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Direct three dimensional tomography of flames using maximization of entropy technique

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ABSTRACT

Presently, there are numerous applications for non-destructive techniques like emission tomography, laser based methods and particle image velocimetry that are used to study flame characteristics. Reconstruction of the flame intensity field using emission tomography has the advantage over other technologies that it gives accurate results but at the same time requires relatively inexpensive equipment, and therefore, has numerous industrial applications. In the present paper, a new algorithm performing Direct-3D reconstruction using the maximization of entropy (MENT) methodology has been introduced. Through detailed studies using a mathematical object, it has been shown that the Direct-3D algorithm shows significantly reduced errors as compared to 2D slice-by-slice reconstruction algorithms. Secondly, the major features of the proposed algorithm, for e.g., effect of orientation, effect of number of views, and robustness have been discussed. Finally, a few qualitative results from actual flames have been presented using a candle and a gas fired burner, and the results match well with the actual flame geometry and intensity distribution.

1. Introduction

In the past few decades, flame studies have become an important subject for researchers in analyzing various phenomena that occur in flames, such as temperature distribution, flame propagation, wrinkling, vortex shedding and flame quenching. While initial attempts to study such flames used mechanical probes, due to the intrusive nature of these probes, the results obtained were inaccurate. This has led to the development of non-intrusive experimental methods. Laser based non-intrusive methods, such as laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) for velocity measurements, and laser induced fluorescence (LIF) and Raman–Rayleigh method for scalar measurements, are widely used. These methods have the advantage of giving high spatial and temporal resolution. However, most of these techniques can focus only on a section of the flame at one point of time. Interpretation of LIF signals is complex because of space and temperature dependent signal quenching rates. The Raman techniques can only be applied to clean environments free of soot particles and background luminosity. Moreover, all these methods have high cost as they require sophisticated and powerful lasers, high resolution and high speed cameras and various other optical devices [1–9]. Simulation based techniques developed to analyze flames include direct numerical simulation (DNS) [10] and large eddy simulations (LES) [11], which can be used for developing time resolved three dimensional data for reacting flows. These are relatively new techniques and hence, it becomes important to compare and validate the results with more established experimental methods [1].

All these shortcomings point towards the need for a non-destructive experimental method for flame studies that can be applied to small laboratory experiments as well as large industrial settings without any appreciable scaling in the costs involved, thus making it more pertinent to real life applications. At the same time, the method should be able to provide adequate temporal and spatial resolution. It is for such applications that computed tomography (CT) using optical images, becomes a valuable tool. CT methods offer some important advantages like, ease of data collection, species specific signals of strong intensities, robustness, large field of view, and the ability to leverage various data reconstruction algorithms developed for medical CT [12,13]. The spatial and temporal resolution in CT techniques is lower compared to other methods mentioned above, but it can be increased by using advanced optics which can enable fast scanning of planes. With sufficiently fast image acquisition, the direct 2D and 3D measurements can provide important data for even turbulent flames [2,13,14]. CT methods have been used in combustion studies for refractive index measurements and laser absorption measurements [15,16]. Computed Tomography of Chemiluminescence (CTC) has been used widely to study different aspects of flames and combustion process in 2D and 3D measurements. It has been successfully used to study

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combustion properties such as equivalence ratio, heat release rates, and model the process of chemiluminescence. Also, the 3D information obtained from chemiluminescence measurements has been used in simulation based studies [1,3,13,17,18]. Among some recent findings, different approaches for tomographic reconstruction like hyperspectral tomography (HT) [12,19], tomographic PIV [20], and chemical species tomography (CST) using Near-Infrared Absorption Tomography (NIRAT) [21] have been proposed. Most of these methods require a lot of data (as high as 1000 images per run) and focus on a uniform planer region or a very small spot with varying properties. This limits their applicability towards reconstruction of a 3D volumetric distribution of a property, and for systems where data acquisition is not very easy.

