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Instantaneous 3D flame imaging by background-oriented schlieren tomography

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ABSTRACT

We apply background-oriented schlieren (BOS) imaging with computed tomography to reconstruct the instantaneous refractive index field of a turbulent flame in 3D. In BOS tomography, a network of cameras are focused through a variable index medium (such as a flame) onto a background of patterned images. BOS data consist of pixel-wise "deflections" between a reference and distorted image, caused by variations in the refractive index along the path between the camera and background. Multiple simultaneous BOS images, each from a unique perspective, are combined with a tomography algorithm to reconstruct the refractive index distribution (or optical density) in the probe volume. This quantity identifies the edges of the wrinkled turbulent flame surface. This is the first application of BOS imaging to flame tomography, setting the stage for low-cost 3D flame thermometry. Tomography is carried out within the Bayesian framework, using Tikhonov and total variation (TV) priors. The TV prior is more compatible with the abrupt spatial variation in the refractive index field caused by the flame front. We demonstrate the suitability of TV regularization using a proof-of-concept simulation of BOS tomography on an LES phantom. The technique was then used to reconstruct the instantaneous 3D refractive index field of an unsteady natural gas/air flame from a Bunsen burner using a 23-camera setup. Our results show how BOS tomography can capture and visualize 3D features of a flame and provide benchmark data for simulations.

1. Introduction

Industrial combustion often involves turbulent flames, having structures that span a large range of length and time scales, increasing mixing and heat transfer. Flame front propagation is determined by local stoichiometric conditions and turbulent mixing [1]. Turbulence-chemistry interactions are key to flame ignition and stabilization; the formation of pollutants, including NO_x and soot; the onset of flash back and engine knock; and the overall efficiency of energy conversion. Turbulent combustion simulation is essential for designing next-generation clean gas turbines, coal combustors, chemical reactors, and piston engines, among other devices, which can reduce the cost of combustion and mitigate its harmful effects. These simulations must be benchmarked against experimental measurements of temperature, velocity, species concentration, flame front geometry, and other parameters to ensure validity of the numerical model.

Data for benchmarking can be obtained from physical probing or optical diagnostics. The latter are generally favoured since the former cannot provide sufficient spatial resolution to capture the structures of interest in a turbulent flow. Moreover, unlike physical probes, optical systems do not normally perturb reactions and transport processes in the flame. In laser-based absorption spectroscopy, a collimated light source is shone through a gas mixture at a wavelength aligned with a spectral feature that is unique to the target molecule [2]. The attenuated intensity signal is compared to a reference to infer line-integrated quantities of temperature, pressure, velocity, and composition [3,4]. This line-of-sight (LOS) treatment can be extended to planar imaging with multiple measurements and a tomography algorithm [5]. Laser-induced fluorescence (LIF) uses a laser sheet to excite target molecules and a camera system, typically positioned normal to the laser sheet, to capture fluorescence from the imaging plane [6]. Multispectral signals and tracers are employed to quantify the temperature and composition of targets [7] and the plane can be swept through

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the domain and imaged from multiple angles to obtain quasi-instantaneous volumetric information [8]. Raman and Rayleigh spectroscopy are based on inelastic and elastic collisions, respectively, between light from a laser and a participating medium [9]. In these experiments, light is scattered by the medium in proportion to a target molecule's scattering cross section; the target's thermodynamic state is inferred from the shift in energy between incident and scattered light.

Raman, Rayleigh, LIF, and absorption spectroscopy have been combined to generate rich data sets to benchmark simulations [10]. Each of these techniques yields high-resolution measurements and advanced setups can simultaneously image multiple quantities. At the same time, laser-based approaches are costly; feature intricate optics, controls, and data acquisition systems; and pose cost and safety concerns that limit the mobility of the apparatus and range of potential targets. More fundamentally, the vast majority of laser diagnostics are limited to 2D measurement. (Advances in volumetric LIF and 3D absorption tomography are recent exceptions.) Quantitative 3D measurements of combustion variables are required to obtain key statistics, including fluctuations in curvature, out-of-plane dissipation rates, and the destruction of flame wrinkling. The need for instantaneous 3D data and the high cost and complexity of laser diagnostics motivate the development of alternative devices for combustion measurement.

The refractive index of a heated gas or flame has long been used to estimate the distribution of temperature and visualize density gradients in a compressible flow [11]. Measurements of optical density are made by schlieren imaging, which captures the deflection of light rays caused by gradients in the refractive index field. Conventional schlieren arrangements comprise an intricate system of lenses and mirrors that focus light from a calibrated source onto a detector. Light rays that pass through the measurement domain follow a curved path due to the variable speed of electromagnetic waves in the medium. The resulting image contains deflected patterns of light, relative to a reference image. Visualizing these deflections offers a direct, qualitative account of the density and temperature. In some cases, quantitative data can be extracted from schlieren images through post-processing [12–14].

