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Numerical study of two-dimensional water vapor concentration and temperature distribution of combustion zones using tunable diode laser absorption tomography

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HIGHLIGHTS

- We realize temperature and concentration reconstruction of combustion zones simultaneously.
- We propose small amount of ray reconstruction techniques in combustion diagnosis.
- High density of parallel rays scanning geometry might improve the reconstruction accuracy.
- We put forward a grid partition technique in order to obtain accurate reconstruction results.

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ABSTRACT

The principle of gas temperature and concentration measurement based on Tunable Diode Laser Absorption Spectroscopy (TDLAS) is introduced. Combining Computed Tomography (CT) with TDLAS, herein referred to as Tunable Diode Laser Absorption Tomography (TDLAT), reconstructs temperature and concentration distribution which are assumed as Gaussian function or paraboloid function. A pair of water absorption lines (7153.722 cm^{-1} and 7153.748 cm^{-1} and 7154.354 cm^{-1}) is selected to measure temperature by means of two-line technique. Radon transform is used to calculate projections of different path for reconstructing temperature distribution based on filtered backprojection algorithm. With a general normalization process, water vapor concentration distribution can be obtained simultaneously. The reconstruction results agree well with the original model. In consideration of laboratory verification and experimental condition, the TDLAT data consist of 13 projection angles and 11 parallel rays at each angle is discussed in this article, obtaining distribution map with a resolution of 20×20. Although the reconstruction value of the edge deviates a little from the original parameters, this method achieves relatively satisfactory outcome in general. The reconstruction error roughly increases with decreasing projection angles and parallel rays, additionally, the reconstruction accuracy is more dependent on the parallel ray number at each angle than the projection angle number. Appropriate grid partition is also important in reconstruction study, the optimal grid partition is 30×30 or near this magnitude when the system contains totally 18 projection angles and 27 parallel rays at each angle. This work proposes a feasible formula for reconstruction research with a small amount of projections and rays, theoretically, laying a foundation for experimental validation in the future.

1. Introduction

Tunable Diode Laser Absorption Spectroscopy (TDLAS) is a non-intrusive, high sensitivity, interference immunity measurement technique for determining temperature, species concentration, velocity, pressure and other gas-dynamic properties in different gaseous environment [1–3]. TDLAS can be roughly divided into two categories in terms of laser operation and signal detection: direct absorption (DA) spectroscopy and wavelength modulation spectroscopy with second harmonic detection (WMS-2f), which have become two of the most important research methods in combustion diagnosis in recent years [4–7]. Traditional infrared TDLAS is a path averaged one-dimensional line-of-sight

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measurement of fluid properties made along the optical path of the laser, the measured value represents an integrated absorbance along that path, while the temperature and concentration among combustion area are usually non-uniform; therefore, it is essential to develop a two-dimensional reconstruction technique based on computer tomography for the determination of spatially resolved parameters. Some researchers have conducted plenty of theoretical and experimental study toward combustion diagnosis. Reynaldo Villarreal and Philip L. Varghese used a rapid tomographic inversion algorithm to facilitate the reconstructions of temperature and CO_2 mole fraction in an axisymmetric atmospheric pressure flat-flame burner, the procedure showed the advantage of reconstructing detailed spectra at each radial node [8]. Avishek Guha and Ingmar Schoegl explored the performance of tomographic reconstructions of water vapor concentration and temperature radial distribution from wavelength-modulated TDLAS measurements within the plume of an axisymmetric McKenna burner by using Tikhonov regularized Abel inversion, which validated the technique as a viable diagnostic tool for flame measurements [9]. At the University of Virginia, Martin et al. simulated and analyzed the reconstruction of spectroscopic measurements for a scramjet wind tunnel whose projection was created by the fan beam function in the MATLAB Image Processing Toolbox, results showed that TDLAT data collection time can be significantly reduced while maintaining reconstruction accuracy by taking fewer projections with a high density of rays [10]. Bryner et al. employed an optical system allows the emitter and detector to be housed in the same instrument to obtain collected data for this study consists of 1725 integrated line-of-sight measurements, from which the reconstructed spectra were calculated by filtered backprojection algorithm; however, they have not given temperature and concentration distribution yet [11]. Christopher et al. reconstructed a numerical phantom of 30×30 grids using the ML-EM algorithm from 259 simulated line-of-sight measurements taken in different positions, the reconstruction percent error is 11.7% [12]. Wang et al. realized 400 rays evenly scattered in 4 different fan scanning positions by the way of rotating laser transmitter [13]. Fei et al. designed a set of TDLAT system with 6 parallel rays which were arranged in different positions, they reconstructed the temperature and concentration distribution of scramjet combustor exit using algebraic reconstruction technique (ART) [14]. Twynstra and Daun considered the effect of the optical components' layout on reconstruction accuracy by simulating laser-absorption tomography experiment, they obtained optimal beam arrangements using a genetic algorithm, which produced more accurate reconstructions compared to other beam arrangements presented in the literature [15]. The efforts above predominantly relied on the use of one or two wavelengths, on the contrary, a new method called multispectral absorption tomography (MAT), which greatly facilitated the practical implementation and application of the tomography technique, has been proposed to obtain simultaneous tomographic images of temperature and species concentration [16–18].

