Three-dimensional Luminescence Measurements on a Sonic Diffusion Jet Flame Based on Tomographic Reconstruction at 15 kHz

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Abstract

This work describes an experimental study on a sonic C_2H_4/air diffusion jet flame based on the three-dimensional (3D) measurements at 15 kHz. The 3D measurements are obtained by a combination of the tomographic reconstruction of luminescence field and the fiber-based endoscopes. Key properties of the flame are extracted based on the 3D measurements. The properties include the detailed 3D flame structure and the 3D luminescence distribution. The results show the capabilities and potentials of the presented technique to resolve the flame properties for the high-speed combustion.

Keywords: High-speed combustion, three-dimensional measurements, tomographic reconstruction, fiber-based endoscopes

1. Introduction

A deep understanding on the ignition and flame stabilization mechanisms for the high-speed combustion (i.e., the sonic and supersonic combustion) is necessary for the design of combustion chamber of supersonic/hypersonic propulsion systems [1]. Experimental measurements for key parameters of flames, such as flame structure [2]**Error! Reference source not found.**, concentration distribution [3-5] and reaction zone characteristic [6], can indicate the mechanisms underlining the high-speed combustion process.

However, the high-speed nature of the turbulent flames poses several challenges for the experimental measurements. First, it requires the measurement technique being able to perform measurements with a high repetition rate (i.e., ≥ 5 kHz) and high spatial resolution (i.e., 0.5 mm in all 3D space) to fully resolve the characteristics of the high-speed combustion. Second, it requires the measurement devices enduring the unfriendly environment (i.e., the high temperature and sooty environment).

The optical diagnostic techniques have the potential to address the above practical measurement issues since they are intrusive, in-situ and have the high temporal-spatial

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resolutions. The optical techniques for combustion diagnostics can be roughly divided into two categories: passive methods and laser based methods. The passive methods enjoy the advantages of being cheaper and simpler to implement because they usually utilize the self-emission signals (i.e., the chemiluminescence and luminous) generated by the combustion products [7]. The laser based techniques are demonstrated to be more powerful and accurate, since they can measure the flow speed [8, 9], quantitative species concentration [10, 11], temperature [12, 13] and density [14, 15]. However, the complicated arrangement limits its application in most of the practical combustion systems.

This work utilizes the luminescence technique (a representative of passive methods) to study the high-speed (sonic) flames. Briefly, luminescence signals are generated from the soot of combustion products. Based on the luminescence images, key flame parameters can be inferred, such as the flame structure, anchoring location, fluctuation frequency and movement speed **Error! Reference source not found.**[16].

Unfortunately, the major disadvantage of luminescence technique is its line-of-sight nature, which decrease its capability to resolve the 3D spatial distribution of the flame. To address this issue, this work also uses the tomographic reconstruction technique to overcome the line-of-sight limitation and to resolve the flame in 3D. The basic principle of the tomographic reconstruction is described as follows. Firstly, cameras from different orientations collect the luminescence signals of the target flame, simultaneously. The images recorded on the camera are termed as projections. Second, the projections from multiple angles are fed into a reconstruction algorithm to reconstruct the 3D distribution of the flame [17]. Third, based on the reconstruction, 3D parameters of the flame can be obtained by a post-processing program. Theoretically, the spatial resolution of tomographic reconstruction is proportional to the number of cameras (angles) used. Thus, it is desirable to align cameras as much as possible for the practical measurements. However, challenges to obtain multiple measurements in practical combustion system include: 1) the high cost of optical devices (especially the high-speed cameras); 2) the limited optical access and the harsh environment [5]**Error! Reference source not found.**.

The fiber-based endoscopes (FBEs) provide the feasibility to effectively solve these practical issues. FBEs have a relatively small footprint (~2 cm fiber core), when compared to a standard high-speed camera, and they are flexible enough to be installed when optical access and physical space are limited [18]**Error! Reference source not found.**. Furthermore, customization of the FBEs allowed for the recording of nine projections onto a single camera, significantly reducing the equipment cost and implementation difficulty [19]**Error! Reference source not found.**.

Based on the above understanding, this work reports 3D measurements of luminescence on the high-speed sonic diffusion jet flame. The 3D measurements are based on the combination of tomographic reconstruction and fiber-based endoscopes. After the 3D reconstructions, the 3D flame structure and luminescence distribution are obtained to demonstrate the capabilities of the current technique for making spatially resolved measurements of high-speed flames.

2. Tomographic reconstruction

Computed tomography (CT) was first introduced in the early 1970s as a medical diagnostic tool, providing the 3D density distribution in a patient's body from the attenuation of X-ray radiation passed through it. In the time since, CT has been used by researchers in the fluid engineering fields for applications requiring true three-dimensional, non-destructive, and non-contact imaging of flow features.

