# Swirl Flames Diagnostics Using Diode Laser Absorption Tomography with High Temporal-Spatial Resolution

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## 1 Introduction

Among all the laser diagnostics developed for combustion flows, tunable diode-laser absorption spectroscopy (TDLAS) has been demonstrated as an attractive technique offering unique advantages such as fast temporal resolution, quantitative measurements, and low cost. As a result, variations of TDLAS have been developed to monitor multiple flow parameters, including temperature, pressure, velocity, density, and flow rate. Applications of TDLAS have been demonstrated in a wide spectrum of combustion systems ranging from aircraft engine, IC engine, high enthalpy wind tunnel, and 2-D supersonic combustion flow [1-4]. Readers interested in a comprehensive and in-depth discussion of the capabilities and applications of TDLAS are referred to a review paper [5]. Despite these unique advantages, the limitation of TDLAS is well recognized: it is a line-of-sight technique in nature and hence its application is limited to flows with negligible non-uniformity. For instance, measurement of flow-parameter distribution is crucial for analyzing combustion characteristics in some combustors. Therefore, improving spatial-resolution is one of the most insistent research areas for TDLAS technique.

A considerable amount of research efforts has been invested in overcoming this limitation. Combined with Computed Tomography (CT), TDLAS can truly improve its spatial solution, called as Tunable Diode-Laser Absorption Tomography (TDLAT). There are several TDLAT strategies: 1) two absorption line combined with optical structure of optimization non-orthogonal beams [5,6]; 2) two absorption lines combined with parallel/fan beams[7,8]; 3) multi-spectroscopy light resource (can scanning several absorption lines) combined with orthogonal beams, called Hyperspectroscopy Tomography (HT) [9,10]. Most TDLAT reports are validation studies on flat burner or other simple flame [11,12]. For practical facility application, Andrew[13] firstly measured temperature and water concentration with spatial resolution at the nozzle exit of an augmented gas turbine engine. Parallel-beam and rotating strategy were applied with three water absorption features and 16 angles. Busa [14] used fan-beam and rotating strategy to measure temperature and water concentration distribution at exit of a scramjet engine, which is the first report of TDLAT application in

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supersonic flow. Unlucky, the former two strategies use large numbers of beams, usually hundreds, complicating measurement system and weakening its applicability in harsh environment. For example, small size and few optical windows embarrass the utility of these two strategies in swirl burner. On the other hand, the third HT strategy only uses tens of beams, which make it a potential method for burner application [9]. HT was developed by Dr. Ma from Virginia Tech and Dr. Sanders from University of Wisconsin System [10]. A Fourier Domain Mode Locked (FDML) fiber laser was used to scanned about 30 nm wavelength spectrum range at tens kHz. This kind of laser resource is expensive, and its stability and linearity are not as good as distributed-feedback (DFB) laser which is widely used as TDLAS light resource. Due to the high frequency and large wavelength scan-range, the dynamic response and sampling rate of the detector should be much larger than traditional TDLAS technique. All these weakness limits the application of HT. In order to avoiding these limitations, four DFB diode lasers were combined to form hyperspectroscopy laser resource in our experiments. Optical structure with 21×21 orthogonal laser beams was fixed at the combustor of the burner with *85*85 mm* cross section, and a reconstruction routine based on simulated-annealing algorithm was used to reconstruct the distributions of T and PX during post data processing.

## 2 Experimental

Suitable absorption lines can optimize the spatial resolution. Therefore, selection of absorption feature is essential for HT. Normally, three selection rules should be followed: 1) low-state energy should be large enough to eliminate the interference of water absorption in room air; 2) difference between each two absorption lines should be as large as possible to provide high temperature-sensitivity; 3) line strengths should also be as large as possible to provide high signal-to-noise ratio. Four water vapor absorption lines, *7185.6* $cm^{-1}$, *7444.3* $cm^{-1}$, *7466.3* $cm^{-1}$, and *6807.8* $cm^{-1}$, were selected and used in our HT sensor. Their line strengths and low state energies are shown in table 1. Spectroscopic parameters are taken from database *HITRAN2016* [15], which are widely used for TDLAS technique. Parameter error, especially line strength, is supposed to be less than 2-5%, which is validated in literature [16].

Table 1 Spectroscopic line parameters used in the current study

| *No.* | wavelength number $\nu_0$ ($cm^{-1}$) | line strength $S$ (296K) ($atm^{-1}cm^{-2}$) | low-state energy $E''$ ($cm^{-1}$) |
|---|---|---|---|
| 1 | 7185.597 | $1.97\times10^{-2}$ | 1045.058 |
| 2 | 7444.35+<br>7444.37 | $1.12\times10^{-3}$ | 1774.751<br>1806.670 |
| 3 | 7466.337 | $1.24\times10^{-5}$ | 2660.945 |
| 4 | 6807.834 | $1.02\times10^{-6}$ | 3319.448 |