Generally speaking, TDLAT is still in the development stage, most research institutes devote to the measurement of single optical path system rather than two-dimensional reconstruction. Even though some researchers have performed relevant work for reconstructing distribution, especially focused on numerical and simulated study [19,20,26], however, a large number of rays increase the difficulty of data reduction, the complexity of machine structure, and the detention of data acquisition time, in this paper we use radon transform to reconstruct 61×61 temperature and water vapor concentration image matrix simultaneously with default rays of radon function at first, then we realized relatively high-resolution reconstruction with a scanning mechanism of 13 projection angles and 11 parallel rays at each angle using filtered backprojection algorithm, achieving a 20×20 grid distribution of temperature and concentration, optical mechanism of 13 projection angles and 11 parallel rays at each angle can be implemented by rotating platform and optic fiber splitter in the future. We also found that grid partition of reconstruction area has no relationship with ray number and beam arrangements, but there was an optimal selection of grid partition for specific parallel ray and projection angle layout. The results of this study make the TDLAT technique a promising application for combustion diagnosis.

2. Theory

The two-dimensional spatial reconstruction of temperature and species concentration takes part in two steps: absorption spectroscopy and tomographic reconstruction.

2.1. Absorption spectroscopy

The relationship between the transmitted and incident intensity of radiation that has passed through a gas medium of pathlength, L, is described by the Beer–Lambert law:

$$I/I_0 = \exp(-k_v L) \tag{1}$$

where I_0 is the incident intensity, I is the transmitted intensity, for a single transition i, k_v [cm^{-1}] is:

$$k_v = PX_{abs}S_i(T)\phi_v \tag{2}$$

P is total static pressure [atm], X_{abs} is the mole fraction of the absorbing species, $S_i(T)$ is the transition line strength [$\mathrm{cm}^{-2}\,\mathrm{atm}^{-1}$], and ϕ_v is the normalization lineshape function [cm], namely, $\int \varphi_v \mathrm{d}v = 1$, from Eqs. (1) and (2) we can calculate integrated absorbance, which exactly represents projection value of different path [21]:

$$A_i = \int \ln(I_0/I)\mathrm{d}v = PX_{abs}S_i(T)L \tag{3}$$

The absorption coefficient can be defined as flows regardless of L from Eq. (3)

$$\alpha = PX_{abs}S_i(T) \tag{4}$$

The temperature dependant line-strength can be calculated as follows:

$$S(T) = S(T_0)\frac{Q(T_0)}{Q(T)}\frac{T_0}{T}\exp\left[-\frac{hcE''}{k}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \times \left[1-\exp\left(\frac{-hcv_0}{kT}\right)\right]\left[1-\exp\left(\frac{-hcv_0}{kT_0}\right)\right]^{-1} \tag{5}$$

h is Plank's constant, c is the speed of light, k is Boltzmann's constant and $Q(T)$ is the partition function for the absorbing species [22]. The temperature can be approximately determined from the ratio of two isolated transitions when the two selected transitions are close to each other [25]:

$$T = \left(\frac{hc}{k}(E_2''-E_1'')\right)\Big/\left(\ln\left(\frac{S_{v1}(T)}{S_{v2}(T)}\right)+\ln\left(\frac{S_2(T_0)}{S_1(T_0)}\right)+\frac{hc}{k}\frac{(E_2''-E_1'')}{T_0}\right) \tag{6}$$

where T_0 is the reference temperature for the line strength. The quantity hc/k has a numerical value of 1.438 cm K. $S_{v1}(T)$ and $S_{v2}(T)$ are absorption line strengths of specified gas species. E'' is the lower state energy for the given line.

In order to get the two dimensional distribution of temperature and species concentration by tomographic principle, the reconstruction area in which laser penetrated is discretized into $N = n \times n$ sub-grids. In each grid, the temperature and target gas species concentration are assumed to be uniform, so the integrated