For a typical CT problem, the 3D distribution of target is discretized into voxels, denoted as f(x, y, z). The imaging system collects the 2D line-of-sight integrated information, constituted, for example, by the light emission intensity of a flame from different orientations. Those 2D images are termed as projections $P\alpha$. The measured $P\alpha(s)$ depends on the viewing angle α, which represents the orientation of *f* with respect to the acquisition plane; s denotes the projection coordinate. In practical measurement setups that the dimension of the flame is much smaller than the objective distance, the measured $P\alpha(s)$ correspond to parallel lines perpendicular to the z-axis. Thus, $P\alpha(s)$ is known as the Radon transform of f(x,y,z) and can be formally defined as:

$$P_{\alpha}\left(s\right) = R\left\{f\left(x, y, z\right)\right\} = \int_{\psi(\alpha,s)} f\left(x, y, z\right) dl \quad (1)$$

where R{} denotes the Radon transform, and $\psi(\alpha,s)$ is a parameterization of the line corresponding to a given viewing angle α and the signed distance of the line to the origin.

The tomography problem is essentially to solve f(x,y,z) with known $P\alpha(s)$. If the projections are sampled continuously in both transverse coordinate and angle, as in the case of medical tomography, the field may be reconstructed analytically using the Fourier slice theorem. The Fourier slice theorem states that the Fourier transform of $P\alpha(s)$ with respect to s at constant axial coordinate z0 gives the values of the 2D Fourier transform of f(x,y,z0) along a line with constant polar angle α. When the data are sampled discretely from a few viewing directions, as in the case of flow tomography, the field is reconstructed using an algebraic formulation. In the current work, an algebraic algorithm, multiplicative algebraic reconstruction technique (MART) algorithm [20], is used to perform the tomography reconstruction of the 3D combustion luminescence field. The reconstructed domain is represented as a uniform grid of cubic B-spline basis functions with a grid spacing of 0.375 mm. The dimensions of the domain are 60×60×60 mm corresponding to the location of the root part of the flame.

3. Experimental setup

The experimental setup is schematically shown in Fig. 1. As shown, the setup consists of two major components: the burner and the image acquisition system. The burner consists of a central sonic nozzle (ID=1 mm) surrounded by an 80 mm hot coflow generated from a rich premixed ethylene/air flame. The velocity of the coflow is 1.5 m/s and the equivalence ratio of the ethylene/air mixture is 0.48. The sonic nozzle injects the pure ethylene into the coflow with the injection pressure of 1.8 atm. The total temperature of the injected ethylene is fixed at 300 K for all experiments, and the velocity is 313 m/s (i.e., Mach number = 1).

The image acquisition system first includes an annular optical rail with the angle graduations marked on its edge, the precision is 0.2°. The fiber-based endoscope system (including nine independent fibers) were installed on the rail. The customized annular optical rail is to avoid a calibration process to determine the distances and angles of fibers from different orientations, which introduces a 0.6° error based on the previous work **Error! Reference source not found.**. Each fiber was equipped with a Nikon lens (50 mm focal length and f/1.3). The fibers record the luminescence signals from nine orientations and the inputs of nine fibers were combined into one output, so that luminescence signals collected by all nine inputs can be captured by one high-speed camera (IX speed 716). The position of No.1 lens is defined as 0° and the angle graduations for all nine fibers read from the rail are: 0°, 18.4°, 35.4°, 50.2°, 61.8°, 83.4°, 102.4°, 121.2°, 137.8°, respectively. The repetition rate of the camera is 15 kHz, and the exposure time is 33 μs. The images captured from all nine orientations were then fed into a tomography algorithm to reconstruct the 3D luminescence distribution of the target flames.

