

Application of High-Speed Background-Oriented Schlieren (BOS) in Studying Flame-Wall Interaction

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ABSTRACT

This study presents an application of Background-Oriented Schlieren (BOS) to resolve the near wall refractive index field in flame-wall interactions under high temperature reacting flow conditions. BOS is applied to a low-swirling flame impinging on an internally air-cooled surface inclined at 30° relative to the vertical axis. It was applied to capture density gradient structures associated with thermal boundary layer development without direct temperature measurement. Experiments were conducted in a flame-wall configuration with back-side cooling flow of the wall at Reynolds number of 12,000. Adiabatic flame temperatures between 1991 K and 2221 K were obtained by varying equivalence ratio for $\phi = 0.80, 0.90, 1.00$. BOS images were processed using a cross-correlation scheme to extract displacement fields representing line-of-sight refractive-index variations associated with flame-wall interaction and were compared with the OH* chemiluminescence imaging, providing visualization of thermal-field development and regions of heat release. The results demonstrate the capability of BOS to visualize the near-wall flow and temperature structure in high-temperature reacting environments where conventional thermometry is difficult or impractical.

1. Introduction

Background-oriented Schlieren (BOS) is a relatively recent development in optical density-gradient visualization, with the first demonstrations reported by Dalziel et al. (2000) under the name “synthetic Schlieren,” where image correlation of background patterns was introduced to measure density variations in fluid flows (Dalziel et al., 2000). Around the same time, (Raffel et al., 2000) formalized the BOS concept using random dot backgrounds and applied it to large-scale aerodynamic flows, notably helicopter rotor wakes. The principal motivation behind BOS was to simplify traditional optical Schlieren setups by replacing complex mirror and knife-edge arrangements with digital image correlation and incoherent light illumination which significantly improves experimental flexibility and optical accessibility (Raffel, 2015). Over the following two decades, BOS has evolved into a robust diagnostic technique with applications such as

compressible aerodynamics, combustion, jets, shock waves, and industrial flow environments (Schmidt et al., 2025). The development of BOS has been supported by advances in high-speed cameras, LED illumination, and improved correlation and tomographic reconstruction algorithms (Schmidt et al., 2025).

BOS has been under significant development over the past decade, driven by progress in both image-processing algorithm and imaging modalities. Methods for extracting background displacement have expanded beyond standard multi-pass cross-correlation to include iterative least squares (Pan et al., 2009), Fourier demodulation (Wildeman, 2018), and optical flow formulations (Cakir et al., 2023), to improve sensitivity and robustness, especially for small refractive-index changes. On the imaging side, BOS has moved beyond low speed CCD and CMOS cameras. Demonstrated implementations include high-speed imaging for transient flow analysis (Si et al., 2025), plenoptic imaging for depth-resolved reconstruction (Schmidt & Woike, 2021), event-based sensors for fast and long-duration measurements (Lyu et al., 2024), tomographic BOS for three-dimensional density-field recovery (Davis et al., 2022), and even smartphone-based camera intended for field diagnostics (Rabha et al., 2025).

These developments have enabled the application of BOS to a range of flows that generate refractive-index fields with very different characteristics, such as visualization of helicopter rotor wakes (Braukmann et al., 2021) and shock structures of supersonic air craft in flight (Heineck et al., 2021). Recent work has extended these applications into combustion, including studies of laminar Bunsen flames (Cakir et al., 2025), thermoacoustic flame oscillations (Tasmany et al., 2024), and the thermal structures of rocket jet exhaust (Léon et al., 2025). These efforts provide proof of concept for using BOS as a tool for different scenarios, with many additional applications yet to be investigated.

For this work, the interest in flame-wall interaction is motivated by challenges associated with gas-turbine combustor liner cooling, where different methods are used to protect surfaces exposed to high-temperature reacting flows (Greifenstein & Dreizler, 2021). These methods range from internal convection, to effusion, and transpiration cooling (Broumand et al., 2024). Understanding the near-wall thermal flow field, between the flame and inner surface of the liner, is critically important to effectively evaluate the performance of cooling strategies. However, experimental measurement of this region remains challenging, particularly under turbulent combustion conditions where strong temperature gradients and unsteady flow structures are present (Greifenstein et al., 2019). In this context, BOS offers a valuable non-intrusive diagnostic approach, linking measured refractive-index variations to underlying density and temperature gradients (Cakir et al., 2025; Léon et al., 2025). Although BOS provides line-of-sight integrated information

rather than local point, or planar measurements, it remains highly effective for visualizing flow and thermal structures.

