12th Asia-Pacific Conference on Combustion,
Fukuoka International Congress Center, Fukuoka, Japan
1st -5th July 2019.

Heat Release and Temperature Diagnostics for Swirling Flames using Chemiluminescence and Absorption Tomography

Xin Lin[1], Kuanliang Wang[1,2], Fei Li[1,*], Xilong Yu[1,2]

[1] State Key Laboratory of High Temperature Gas Dynamics, Institute of Mechanics, CAS

Beisihuanxi Road, Beijing, 100190, China

[2]School of Engineering Science, University of Chinese Academy of Sciences

Beijing 100049, China

Abstract

A laboratory-scale gas turbine model combustor fueled with methane is studied experimentally with the help of three-dimensional computed tomography of chemiluminescence (3D-CTC) and tunable diode laser absorption tomography (TDLAT). In the combustion structure transition, the three-dimensional relative emissions of CH* were measured and taken as qualitative indicators of the heat release rate. This 3D measurement method utilizes 8 multi-directional CH* images as inputs combined with tomographic algorithms to compute the 3D distribution of CH* intensities. The TDLAT system composed of 42 beams (21×21, 21 parallel beams and 21vertical beams). Four water vapor absorption lines, 7185.6 cm-1, 7444.3 cm-1, 7466.3 cm-1, and 6807.8 cm-1, were utilized in each beam using time-division-multiplexed (TDM) method at total measuring frequency of 2.5 kHz. A reconstruction routine based on simulated-annealing algorithm was used to deduce distributions of temperature T and water partial pressure PX. Various lean operating conditions were conducted to examine the impact of flow velocity on heat release rate oscillation and spatial structure transition with an overall equivalence ratio of about 0.65 and dump plane velocity of 2.9-18.3 m/s. During the increase of Reynolds number, the heat release zone and high temperature zone changing obviously along the nozzle radial and axis direction, and the largest heat release plane moves forward significantly.

1 Introduction

Swirling burner is vital to gas turbine (GT) combustor, which creates the low pressure zone by the swirl jet flow and then generate hot reflux to stabilize the combustion. In recent years, increasing attention has been drawn to flame shape transitions for the need for understanding and predicting periodic state and transient behaviors in certain combustion systems [1-2]. Measurements are quite difficult for this kind of burner especially temperature and heat release which are vital for this inner flame with windows. Here two diagnostics are developed, 2D temperature distribution were measured using TDLAT (tunable diode-laser absorption tomography) and 3D heat release was measured using 3D-CTC (computed tomography of chemiluminescence).

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. 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. 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) [3,4]. Four DFB diode lasers were combined to form hyperspectroscopy laser resource in our experiments. Optical structure with 21×21 orthogonal laser beams was used with spatial resolution as high as 4mm.

As the identification of combustion reaction zone, the heat release rate is a basis for monitoring the flame state to control combustion oscillation and plays an essential role in the study of flame shape transition and combustion dynamic oscillation [5]. At present, there is no feasible direct measurement method for the heat release rate of swirling flames, most of which use indirect measurement methods based on the emission of chemiluminescence [6]. Among all the chemiluminescence species, the intensity of CH* emission is more suitable as the heat release rate indicator, and based on which the three-dimensional computed tomography of chemiluminescence (3D-CTC) could be utilized to obtain the 3D distribution of heat release rate for swirl flames and the variation of its 3D shape.

The 3D-CTC method was firstly demonstrated by J. Floyd et al. [7,8] for thermal-fluid studies, and is attractive for applications in harsh industrial environments due to the highly desirable of time resolved 3D data. The adoption of fiber-based endoscopes for 3D-CTC experiments, making it much more flexible by not requiring direct line-of-sight [9]. The evolution of the structural features at 4 kHz have been captured by the CTC method, that suggested a rotating helical structure of the swirl flame [10]. Unfortunately, all those CTC investigations for swirl flames are in the opening environment with no restriction of combustion chamber that makes the dynamic characteristics are far from gas turbine (GT) flame flow fields such as the outer recirculation zone generated due to confinement effects.

The aim of this work is to investigate the effects of flow velocity on temperature and heat release rate in a swirling no-premixed methane flames. The spatial evolution of heat release rate was discussed by the shape transition of CH* captured by 3D-CTC method. Dynamic 2D temperature distribution at different height was reconstructed by TDLAT using the 42

Corresponding author. Fax: +86-10-8254-3835
E-mail address: lifei@imech.ac.cn

beams each with 4 wavelengths.

