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Measurements from flame chemiluminescence tomography of forced laminar premixed propane flames

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ABSTRACT

The unsteady, visible, chemiluminescence fields of two non-axisymmetric, forced, laminar, premixed, propane–air flames are tomographically reconstructed using between 3 and 36 equally-spaced views. Algorithms for measuring flame surface area, flame curvature, flame thickness, and the normal component of the flame propagation velocity (surface speed) are demonstrated. The sensitivity of each measurement to the number of views used in the reconstruction is then assessed. For both flames studied, the difference between flame surface area fluctuations measured using 36 views and those measured using as few as 9 views was less than 1%. For the other three quantities, a measurement sample is acquired over the entire flame surface at one phase of the forcing cycle for each flame. The sensitivity to the number of views is compared by assessing the similarity of measurement distributions obtained using the maximum number of views to those obtained using fewer views. The surface speed measurement distribution is found to converge fastest as the number of views was increased, though results for mean curvature are similar. However, the flame thickness measurement distribution was found to have significantly slower convergence and more than twice the number of views are required to measure flame thickness compared to curvature or surface speed. The demonstrated measurement algorithms are generally applicable to the chemiluminescence fields of wrinkled, premixed flames. The results suggest that for laboratory-scale, weakly turbulent, premixed, jet flames, statistical measurements of flame curvature and surface speed may be accurately obtained using as few as six views, while greater than 20 views are likely to be required to obtain useful measurements of flame thickness.

1. Introduction

There has recently been significant progress in the development of measurement methods capable of obtaining pseudo-instantaneous and time-resolved flame measurements over an entire combustion region. Two main approaches are used: laser scanning methods [1–4], and tomographic methods [5–24].

Tomographic methods involve reconstructing a three-dimensional scalar field from integral measurements. The use of tomography in combustion has been limited primarily by the difficulties and cost associated with obtaining measurements of the required number of projections. As reconstruction algorithms are optimized for combustion applications, and optical equipment continues to decrease in price, tomographic methods are anticipated to have greater applicability in both combustion research and for online diagnostics of industrial combustors [25].

Most previous high resolution flame tomography has used one of two approaches: light scattered by oil droplets or solid particles in the unburned premixture, and using the light emitted from the flame itself. The latter is known as Flame Chemiluminescence Tomography (FCT) and is the subject of this paper. The following review of light scattering methods is therefore kept concise. Upton et al. demonstrated tomographic reconstruction of oil droplet evaporation on turbulent premixed flames using 12 flame images [26]. Tomographic particle image velocimetry (PIV) is a related method that uses lower seeding densities to allow reconstruction of the scattering from individual droplets [11,27] or solid particles [12]. The resolution of the flame front position is limited by the sparse seeding density, typically to approximately 1 mm. In comparison, FCT involves imaging the light emission from the flame, and likely provides a more accurate determination of the reaction zone and the combustion processes. Chemiluminescence imaging is also non-intrusive and passive. Recently, tomographic reconstruction of laser induced fluorescence (LIF), termed 'volumetric LIF' has also been demonstrated [17,18]. This approach has the advantage that the entire flame need not be reconstructed, but

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in many ways is similar to FCT, and the algorithms used to obtain measurements from the reconstructed fields are likely to be similar.

Several works detail the reconstruction methods typically used in FCT, e.g. [14,28]. Methods can be categorized as series expansion methods and transform methods. Series expansion methods involve representing the field as a set of basis functions and solving a system of equations for the basis function coefficients [28,29]. Series expansion methods have been favored over transform methods for FCT due to the limited number of views often available. The system of equations is typically underdetermined and sometimes inconsistent, so several methods to find an optimal reconstruction have been proposed.

The additive and multiplicative variants of the algebraic reconstruction techniques (ART/MART) are the series expansion methods which have been the most widely used in previous FCT implementations [5,13,23,30]. Other methods involve formulating the problem with additional optimization criteria, often incorporating prior knowledge of the field. Anikin et al. reconstructed the OH^* emission of a turbulent bluff-body flame using a regularization parameter based on the Euclidean norm [31]. Ishino and Ohiwa used Maximum Likelihood Expectation Maximization to reconstruct the broadband chemiluminescence of a turbulent jet flame [15]. Cai et al. reported improved results over ART by using a total variation regularization method in reconstructing artificial data representing a modified McKenna burner [32]. Denisova demonstrated an improvement of the maximum entropy (MENT) method over ART in the reconstruction of two numerical examples, but did not consider examples representative of flame chemiluminescence [33]. Denisova et al. later reported reconstructions of a conical flame using MENT and showed the MENT method could be improved by local smoothing of the projections [14]. Further study was said to be required for applying this method to non-axisymmetric flame tomography.