This work presents an application of BOS based on cross-correlation analysis to qualitatively capture refractive-index variations generated by the interaction of a swirling natural-gas flame impinging on an internally air-cooled wall under forced-convection. High-speed imaging is employed to measure the time-resolved BOS displacement fields and to enable both reference-based and dynamic BOS. In addition, OH* chemiluminescence imaging is applied to compare the global flame shape with the refractive-index fields obtained from BOS.

2. Background-Oriented Schlieren (BOS)

Figure. 1 illustrates the basic schematic of the BOS setup. In this arrangement, a digital camera is focused on a background pattern composed of randomly distributed dots while the flow of interest lies between the camera and the background. Any spatial variation in gas density arising from thermal gradients or compressibility effects induces a refractive-index gradient that slightly bends the light rays passing through the flow. These deflected rays reach the camera sensor at displaced positions relative with the reference image acquired without the flow. The resulting apparent shift of the background pattern is proportional to the line-of-sight-integrated refractive-index gradient, which reflects the density and temperature field.

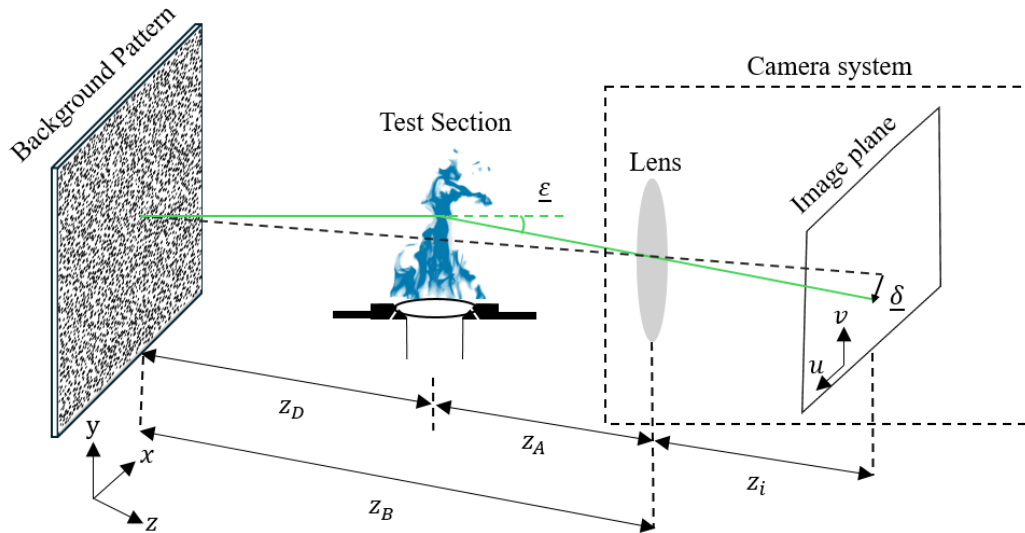


Figure. 1 Schematic of the BOS setup parameters.

According to Figure. 1, to describe the BOS measurement quantitatively, the optical path is idealized as a background flow camera system with distances Z_D (background-to-flow) and Z_A (flow to camera). The total background to camera distance is $Z_B = Z_A + Z_D$, and the image magnification of the optical system is defined as $M = f / (Z_B - f)$, where f is the lens focal length.

When a light ray is refracted by an angle, $\varepsilon = (\varepsilon_x, \varepsilon_y)$, due to local refractive-index gradients, its apparent displacement on the camera sensor, can be written as:

$$\delta u = \psi M Z_D \varepsilon_x \quad (1)$$

$$\delta v = \psi M Z_D \varepsilon_y \quad (2)$$

where ψ is the pixel pitch (pixel/mm). The product $S = M Z_D$ defines the geometric sensitivity of the BOS setup, indicating that larger background distances or longer focal lengths enhance sensitivity, although at the cost of reduced depth of field.

