temperature and the soot volume fraction can be got. After three times of iteration, the convergence can be achieved in calculation.

Fig. 9 The calculated distributions of soot temperature (K) (a) and volume fraction (ppm) (b) in the three cases, respectively.
Fig. 10 Temperatures (a, c, e) and soot volume fraction (b, d, f) in three cross sections at the top (a, b), middle (c, d) and bottom (e, f) parts of the flame. 1: the initial guess with optically-thin assumption; 3: converged results three times of iteration without optically-thin assumption.
From Fig. 10 it can be seen that the temperatures close to the edges of the flame will keep unchanged even if the optically-thin assumption is given up. But the temperatures at the center of the flame change significantly, and the peak temperature will increase about 100 K. Consequently, the peak concentration of the soot decreases about 1 ppm, which should be taken into account.

4. CONCLUSIONS
In this review paper, the recent achievements in measurements of soot volume fraction and temperatures in a coflow, diffuse Ethylene-air flame by visible image processing are briefly outlined. For the inverse analysis of the radiative properties and temperatures, different methods show different features. The least-squares method, a regularization method and a linear programming method are all suitable for this problem, and a linear programming method can give more reasonable results. The red, green and blue flame images, which can be captured by some colour CCD camera, can be taken approximately as monochromatic images, and can be used to reconstruct temperature and soot volume fraction. But more ideal is the true monochromatic images filtered by filters at certain wavelengths. Finally, the optically-thin assumption, which is adopted widely, will cause large errors, about 100 K for temperature and 50% for soot volume fraction, as the absorption of the flame medium is neglected.

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NOMENCLATURE

| Symbol | Description | Unit |
|--------|-------------|------|
| I, l, d | radiation intensity | W/m²/sr |
| f_s | soot volume fraction | ppm |
| m | real part of the refractive index | / |
| n | imaginary of the refractive index | / |
| T | temperature | K |
| κ | absorption coefficient | m⁻¹ |
| λ | wavelength | nm |
| b | black body | |

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