2 Experimental

2.1 Gas turbine model combustor and operating conditions

The atmospheric-pressure gas turbine model combustor used in this work is sketched in Figure 1, that comprises a section diagram of the whole burner, a state of on fire, a swirl core inside the burner and the schematically shown of gases feeding. The air flows delivered to the flame through the central nozzle and the outermost annular nozzle are co-swirled by the swirl core beforehand. The non-swirling CH4 is fed through the middle annular nozzle from two thin injector tubes with a diameter of 3 mm. The combustion chamber has a square section of 85 × 85mm and a height of 110 mm, and the diameters of three nozzles are d1 = 15 mm, d2 = 17 mm and d3 = 25 mm, which configuration is designed based on the model combustor of citation [11].

Three operating conditions of gas feeding velocity were investigated with the Reynolds numbers from 5000 to 16100, and the global equivalence ratio were all in lean values. The resulting values for volume flow rates, mass flow rates, global equivalence ratio (Φglob) and corresponding Reynolds numbers (Re) are summarized in Table 1. Air, generated by air-compressor, was pre-dried and then controlled by a mass flow controller (Bronkhorst In-Flow). CH4 was also controlled by a mass flow controller before being divided to two branches and flowed through two thin injector tubes accordingly, and the ignition place of combustor was at the exit of exhaust tube.

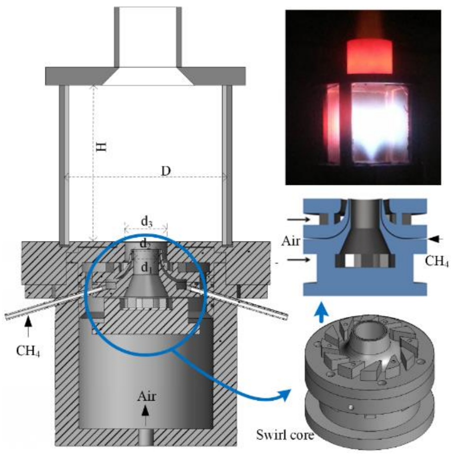


Figure 1: The swirl burner

	Air		CH4		Θ	Re
	sl/min	g/min	sl/min	g/min		
A	79	102.3	5.4	3.86	0.65	5036
B	160	207.1	11.1	7.93	0.66	10202
C	253	327.5	16.6	11.9	0.62	16100

Table 1: Parameters of the flames investigated

2.2 TDLAT setup

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 TLDAT sensor. Their line strengths and low state energies are taken from database *HITRAN2016* [12], which are widely used for TDLAS technique. 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. 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, 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 captured the transmitted beams into multimode fibers. Forty-two lenses then focused the beams out of the fibers onto 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. Finally, 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.

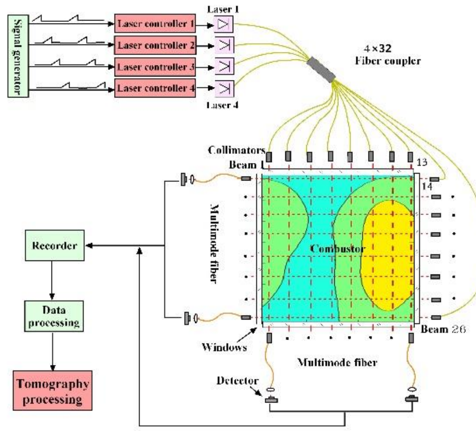


Figure 2: Optical layout of the TDLAT system.

2.3 3D-CTC setup

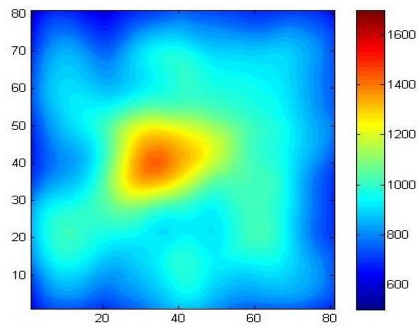
For the challenging capture of spatial flame mode transition, our multi-directional imaging system used customized 8 × 1 endoscopes and only one CCD camera (IMI 147FT). The fiber bundle with eight inputs and one output that can obtain all projection by one shoot without synchronized triggering. Gradient-index (GRIN) lens were used before the fiber that establish a field angle of about 50° [13]. To achieve the best reconstruction, 8 projections should be scattered as much as possible that we arranged two lens for each optical window with opposite pitch angles. Narrowband filters (center wavelength 430 nm, half width 10 nm) guaranteed the imaging of CH* and the exposure time was 60 ms that the 3D-CTC reconstruction was the average intensity during this time period.