The deflection angles, ε_x and ε_y are related to the refractive index gradient field through the integrated ray equation derived from geometric optics. Assuming small angles and a nearly uniform reference refractive index n_0 , the deflection vector is expressed as:

$$\varepsilon = (1 / n_0) \int \nabla n \, ds \quad (3)$$

where ds is the path element along the ray. For gases of constant composition, the refractive index and density are connected through the Gladstone–Dale relation $n = 1 + G\rho$, with G being the Gladstone–Dale constant. Substituting this relation gives:

$$\varepsilon = (G / n_0) \int \nabla \rho \, ds \quad (4)$$

highlighting that BOS measures the projected density gradient integrated along the line of sight. In practical terms, BOS processing compares a reference background image taken without flow to an image taken with flow to obtain displacement fields $\delta u(x, y)$ and $\delta v(x, y)$, which quantify the optical shifts induced by refractive-index variations. These are typically obtained using multi-pass cross-correlation algorithms similar to those used in particle image velocimetry (PIV), enabling sub-pixel accuracy. The resulting displacement maps can be differentiated to estimate refractive-index gradients, or inverted through Poisson-type reconstruction to recover projected density and, under certain assumptions, temperature distributions (Raffel, 2015).

3. Methodology

The experimental configuration used to investigate flame–wall interaction using BOS is illustrated in Figure. 2. The test section consists of a 400 mm × 600 mm cooled inclined wall incorporating an internal straight cooling channel 16 mm in height. A solid coupon of 189 mm × 289 mm is embedded flush with the surface of the wall. Cooling air is supplied through the internal channel at a bulk Reynolds number of $Re = 8000$ to establish forced-convection conditions along the coupon surface. A premixed burner, positioned below the wall, generates a lifted, turbulent swirling flame. The wall is inclined at 30° from the vertical y-axis and positioned relative to the

burner to ensure flame impingement and lateral flame spread over the coupon surface. The experiments were conducted with natural-gas flames at equivalence ratios of $\phi = 0.8, 0.9, 1.0$ from fuel-lean to stoichiometric condition.