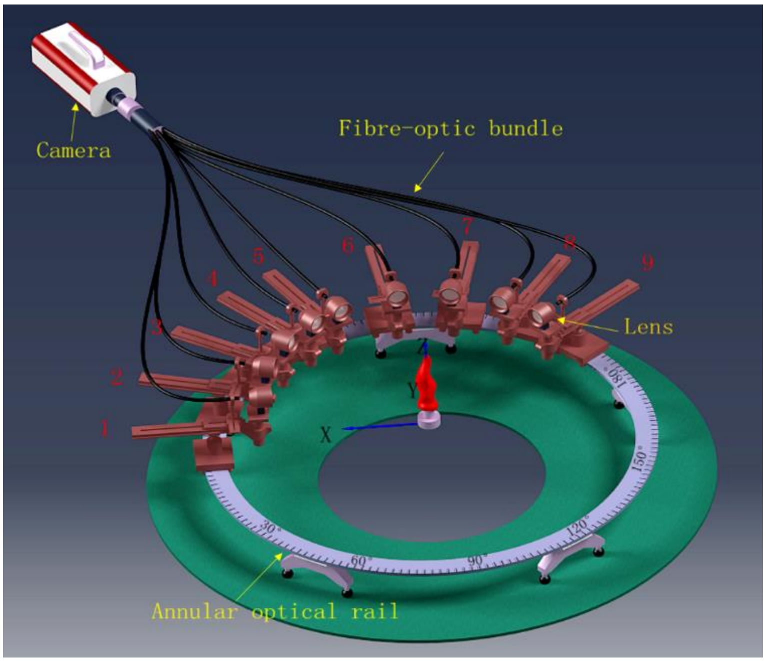

Fig 1. Schematic setup of 3D flame measurement system

4. Results and discussion

Figure 2 shows a set of measured projection examples captured by the nine fibers, simultaneously, from the different orientations as shown in Fig. 1. As shown, the flame is highly turbulent and has a distinctly different shape in each view. As previously discussed, these data are line-of-sight-integrated measurements of luminescence from the flame soot. Based on those projections, the 3D reconstruction was performed to reconstruct the 3D luminescence distribution using the method discussed in section 3.

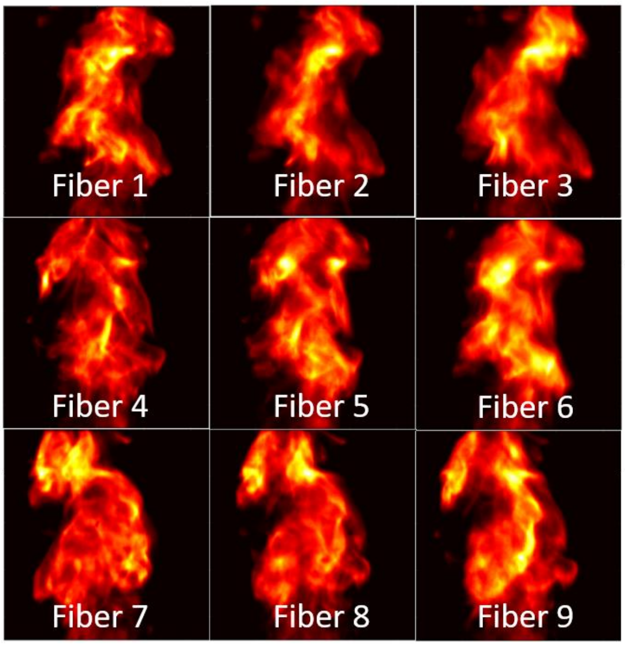

Fig. 2 A set of measured projection examples captured by nine fibers from different orientations

Figure 3 shows the 3D reconstruction obtained using the projections shown in Fig. 2. Fig. 3(a) first shows the 3D rendering of the envelope of the flame extracted from the 3D reconstruction. In this work, the flame envelope was determined based on the 3D reconstruction using a thresholding method. The method consisted of two steps. First, the average background level was determined from the raw projection measurements. Second, the background level was applied as the threshold value to the 3D reconstructions to determine the flame envelope. More specifically, the 3D reconstructions were separated into two zones by an iso-surface (i.e., the flame envelope): a flame zone with luminescence signal larger than the threshold value and a non-flame zone otherwise. As seen from the Fig. 3a, the 3D reconstruction captured the turbulent wrinkles and flame detachment as one can expect from the projections in 3D. Fig. 3(b) and (c) show five planar slices of the 3D reconstruction from the Y axis and Z axis, respectively, presenting the detailed flame luminescence distribution at different locations. Note that, the horizontal slices shown in Fig. 3(c) usually could not be directly accessible with the experimental images, illustrating the utility of the 3D reconstruction.

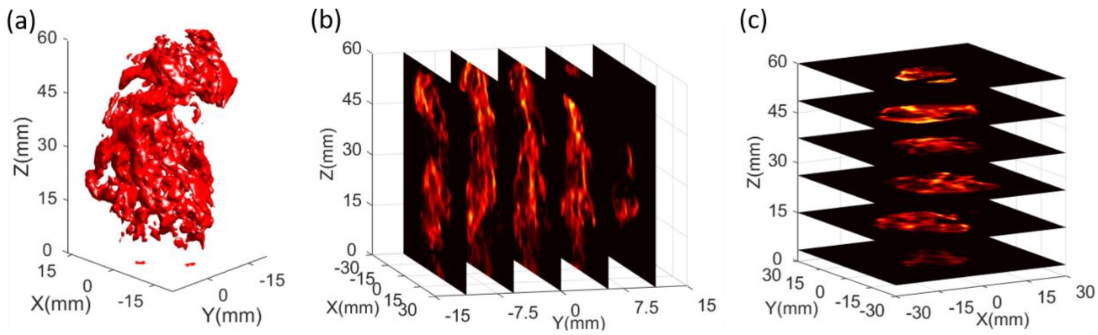

Fig. 3 Three-dimensional reconstruction of the luminescence distribution. Panel (a): 3D

