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Two-step tomographic reconstructions of temperature and species concentration in a flame based on laser absorption measurements with a rotation platform

Huihui Xia[a,b], Ruifeng Kan[a,*], Zhenyu Xu[a], Yabai He[a], Jianguo Liu[a], Bing Chen[a], Chenguang Yang[a], Lu Yao[a], Min Wei[a,b], Guangle Zhang[a]

[a] Key Lab of Environmental Optics and Technology, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Science, Hefei 230031, China
[b] University of Science and Technology of China, Hefei 230022, China

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ABSTRACT

We present a system for accurate tomographic reconstruction of the combustion temperature and H_2O vapor concentration of a flame based on laser absorption measurements, in combination with an innovative two-step algebraic reconstruction technique. A total of 11 collimated laser beams generated from outputs of fiber-coupled diode lasers formed a two-dimensional 5×6 orthogonal beam grids and measured at two H_2O absorption transitions (7154.354/7154.353 cm^{-1} and 7467.769 cm^{-1}). The measurement system was designed on a rotation platform to achieve a two-folder improvement in spatial resolution. Numerical simulation showed that the proposed two-step algebraic reconstruction technique for temperature and concentration, respectively, greatly improved the reconstruction accuracy of species concentration when compared with a traditional calculation. Experimental results demonstrated the good performances of the measurement system and the two-step reconstruction technique for applications such as flame monitoring and combustion diagnosis.

1. Introduction

Measurements of temperature and species concentration are extremely meaningful for both combustion efficiency evaluation and energy conservation. Over past decades, tunable diode laser absorption spectroscopy (TDLAS) has become a major diagnostic technique for combustion systems due to its advantages of fast response, high sensitivity, strong resistance to interference, unique spectrum-selectivity, capability of measuring both scalar and vector flow parameters, such as temperature and velocity [1,2]. TDLAS usually falls into two categories: direct absorption spectroscopy (DAS) and wavelength modulation spectroscopy (WMS), which are applicable for strong absorption and weak absorption, respectively. Generally, traditional TDLAS is restricted to measure the average absorption information since it is a line-of-sight (LOS) measurement technique, while the temperature and concentration among combustion area are usually non-uniform. In order to obtain an inside characterization of a specific combustion environment, one approach is to scan multiple absorption lines at a certain LOS path so as to get one-dimensional temperature probability distribution along the beam path [3–5], but without the ability to determine the corresponding locations. Another way is tunable diode laser absorption tomography (TDLAT), which actually combines TDLAS with computed tomography (CT) to detect spatially-resolved distributions. TDLAT can be roughly divided into two categories in terms of reconstruction algorithm: transform-based reconstruction, of which the representative strategy is the filtered back projection (FBP) algorithm, which needs a large amount of projection data for accurate reconstruction. Therefore, many research activities have been based on numerical studies [6,7]. The other method is finite series expansion technique, for example, the algebraic reconstruction technique (ART); as a classical iterative method, ART has been widely used in practical engineering for 2D distribution determination of temperature and concentration because of its better capability in cases of incomplete projection data [8–12]. Kasyutich et al. reconstructed a non-axisymmetric temperature distribution with a scanning mirror mounted on a moveable carriage based on the ART algorithm [8]. Wang et al. retrieved simultaneously flame temperature and H_2O concentration distributions by 24 laser-beam absorption signals acquired from different angles [9]. Song et al. proposed a virtual ray method combined with reconstruction algorithms to improve the accuracy of reconstruction results for symmetric and non-axisymmetric temperature distributions [10]. Ning et al. developed a modified

* Corresponding author.
E-mail address: kanruifeng@aiofm.ac.cn (R. Kan).