3 Results

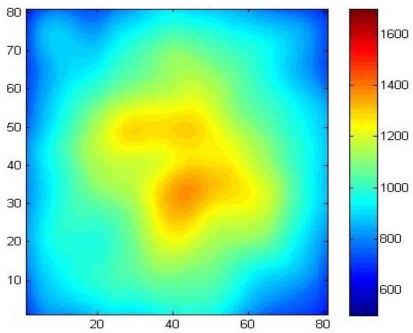
3.1 TDLAT results

This TDLAS-HT system has been validated using a CH_4/Air flat burner [14]. It can capture the dynamic process of the burner igniting. For swirl burner application here, integrated absorbance data of 4 wavelengths and 42 beams are obtained simultaneously. They have the good SNR and periodic variation indicating combustion instability of the swirl flame. As input of processing routine, this SNR determined the final reconstruction accuracy.

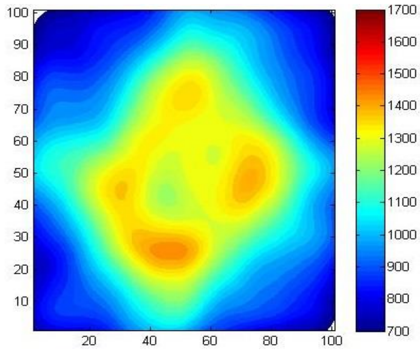
Reconstruction was done during every measurement period (i.e., 0.4ms). Figure 3 shows the 2D temperature reconstructed at height of 14mm, 19mm, 24mm and 34mm. It can clearly capture the main characteristic of the flame core along flow direction. At 14mm, flame just stabilizes, high temperature zone present as circle with diameter about 15mm. Of course diameter of flame core should be smaller than it as shown in 3D-CTC results. 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.



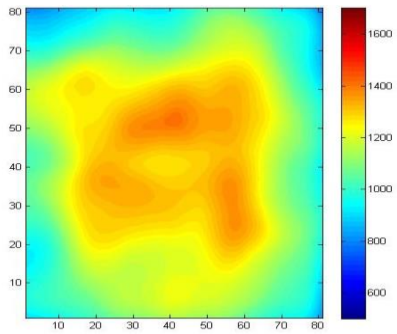
(a) H=14mm



(b)H=19mm



(c) H=24mm



(d) H=34mm

Figure 3: TDLAT results at different height

2.3 3D-CTC results

After the arrangement of imaging system, the weight matrix was calculated by the intrinsic parameters which were calibrated based on lens imaging theory. The calibration results shows that the distances between lens and the coordinate center of the object domain (90 × 90 × 70 mm3) are from 135 mm to 170 mm, meaning a largest viewing angle of about 37°. The projections of CH* chemiluminescence were then obtained and were inputted to the reconstruction algorithm to compute the distributions of heat release rate. Figure 4 illustrates the 3D profiles of heat release rate for the responding flames.

A V-shape liked zone can be seen clearly, that an inner recirculation zone (irz) and an outer recirculation zone (orz) are formed by the strong swirling effects and confinement. Between the irz and orz, the main heat release zone interacts strongly with the swirling flow field. The 3D structure of the main heat release zone is not axisymmetric to the nozzle axis, as shown in Figure 4, which is due to the restriction of flow field by the square section shape chamber. There are four convex peaks of the main heat release zone, and each is close to the corner of square section. Similar behavior could also been found in TDLAT results

In order to facilitate the quantitative analysis of the heat release characteristics of the swirling flames, the horizontal and vertical intensity changing under four conditions were compared. The curves of distribution (a) is along the nozzle (Z axis in Figure 4), and is the summary of voxels on each x-y plane that can reveal the overall heat release characteristics axially. We can see the maximum heat release appears at the height of 10.8 mm, 14.5 mm, and 21.1 mm for flame A, B, and

C, that the main heat release region shows an obvious forward trend with the increase in Reynolds number.