rendering of the envelope of the flame extracted from the 3D reconstruction. Panel (b): five planar slices of the 3D reconstruction from the Y axis. Panel (c): five planar slices of the 3D reconstruction from the Z axis.

After the demonstration of the 3D reconstruction, Fig. 4 then shows a time series of 3D reconstructions, showing the evolution of the flame structure. The interval between two time index is 67 μs (i.e., with a 15 kHz acquisition rate). As can be seen from Fig. 4, the flame structure slightly changes with time, illustrating that the image acquisition rate used in this work is sufficient to resolve the dynamic evolution of the sonic flame. More specifically, the flame structure at time index 1 shows two distinct flame parts: the tip part and root part. And the two parts gradually merge by observing the shrink of the cavity indicated with the blue circle in Fig. 4.

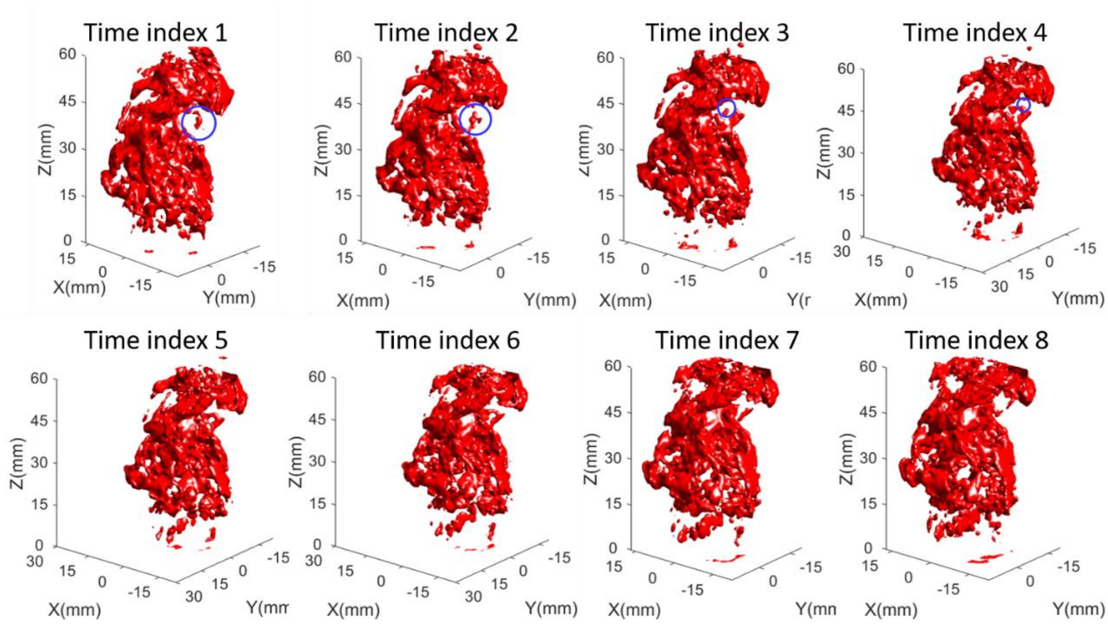

Fig. 4 Time evolution of 3D flame structure. The interval between two time indexes is 67 μs.

A primary motivation of this work is to demonstrate the capabilities of current experimental techniques for making advanced 3D measurements of high-speed reacting flows. A logical next step is a quantitative determination of the flame surface area and the flame surface area per unit volume (the flame surface density), based on which the average turbulent flame speed and the local burning rate can be calculated. An elaborate discussion of these results will be reported separately.

5. Conclusion

This work reports a temporal- spatially- resolved measurement on a high-speed sonic diffusion jet flame based on the combination of tomographic reconstruction and fiber-based endoscopes. More specifically, the measurement reconstructed the 3D flame structure and luminescence distribution in a 6 cm × 6 cm × 6 cm space with a temporal repetition rate of 15 kHz. The results show that the measurements captured the detailed 3D flame structure and the dynamic evolution of the flame. Future work will focus on the quantitative analysis of the flame based on the temporal resolved 3D measurements, such as the estimation of the average turbulent flame speed and the local burning rate.

Acknowledgments

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