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adaptive algebraic reconstruction technique (MAART) with an auto-adjustment relaxation parameter and smoothness regularization to reveal the tomographic reconstruction of H_2O concentration distributions from incomplete projections [11]. Liu et al. employed a single view fan-beam scanning geometrical structure for measuring axisymmetric temperature distribution by using ART algorithm [12]. The efforts to measure temperature as mentioned above mainly relied on two-line absorption ratio measurements. On the contrary, a new approach called multi-spectral absorption tomography (MAT) was established to conduct optimal reconstruction by scanned dozens or even hundreds of spectral absorption lines [13–15]. Obviously, complex calculations are needed when implementing this type hyper-spectral tomography. As WMS enjoys some significant advantages compared to DAS, Cai and Liu combined WMS with DAS for the simultaneous imaging of temperature and species concentration in harsh combustion environments [16,17]. Other research groups have considered the effect of the optical components layout on reconstruction accuracy [18–20], aiming to reduce the number of beams and the complexity of optical systems.

In the past, most reported research works were concentrated on reconstruction of temperature, whereas the reconstruction of species concentrations was less accurate using the traditional method [7].

This work aims to propose a two-step approach for the tomographic reconstructions of temperature and species concentration. In a first step, the temperature distribution was reconstructed; then in a second step, the species concentration was constructed to achieve improved accuracy. The modified-ART algorithm [11] was used in both the reconstruction processes. The improvement in accuracy of concentration was achieved by determining them via a global fitting process instead of based on local temperatures and absorption coefficients.

Spatial resolution of a reconstructed image has been limited by the number of available measurement laser beams. The more measurement laser beams passing through the combustion area, the higher spatial resolution and reconstruction accuracy. In a practice, the installation of numerous optical sensors was limited by available space and associated cost and system complexity. However, we designed a novel rotary measurement platform to achieve a two-fold enhancement in spatial resolution with a simple 90° rotation of the measurement platform. Temperature information was inferred by TDLAS measurements of temperature-dependent absorptions at two H_2O absorption wavelengths at 1339 nm and 1398 nm, respectively. Integrated absorbances were determined by applying a fast Voigt line-shape fitting technique [21].

The reported system in this paper can be very useful for 2D combustion diagnostics including non-uniform flames. In the following Sections 2,–4, theoretical background and numerical simulations will be introduced, whereas the experimental setup and results will be presented in Sections 5 and 6, respectively.

2. Theoretical principle

This section provides a brief summary of the theories of 2D temperature measurements based on the direct laser absorption spectroscopy and computed tomography.

2.1. Theory of absorption spectroscopy

When a collimated laser beam of frequency v [cm^{-1}] passes through a medium with a total path length L [cm], the relationship between the transmitted and the incident intensity of the radiation is described by the Beer-Lambert law as:

$$I_t(v) = I_0(v)\exp\left(-\int_0^L P(l)X(l)S_{vi}(T(l))\phi(v)\mathrm{d}l\right) \tag{1}$$

where $I_t(v)$ and $I_0(v)$ are transmitted and incident laser intensities, respectively; $P(l)$ [atm], $X(l)$ and $T(l)$ [K] are the local total pressure, mole fraction and temperature of the absorbing species at position l along the beam path, respectively; $\phi(v)$ is a normalized line-shape function, so that $\int_{-\infty}^{+\infty}\phi(v)dv = 1$; The line strength $S_{vi}(T(l))$ [$cm^{-2}\,atm^{-1}$] of a transition with center frequency v_i [cm^{-1}] is a function of the local temperature T as follows:

$$S_{vi}(T) = S_{vi}(T_0)\frac{T_0}{T}\frac{Q(T_0)}{Q(T)}\frac{\exp(-hcE_{vi}''/kT)}{\exp(-hcE_{vi}''/kT_0)}\frac{1-\exp(-hcv_i/kT)}{1-\exp(-hcv_i/kT_0)} \tag{2}$$

where h [J s] is the Planck's constant; c [$cm\ s^{-1}$] is the speed of light; k [$J\ K^{-1}$] is the Boltzmann's constant; $Q(T)$ is the partition function of the absorbing molecules [22]; T_0 is a reference temperature (usually 296 K); E_{vi}'' [cm^{-1}] is the lower state energy of the transition. The factor T_0/T in Eq. (2) is a correction for number density of molecules which is inversely proportional to temperature, because the line strength S here is expressed in units of [$cm^{-2}\,atm^{-1}$], instead of that for individual molecules.