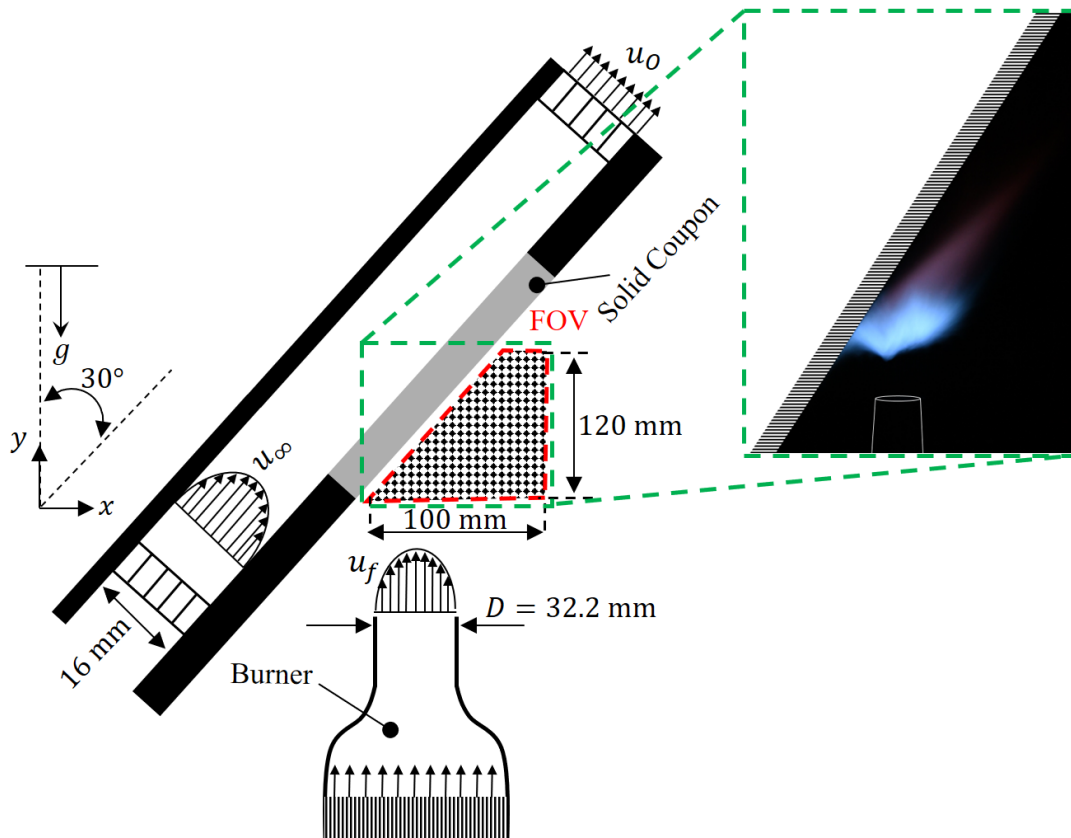


Figure. 2 Schematic of the experimental setup indicating the internally cooled wall along with the burner.

The optical arrangement for BOS and OH^* chemiluminescence imaging is illustrated in Figure. 3. For BOS measurements, a high-power LED light source was employed in a back-illumination shadowgraph configuration shown in Figure. 3(a), projecting uniform light through the background pattern positioned downstream of the test section and observed through the flame-wall interaction region indicated in Figure. 3(b). The background consisted of circular dots with a diameter of 2 mm, randomly distributed to provide optimal spatial correlation properties for displacement-based BOS processing. A high-speed camera (Phantom VEO-E 310L) was used to acquire time-resolved BOS image sequences at a frame rate of 2000 fps, enabling dynamic tracking of refractive-index gradients. This high temporal resolution is important for application of the relative correlation approach, in which each frame is correlated with the immediately preceding image rather than a stationary reference image, allowing the capture of fast transient density-wave propagation and near-wall flow dynamics. As is indicated in Figure. 3(b), the field of view was $100 \text{ mm} \times 120 \text{ mm}$, covering the primary flame impingement and surface interaction region.