Background-oriented schlieren (BOS) considerably simplifies the optical setup required to obtain information about light deflections. In BOS, a camera is focused on a background pattern, positioned behind the probe volume; the pattern is distorted by refraction through the variable index medium. Image processing tools identify the direction and magnitude of deflections in the background plane between a reference and deflected image. The resulting pixel-wise defections constitute a BOS image. BOS was first demonstrated by Dalziel et al. [15], on the internal wave field in an oscillating cylinder, and Raffel et al. [16], who visualized the rotor wake from a helicopter in hovering flight. Numerous gas-phase jets and flames have since been characterized using BOS, as reviewed by Meier [17]. Recent improvements to BOS include the use of a telecentric optical system to accurately measure supersonic flow [18] and coloured patterns to improve the detection of deflections from a distorted image [19].

Deflections in BOS are related to local variation in the refractive index by a Fredholm integral equation of the first kind (IFK), carried out along the optical path. IFKs also form the basic measurement model in classical computed tomography. As a result, multiple BOS images, each from a unique perspective, can be combined to tomographically-reconstruct the refractive index distribution in a measurement volume. Estimates of the refractive index values can be used to infer quantities such as density and temperature and to identify the location of the flame front, characterized by steep gradients in the estimate. Tomographic deconvolution of BOS data is an ill-posed inverse problem, since the inverse measurement operator amplifies noise, and additional information must be included to reconstruct the refractive index field. The accuracy of supplemental information plays a large role in the accuracy of reconstructions and is thus a focus of research on tomography.

Atcheson et al. [20] reported the first demonstration of BOS tomography, which they used to estimate the density of an unsteady gas flow. Subsequent studies followed suit, using multi-camera BOS setups to reconstruct the instantaneous density distribution in natural convection flows, turbomachines, and free-shear gas jets [21–31]. In the case of heated jets of known composition, temperature is obtained by substituting the density field into the ideal gas law. The initial formulation of Atcheson et al. [20] requires three stages: identification of the deflections, reconstruction of the refractive index gradients, and inference of the refractive index field from its gradients via Poisson integration. Nicolas et al. [28] introduced gradient operators into the measurement model and thus combined the second and third stage. As a result, the refractive index is directly reconstructed from BOS deflections. Recently, Lang et al. [31] used a single camera and phase-averaged measurements to infer the temperature of a swirling gas jet, heated by a coil, intended as a surrogate for swirl combustion. However, the BOS literature contains no reports of 3D combustion tomography.

This paper presents the first such application of BOS: we show instantaneous 3D reconstructions of an unsteady flame using phantom measurements and experimental data. Reconstruction accuracy hinges on the veracity of the measurement model and inclusion of prior information that is compatible with flow field attributes. In order to test our reconstruction algorithm, we prototyped BOS tomography with an LES phantom, consisting of a realistic optical density field for a turbulent swirl flame. We introduced a projection matrix to the measurement model to transform hypothetical 3D deflections into apparent deflections in the image plane, reducing model error by up to 63%. Next, a proof-of-concept experiment was carried out using a set of 23 cameras to resolve accurate, instantaneous, 3D features of an unsteady laboratory Bunsen flame. Instantaneous and mean reconstructions of the flame are presented. We show, conclusively, that BOS tomography can be applied to volumetric flame imaging. Moreover, as the technique is readily extended to time-resolved imaging, BOS tomography can provide important information about complex structures in turbulent combustion.

2. Background-oriented schlieren tomography

Background-oriented schlieren tomography reconstructs the refractive index field, n, within a transparent medium from light deflections due to gradients in n. Spatial variation of n, in turn, is caused by variations in temperature and composition. BOS data consists of deflections, inferred from a pair of images: a reference image, captured through a uniform refractive index field, and distorted image, where ray paths have been refracted by a variable index medium. Figure 1 illustrates three aspects of BOS tomography: (a) simultaneous measurement with a system of cameras; (b) a curved ray path through an inhomogeneous medium; and (c) a sample estimate.

Reconstruction requires discretization of the probe volume, typically into cubic voxels that contain a uniform distribution of n, and a measurement model that relates n to the deflections. The BOS measurement equations act as a smoothing kernel; inverting these equations to infer n amplifies noise, which makes the inference ill-posed. Therefore, supplemental information about the distribution of n is required to generate physically-plausible estimates. Here, we present the imaging tool used to sense deflections, measurement model, and reconstruction algorithm for BOS tomography.