Figure 1 illustrates the optical layout of the TDLAS-HT system. The system consisted of four distributed feedback diode lasers (*NLK1B5EAAA, NEL*), each controlled (both the injection current and temperature) independently by a diode-laser controller (*ITC4001, Thorlabs*). The injection current of each controllers was modulated by a ramp signal from two signal generator (*AFG3022, Tektronix*) so that the lasing wavelength scanned a spectral range of 2 $cm^{-1}$ to probe the $H_2O$ absorption transitions shown in table 1. Wavelength of each laser was modulated at a repetition rate of 10 kHz. Laser beams from the two lasers were combined by a 4×42 single-mode fiber coupler. The separation of the absorption signals was then achieved via a time division multiplexing (*TDM*) scheme [4], resulting in a temporal response of 2.5 kHz (i.e., 0.4 ms per measurement) if no averaging was performed. The 4×42 fiber coupler then split the combined beam into forty-two channels. The former 21 channels were delivered into the combustor vertically and the latter 21 channels horizontally.

On the catch side, forty-two collimators with relatively large numerical aperture (*NA=0.49*) captured the transmitted beams into multimode fibers. Forty-two lenses then focused the beams out of the fibers onto forty-two InGaAs detectors with 2 mm diameter sensitive areas. The parameters of the collection optics were designed to minimize the effects of beam steering caused by the turbulence along the measurement path and the mechanical vibration of the swirl combustion [4]. Finally, two digital oscilloscopes (*DL850, Yokogawa*) were employed for recording the data from the detectors at a sample rate of 5 MHz. After integrated absorbance was deduced from data processing, a tomographic routine was used to reconstruct distribution of temperature and water partial pressure.

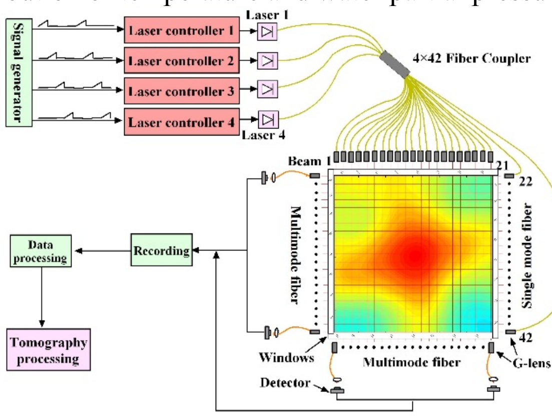



Figure 1 Optical layout of the TDLAS-HT system.

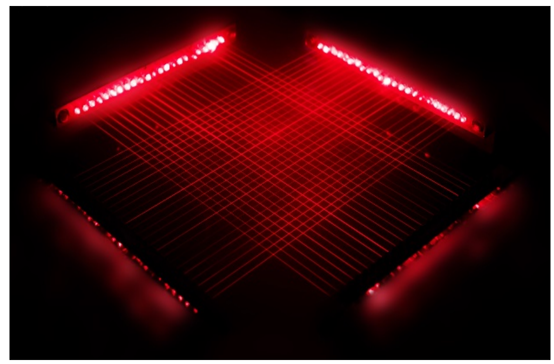


Figure 2 Photographs of these 42 beams.

The swirl burner sketched in Fig.3 comprises a section diagram of the whole burner, a state of on fire, a swirl core inside the burner. The air flows is delivered to the flame throgh the central nozzle and the outermost annular nozzle by the swirl core, and the nonswirling $CH_4$ is fed through the middle annular nozzle. The combustion chamber has a square section of 85×85 mm and a height of 110 mm. Operating condition correspods to Air flux of 160 L/min and $CH_4$ flux of 11.1 L/min with equivalence ratio of 0.65 and Reynolds numbers about 10200.

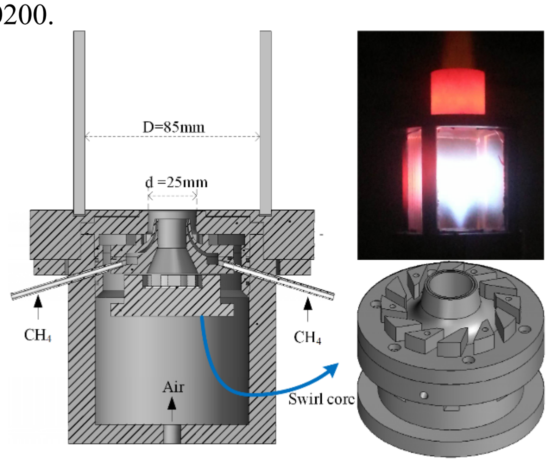



Figure 3 The swirl burner

## 3 Results and discussion

Validation experiments were performed on a $CH_4$/Air flat burner to evaluate the TDLAS-HT system.This TDLAS-HT system has been validated using a $CH_4$/Air flat burner. It can capture the dynamic process of the burner igniting. For swirl burner application here, integrated absorbance data of 4 wavelengths and 5 beams are shown in Fig.4. It shows the good SNR and periodic variation indicating combustion instability of the swirl flame. All the absorbance of forty-two beams and four wavelengths (42×4 data) at the same time composed projection. As input of processing routine, its SNR determined the final reconstruction accuracy.