The integrated absorbance can be inferred from Eq. (1) as:

$$A_{vi} = \int \ln(I_0(v)/I_t(v))\mathrm{d}v = \int_0^L P(l)X(l)S_{vi}(T(l))\mathrm{d}l = \int_0^L \alpha_{vi}(l)\mathrm{d}l \tag{3}$$

where the integrated absorption coefficient $\alpha_{vi}(l)$ at coordinate position l is defined as:

$$\alpha_{vi}(l) = P(l)X(l)S_{vi}(T(l)) \tag{4}$$

For typical combustion environments, the line-shape function $\phi(v)$ is usually given by the Voigt profile $\phi_V(v)$, which is the spectral line shape resulting from the convolution of Lorentz and Doppler broadening mechanisms [23]:

$$\phi_V(v) = \frac{2}{w_G}\sqrt{\frac{\ln 2}{\pi}}\frac{a}{\pi}\int_{-\infty}^{+\infty}\frac{\exp(-y^2)}{a^2+(w-y)^2}\mathrm{d}y \tag{5}$$

where the parameter $a = (\sqrt{\ln 2}/w_G)w_L$, variable $w = (2\sqrt{\ln 2}/w_G)(v - v_i)$, and the integral variable $y = (2\sqrt{\ln 2}/w_G)u$. w_G is the Gauss full width at half maximum (FWHM), and w_L is the Lorentz FWHM, and v_i is a line center frequency.

2.2. Tomographic image reconstruction

In order to get 2D distributions of temperature and gas concentration, the region of interest (ROI) is discretized into J (J=M×N) grids, where the gas parameters such as temperature, pressure and species concentration within each grid region are assumed to be uniform. In this paper, the 2D grids coordinate will be labeled by a pair of x-y indices (m,n). When laser beam i passes through the ROI, the integrated absorbance of transition v_i can be written in a discretization expression as:

$$A_{vi,i} = \sum_{n=1}^{N}\sum_{m=1}^{M}[PXS(T)]_{vi,(m,n)}L_{i,(m,n)} = \sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{vi,(m,n)}L_{i,(m,n)},\quad (i = 1, 2, 3, \dots, I) \tag{6}$$

where i is the index of the laser beam; and I is the total number of laser beams for ROI. m and n are the indices of the row and column of the 2D grid with a size of M×N. $L_{i,(m,n)}$, called weight coefficients, is the geometrical path length of the i-th laser beam passing through the area of grid (m,n). For a general laser-beam-path arrangement, $L_{i,(m,n)}$ can be calculated by a simple and fast algorithm [24]. Generally, Eq. (6) can be compactly rewritten in matrix expression:

$$\begin{pmatrix} A_{vi,1}\\ A_{vi,2}\\ \vdots\\ A_{vi,i}\\ \vdots\\ A_{vi,I}\end{pmatrix} = \begin{pmatrix} L_{1,(1,1)} & L_{1,(1,2)} & \cdots & L_{1,(m,n)} & \cdots & L_{1,(M,N)}\\ L_{2,(1,1)} & L_{2,(1,2)} & \cdots & L_{2,(m,n)} & \cdots & L_{2,(M,N)}\\ \vdots & \vdots & \vdots & \vdots & & \vdots\\ L_{i,(1,1)} & L_{i,(1,2)} & \cdots & L_{i,(m,n)} & \cdots & L_{i,(M,N)}\\ \vdots & \vdots & \vdots & \vdots & & \vdots\\ L_{I,(1,1)} & L_{I,(1,2)} & \cdots & L_{I,(m,n)} & \cdots & L_{I,(M,N)}\end{pmatrix} \times \begin{pmatrix}\alpha_{vi,(1,1)}\\ \alpha_{vi,(1,2)}\\ \vdots\\ \alpha_{vi,(m,n)}\\ \vdots\\ \alpha_{vi,(M,N)}\end{pmatrix} \tag{7}$$