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Imaging light ray deviations for reactive supersonic flow sensing and tomography

Olivier Léon^{1,†}, David Donjat¹, Pierre Doublet¹, Adrien Langenais², Aurélien Plyer³,
Frédéric Champagnat³

¹DMPE, ONERA, Université de Toulouse, France

²DMPE, ONERA, Université Paris-Saclay, France

³DTIS, ONERA, Université Paris-Saclay, France

† olivier.leon@onera.fr

Abstract: This work demonstrates the application of high-speed Background Oriented Schlieren for the quantitative analysis of reactive supersonic jets. Tomographic reconstructions of refractive index fields are compared with OH^{*} visualizations and a reactive RANS model. © 2024 The Author(s)

1. Introduction

High-speed gases exhausted by space launchers and rockets often form imperfectly-expanded reactive supersonic jets, characterized by shock-cells and high-temperature flames, as depicted in Figure 1(a). Quantitatively characterizing such jets poses significant metrological challenges. In this context, this study investigates the applicability of Background Oriented Schlieren (BOS), a line-of-sight technique aiming at measuring light ray deviations [1]. With this technique, optical deviations are determined from images of a textured background captured by a camera, with the inhomogeneous refractive index field induced by the flow located between them, as illustrated in Figure 1(b).

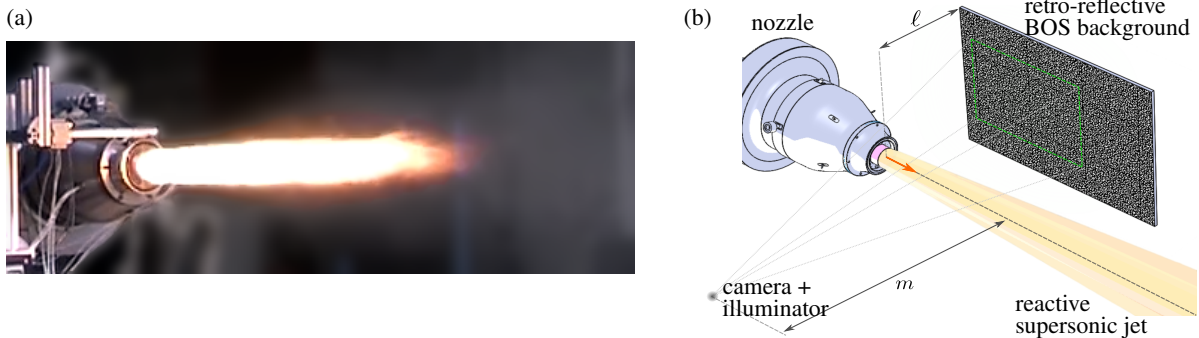


Fig. 1. (a) Photograph of the reactive supersonic jet; (b) Schematic of the BOS setup.

2. Experimental setup

The supersonic reactive jet considered in this work is generated by a small-scale Solid-propellant Rocket Motor (SRM) with an exit nozzle diameter $D = 40$ mm. A non-aluminized propellant is used to avoid the presence of alumina particulates that could otherwise prevent proper observation of the background pattern through the flow. Two flow configurations are investigated: one with the supersonic jet alone, and another with an annular supersonic co-flow of air. The stabilized regime of the jet lasts for approximately 1.7 s while the total experiment duration spans about 4 s.

High-speed BOS measurements were conducted using a high-repetition-rate laser providing short-duration pulses of 100 ns at $\lambda = 527$ nm. A matched laser line band-pass interference filter was installed on the camera lens to reject most of the flame emission. Satisfactory signal-to-noise ratios were achieved by printing the BOS background pattern on a retro-reflective panel. A high-speed 4 MPx camera operating at 800 fps in full-frame and synchronized with the laser provided about 1300 flow snapshots during the useful time window of the experiment.

In addition to BOS measurements, high-speed UV visualizations were performed using a HiCATT intensifier and a 10 nm band-pass filter centered at 310 nm. These visualizations offer a qualitative assessment of the spatial distribution of the hydroxyl radical OH^{*}, a direct combustion by-product.