To the authors' knowledge, for unsteady, wrinkled, premixed flames, there are only two instances in the literature where 3D flame measurements at points on an identified "flame surface" have been made using FCT. Ishino et al. report measuring the flame propagation velocity on a small part of a turbulent flame surface reconstructed using 20 equally-spaced, coplanar views, but do not report their methods [34], and Ma et al. recently reported 3D curvature measurements on a turbulent slot flame calculated on an isosurface of the CH^* chemiluminescence field, reconstructed using 6 coplanar views [16].

FCT based measurements have also been reported in several other combustion studies. Ma et al. reconstructed a combustion region in a Mach-2 combustor using 8 views [20,21] . Flame surface area and volume were computed using an isosurface and voxel thresholding respectively. Cross-sections of the combustion zone did not reveal the presence of wrinkled flames, and the computed isosurface enclosed the combustion region. FCT has also been applied to the reconstruction of time-averaged turbulent flame brushes [7,8,10,13,35]. However, chemiluminescence fields from turbulent flame brushes typically have very different characteristics to 'instantaneous' flame surfaces. Using volumetric LIF, Ma et al. tomographically reconstructed part of a turbulent jet flame and reported flame length measurements, measured on 2D cross-sections [17].

Whilst a significant amount of work has been dedicated to determining optimal reconstruction algorithms for FCT, the identification, demonstration, and development of robust and accurate algorithms for obtaining measurements from the reconstructed chemiluminescence field is equally important for minimizing the number of views required to obtain measurements with a desired accuracy. Furthermore, it is not currently clear which quantities can be most accurately measured when using a low number of views ($\lesssim 20$).

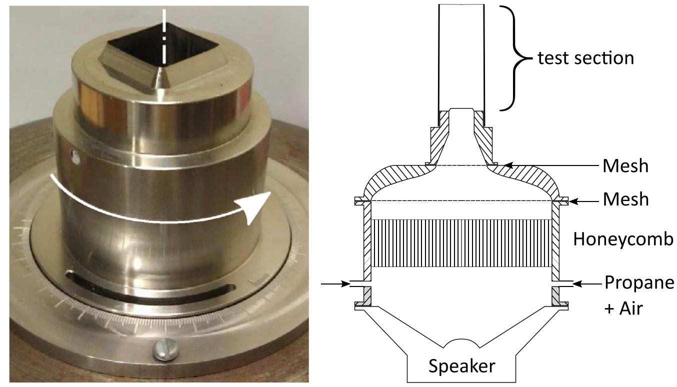

Fig. 1. Left: Photograph of square port flame holder. Right: Schematic of burner plenum and flow conditioning.

In this paper, algorithms for measuring the flame surface area, flame surface curvature, the normal component of the flame propagation velocity (surface speed), and the flame thickness are proposed and demonstrated on the time-resolved chemiluminescence field of two non-axisymmetric, forced, laminar, premixed, propane flames at different equivalence ratios: $\phi = 0.71$ and $\phi = 0.84$. Measurements of the flame thickness and surface speed over an 'instantaneous', unsteady, non-axisymmetric, premixed flame have not previously appeared in the literature. The measurement algorithms are then applied to flame chemiluminescence fields reconstructed using between 3 and 36 views and the relative sensitivity of the measurements to the number of views is assessed.

The presented results: (i) show the relative sensitivity of the measured quantities to the number of views used in the reconstruction, and (ii) provide an estimate of how many views are likely to be required to obtain statistical measurements of these flame quantities in flames of similar character, that is, laboratory-scale, weakly-turbulent, lean, premixed flames. Such measurements are likely to be useful for the validation of theoretical models and numerical simulations.

2. Experimental and tomographic methods

2.1. Forced laminar premixed non-axisymmetric burner

A flame holder with a square port was used to stabilise non-axisymmetric, laminar, premixed flames (Fig. 1). The sides of the port are 22 mm long with rounded corners of 2 mm radius. The lip has a vertical inner surface and is tapered to a knife edge at a 60° angle. The flame holder can be rotated about the vertical axis to allow any number of coplanar views to be obtained without moving the camera. A vernier angle scale is used to measure the viewing angle β to an accuracy of $\pm$ 0.1°.

Flow rates of dry, filtered, compressed air and propane (99.95% purity) were controlled using MKS thermal flow meters, models 1559A and M100B respectively. Two lean, premixed flames of different stoichiometry are investigated in this study. These are referred to as Case 1 and Case 2 (Table 1), and were chosen given their strong flame dynamics, including annihilation events that the group has been studying as acoustic sources [36–38]. The propane and air are mixed approximately three meters upstream of the burner to ensure a well mixed mixture at the burner port [39]. This mixture passes through a 60 mm honeycomb flow straightener in the burner plenum before entering a contraction upstream of the rotatable flame holder. Layers of fine steel mesh before and after the contraction are used to dissipate turbulence. The flame geometry was found to be particularly sensitive to small irregularities in the final mesh layer. This mesh layer was therefore installed to