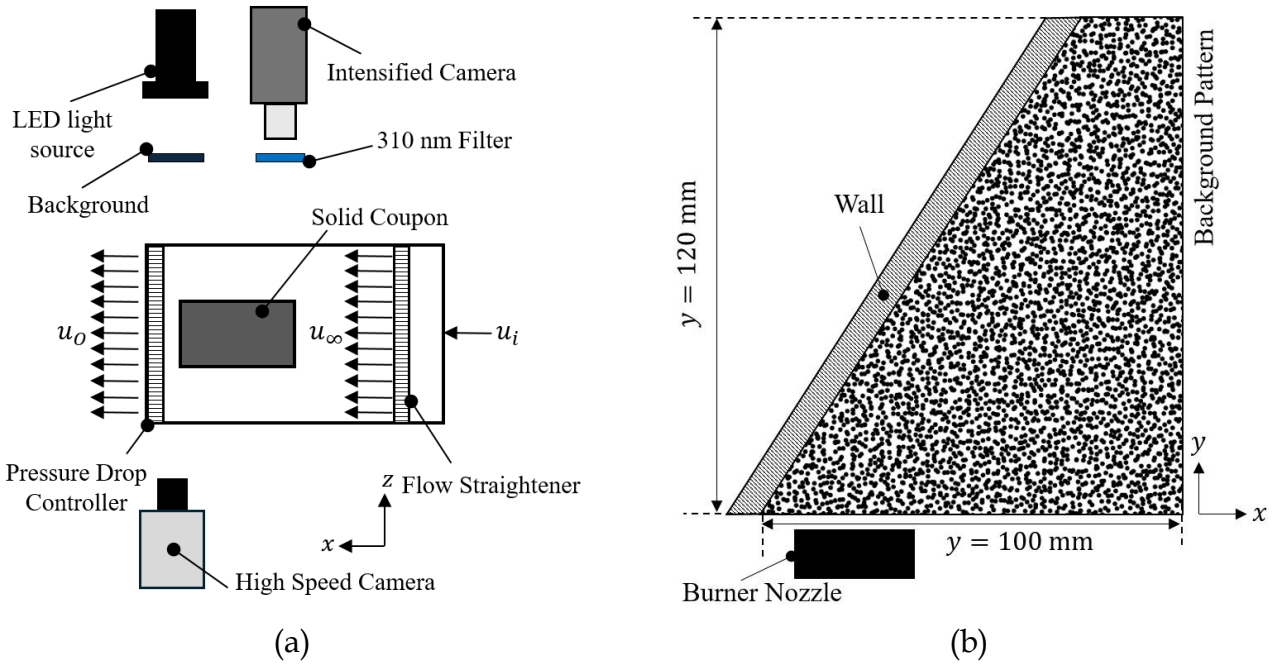


Figure. 3 (a) Top view of the internally cooled wall with the optical configuration for BOS and OH*

chemiluminescence imaging. (b) zoomed view of the BOS field of view (FOV) indicating the used pattern.

For OH* chemiluminescence imaging, an intensified CMOS camera (LaVision NanoStar) with an UV lens (Cenco 100 mm, f2.8) was employed, equipped with an optical 10 nm band-pass filter with central wavelength (CWL) of $\lambda = 310$ nm (Edmund Optics, #34-980). The camera operated with a gate width of 1 ms and an intensifier gain setting of 20 % to selectively capture the weak spontaneous radical emission while minimizing background luminosity. OH* image acquisition was conducted at a frame rate of 10 Hz, providing spatially-resolved visualization of the flame and complementing the fast BOS measurements by mapping the mean and instantaneous flame structures in the vicinity of the cooled inclined wall.

3. BOS Processing

BOS image processing was performed based on the cross-correlation of background images to determine the apparent displacement of background features induced by line-of-sight refractive-index gradients in the flow field. For each interrogation window (IW), a least-squares minimization of the cross-correlation peak is used to estimate sub-pixel displacements in both horizontal (δx) and vertical (δy) directions. Two processing schemes were employed: (i) a reference-based approach, in which each distorted image is correlated with a stationary background reference recorded without flow or flame, and (ii) a dynamic (relative) approach, in which consecutive frames are correlated to extract time-resolved displacement fields suitable for capturing rapidly evolving density structures. The latter method is effective for high-speed measurements, as it minimizes decorrelation errors caused by background drift and enables reconstruction of transient wave propagation and flame-wall interaction dynamics.