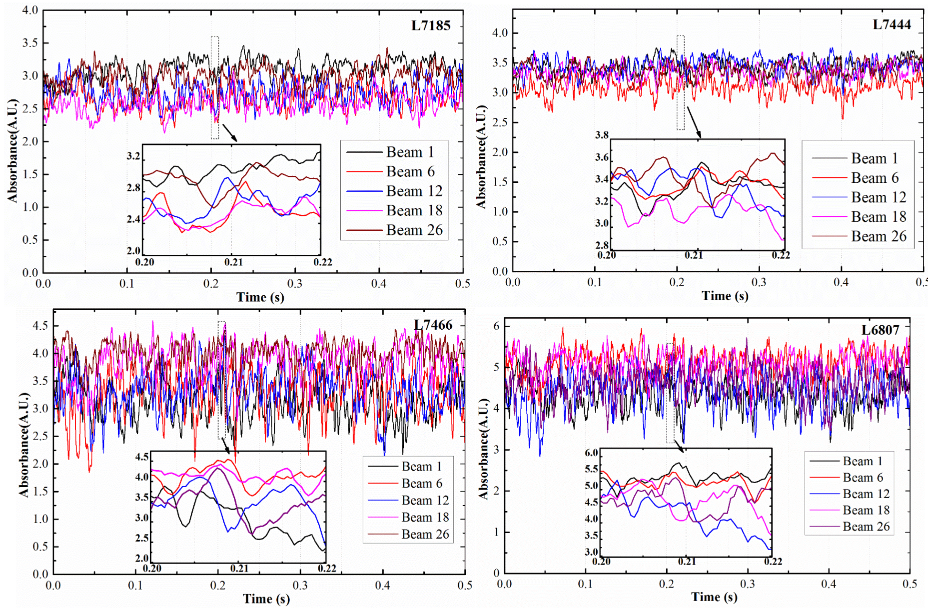
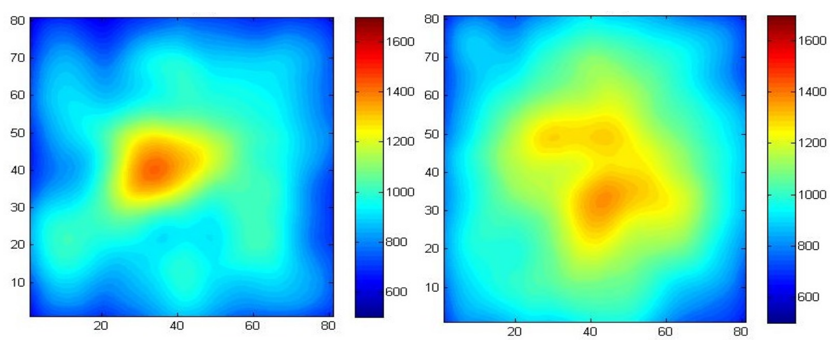
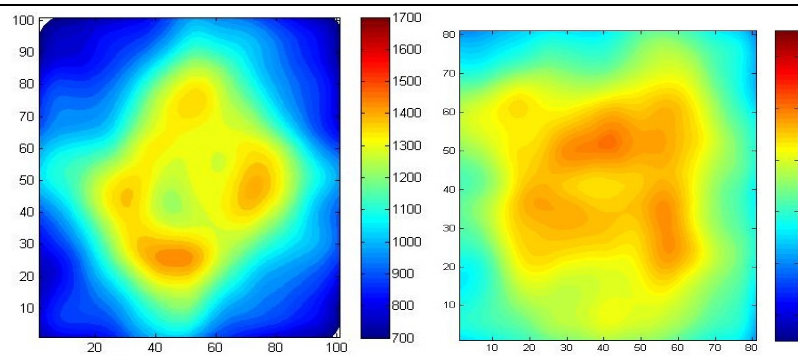



Figure 4 Absorbance versus time

Reconstruction was done during every measurement period (i.e., 0.4ms). Figure 5 shows the 2D temperature reconstructed at cross-section height of 14mm, 19mm, 24mm and 34mm. It can clearly capture the main characteristic of the flame core along flow direction. At 14mm, flame just stabilizes, high temperature zone present as circle with diameter about 15mm. At 19mm, diameter of high temperature increases to about 25mm. And at 24mm, ring configuration appear as expect. Its internal diameter is about 20mm with external diameter about 40mm. At 34mm, temperature continue to increase in the ring and this circle high-temperature shape has a trend changing to square with almost identical size. At cross sections with different height, the highest temperature is almost the same, about 1600~1700K, while high-temperature area and average temperature increase rapidly with distance from the nozzle. TDLAT results the main heat release is between heights from 14 to 34mm. High temporal resolution (0.4ms) and spectral resolution (4×4 mm) can bring abundant information for swirl flame, such as temperature and $H_2O$ concentration distribution along the cross section and flame oscillation in the burner.



(a) H=14mm (b)H=19mm



(c) H=24mm (d) H=34mm

Figure 5 TDLAT results at different height

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