3. Axisymmetric fields of refractive index

Averaging instantaneous optical deviations measured by BOS yields mean deviation maps. In Figure 2(a), the norm of mean deviations obtained for the case without co-flow is depicted, showing a satisfactory signal-to-noise ratio and well-captured shock cells along the jet axis. The corresponding averaged UV visualization is displayed in Figure 2(b), indicating after-burning for $x/D > 7.5D$, after the third shock-cell observed in BOS measurements.

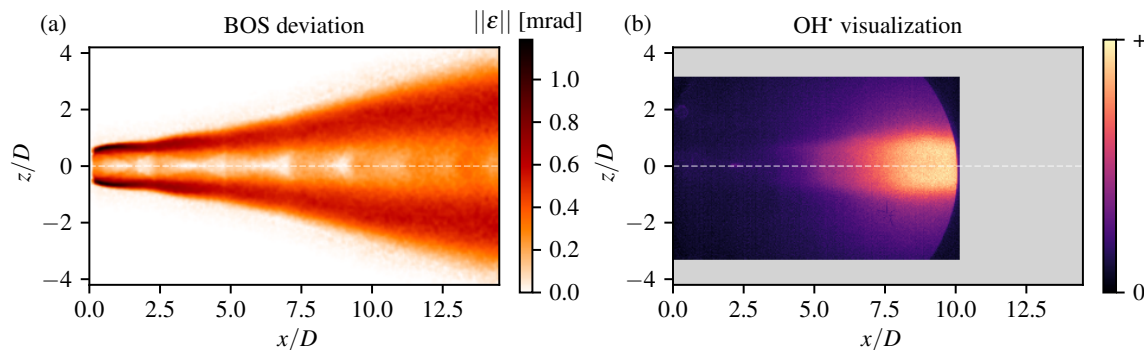


Fig. 2. (a) Norm of mean optical deviation $\boldsymbol{\varepsilon}$ measured by BOS; (b) Mean light intensity at 310 nm.

Given the axisymmetry of the mean flow, tomographic reconstruction [2] of the field of refractive index n inducing the optical deviations shown in Figure 2(a) is performed. This reconstruction aims to provide quantitative insight into the spatial distribution of n , a physical quantity sensitive to both compressibility effects and gas composition. A contour plot of the estimated 3D field is displayed in Figure 3(a), providing a clearer description of the structure of the flow.

This estimated field of refractive index can be used to validate a multi-species reactive RANS model developed at ONERA [3]. Figure 3(b) presents a comparison, displaying slices of normalized refractive index estimated by BOS (top half) and extracted from RANS results (bottom half). Although the BOS results are spatially under-resolved due to the optical resolution of the setup, the model shows satisfactory agreement, prompting a more detailed analysis.

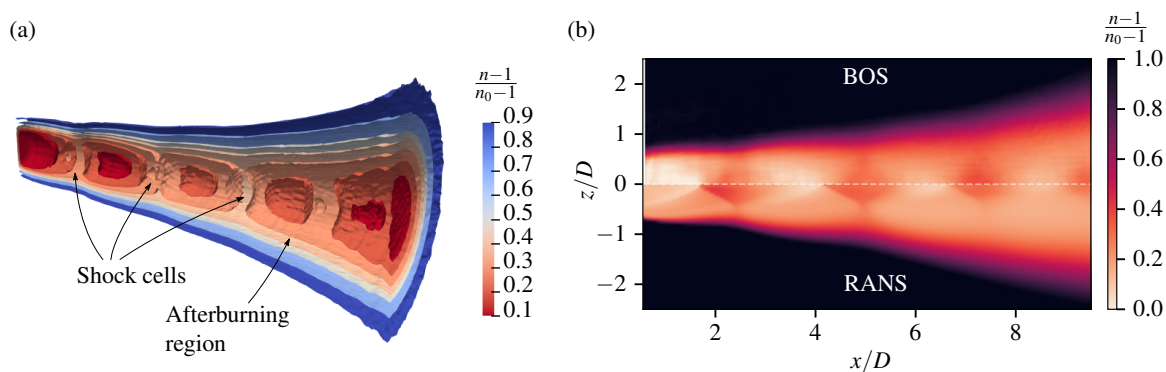


Fig. 3. (a) Reconstruction of the 3D field of refractive index n ; (b) Comparison between BOS reconstruction and a RANS model.

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