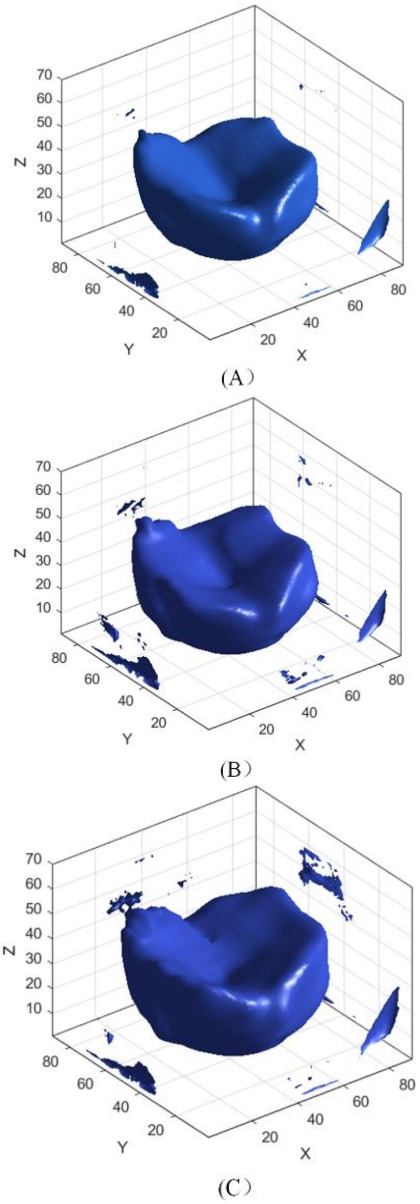


Figure 4: 3D structure of flame at cases A, B, and C

4 Conclusions

For studying the effect of the flow velocity on heat release rate of swirling flame in a laboratory-scale lean GT-like combustor, a fiber-based 3D-CTC system was used to capture the 3D shape of the flame emission (CH*) identifying its 3D heat release rate.

Combine with four DFB diode laser and TDM method, a hyperspectral laser resource was built. Based on this equipment, TDALS-HT technique was applied in a swirl burner. Dynamic distribution of T and PX was reconstructed at 2.5 kHz at different height. 441 grids (21×21) show acceptable spatial resolution of 4×4 mm. Based on the 3D imaging and TDLAT results, a V-shape liked zone can be clearly seen, indicating the irz and orz are formed by the strong swirling effects and confinement. 3D structure of the main heat release zone is not axisymmetric and four convex peaks exist near the corner of square section due to the restriction of flow field by the square section shape chamber. Comparing with cases at different flow rates, it can be found the main heat release region shows an obvious forward trend with the increase in flow velocity while the contours of the irz are nearly identical for all cases.

5 Acknowledgment

This work was sponsored by the National Natural Science Foundation of China (Grant 11372329) and supported by the Scientific Instrument Developing Project of the Chinese Academy of Sciences (Grant YZ201637).

References

References should be indicated in the text by full-size numbers in brackets, e.g., [1] and should be numbered in the order cited. The numbered reference list at the end of the article should conform to the following style:

• Journals: J.C. Rolon, F. Aguerre, S. Candel, Combust. Flame 100 (3) (1995) 422-429.

[1] A. Renaud, S. Ducruix, P. Scouflaire, L. Zimmer, P COMBUST INST, 35 (2015) 3365-3372.

[2] J. Yoon, M.-K. Kim, J. Hwang, J. Lee, Y. Yoon, APPL THERM ENG, 54 (2013) 92-101.

[3]Ma L, Cai W.W, Caswell A.W, OPT EXPRESS 17(2009):8602-8613.

[4] Ma L., Li X.S., Sanders S.T., Caswell A.W.,David S.R., Plemmons H., & Gord J.R,OPT EXPRESS 21(2013):1152-1162.

[5] M. Stohr, R. Sadanandan, W. Meier, EXP FLUIDS, 51 (2011) 1153-1167.

[6] P. Palies, D. Durox, T. Schuller, S. Candel, Combust. Flame,157 (2010) 1698-1717.

[7] J. Floyd, P. Geipel, A.M. Kempf, Combust Flame, 158 (2011) 376-391.

[8] J. Floyd, A.M. Kempf, P COMBUST INST, 33 (2011) 751-758.

[9] M. Kang, Y. Wu, L. Ma, Combust Flame, 161 (2014) 3063-3072.

[10] T. Yu, C. Ruan, H. Liu, W. Cai, X. Lu, Appl Opt, 57 (2018) 5962-5969.

[11] P. Weigand, W. Meier, X.R. Duan, W. Stricker, M. Aigner, Combust Flame, 144 (2006) 205-224.

[12] Rothman L.S., Gordon I.E., Babikov Y., Barbe A. J QUANT SPECTROSC RA, 130(2013):4-50.

[13] K. Wang, F. Li, H. Zeng, X. Yu, Opt express, 25 (2017) 21008.

[14] F. Li, H Zeng, XL.Yu, 2013. The sixth national conference on hypersonic technology, CSTAM 2013-A50-E0036, Tengchong, Yunnan, (in Chinese)