All the CT techniques collate the image data into a system of equations. To solve this system of equations, a number of computational techniques have been developed. Series expansion based methods, also known as algebraic reconstruction technique (ART) were among the first methods to be developed. A number of researchers have given modifications of ART [22–29]. In combustion diagnostics, the number of views is very limited as compared to medical imaging process [12]. This makes the problem ill-posed and under-defined. In an under-defined problem, there might be a number of possible solutions and hence, the problem may be approached as a problem of optimization where one may attempt to maximize the entropy or minimize the energy of the system. Such tomographic methods are known as maximization reconstruction techniques (MRTs) [30–32]. One of the proposed solutions in MRT is known as the maximization of entropy technique (MENT) [30]. MENT is a very powerful method when the reconstruction is to be performed with a very sparse set of projections, like in industrial processes where the object size limits the number of views or it is obstructed by other objects, or when the error due to noise is high [30–32]. The advantage of MENT is that it yields the reconstruction which has the lowest information content that is possible with the given set of projections and thus adds the least unnecessary information or structure into the reconstructed solution [33–35]. Also, it was shown by Minerbo [30] that MENT has a faster rate of convergence even with noisy data compared to multiplicative ART (MART) used with accurate data. While numerous papers refer to 3D reconstruction, they actually reduce 2D projection images to vertically stacked 1D images and reconstruct 2D planes using the corresponding images. The 2D planes stacked one over the other form a pseudo-3D reconstruction [1,13,22,36,37]. The evident advantage of such an approach is that the complexity and computational requirement of the solver decreases as 3D vector algebra is not required. But, 2D planar reconstruction has some disadvantages. It is practically difficult to design the experiments to convert an inherently 3D problem to a 2D problem and requires complex hardware [38]. Direct 3D reconstruction, on the other hand, increases the flexibility of data acquisition and allows projections to be taken from anywhere around the flame. Secondly, it provides a greater view angle between projections, which potentially leads to a lower reconstruction error [22]. Thirdly, complex flows which have swirl have an inherent 3D nature and require 3D analysis to give an accurate solution [1]. Out of plane projections can add information to the reconstruction which coaxial views cannot and hence may be able to capture minute details more accurately than 2D reconstruction [14]. In the past, there have been only a few studies on Direct-3D reconstruction. Minerbo [30] showed that Direct-3D can be used with MENT and he gave an example of the same using four views. Colsher [36] compared Direct-3D reconstruction using four algorithms; summation, ART, simultaneous iterative reconstruction technique (SIRT), and iterative least squares technique (ILST). Floyd et al. [1] developed a formulation for Direct-3D reconstruction using ART and reconstructed both, phantom objects and turbulent opposed jet (TOJ) flames. Cai et al. [14] developed a hybrid algorithm for CTC, based on inversion and maximization methods, and showed the effect of view orientation and noise on reconstruction accuracy using numerical object and actual flames. It has been also pointed out that addition of *a priori* information into the algorithm improves the performance.

In this paper, Direct-3D reconstruction using MENT is studied. The proposed method, owing to its nature of carrying out the reconstruction of the entire 3D field in single pass, is assumed to capture the inter-plane phenomena much better than slice-by-slice reconstruction methods and therefore, is assumed to result in lower reconstruction errors. It is compared with 2D MENT with the help of studies on a mathematical object and studies are conducted to observe change in error corresponding to change of different parameters such as, number of projections and view angle of the projections. Effect of noise in projection data, which is always present in physical systems, is also studied. Lastly, single camera images are also taken for stable flames from a candle and a burner, and they have been used to reconstruct the intensity fields of the same. Section 2 describes the 3D reconstruction problem, the MENT algorithm, and Monte Carlo simulation to calculate volume of intersection between a light beam and a voxel. Detailed analyses of the proposed algorithm using a mathematical object, with focus on reduction in reconstruction error and robustness, are presented in Section 3. Section 4 presents some representative results from actual flame data from a candle and a burner. Finally, we have summarized the paper.

2. Methodology

2.1. Mathematical representation of images of 3D objects as projections

A flame can be assumed as a 3D distribution of luminous intensity in a volume. Based on this assumption, we choose a distribution of scalar property (f_i) representing flame intensity, inside a cubical volume. The cubical volume is discretized into small voxels

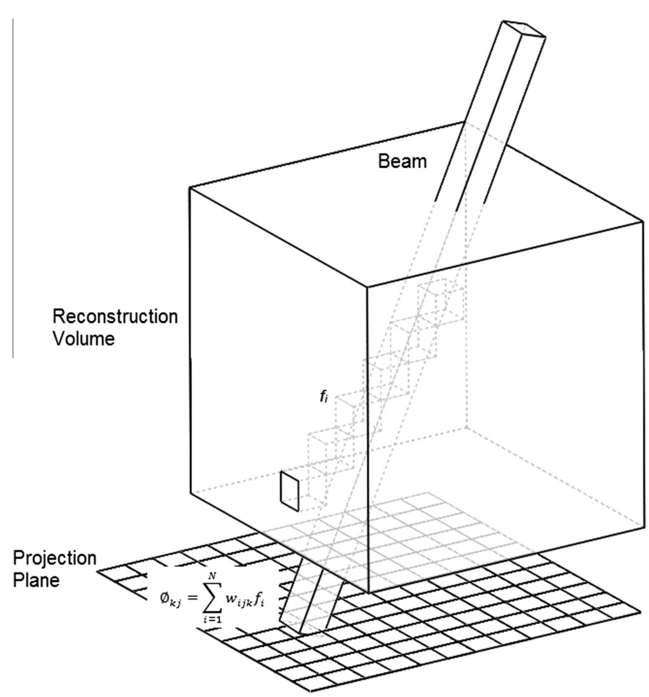

Fig. 1. Visualization of a beam passing through a grid.