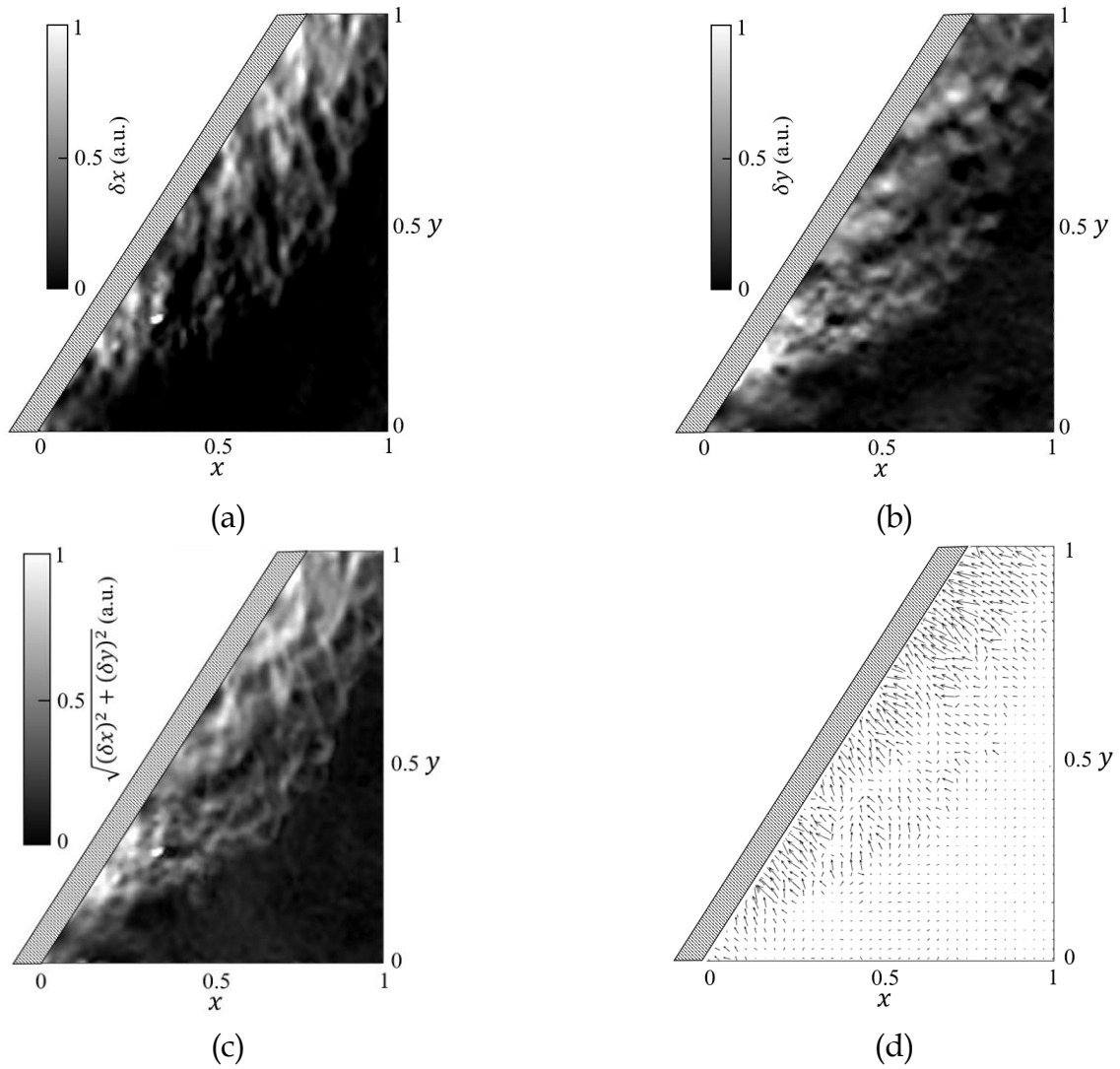


Figure. 4 Processed instantaneous displacement fields: (a) horizontal displacement (δx), (b) vertical displacement (δy), (c) total displacement magnitude $\sqrt{(\delta x)^2 + (\delta y)^2}$, and (d) corresponding displacement vector field indicating integrated refractive-index gradient direction and relative intensity. Grayscale bars denote normalized displacement in arbitrary units (a.u.). x and y axes are normalized to max value of the field of view, $x = 100$ mm and $y = 120$ mm.

The representative instantaneous BOS displacement results are presented in Figure. 4 for $\phi = 0.8$. Figure. 4(a) and Figure. 4(b) show the measured background displacements in the horizontal (δx) and vertical (δy) directions, respectively, reflecting the local light-ray deflections generated by refractive-index gradients associated with thermal expansion and combustion products in the flame-wall interaction region. Figure. 4(c) depicts the total displacement magnitude, calculated as $\sqrt{(\delta x)^2 + (\delta y)^2}$, providing a scalar representation of overall density-gradient strength. The grayscale color bars in Figure. 4(a)–(c) are expressed in arbitrary units, as BOS directly calculates the relative displacement amplitudes rather than absolute refractive-index values. Figure. 4(d)

shows the corresponding displacement vector field, where vector orientation indicates the local direction of refractive-index gradient integrated along the optical path, and vector magnitude represents the relative intensity of the density gradients.

4. Results

Figure. 5 presents the instantaneous and ensemble-average BOS results of the flame-wall interaction region based on the total background displacement magnitude for $\phi = 0.8$. Figure. 5(a) and (b) show two instantaneous frames capturing the unsteady nature of the refractive-index field driven by turbulent flame structures and plume impingement on the inclined wall. These snapshots show localized regions of elevated displacement intensity associated with thermal gradients generated by flame-wall impingement and wrinkling near the wall surface. Figure. 5(c) displays the ensemble-averaged total displacement field, which smooths the short-time turbulent fluctuations and highlights the persistent features of the interaction, including the mean flame impingement region and the downstream development of the thermal boundary layer along the wall. Higher intensity indicates regions with higher displacement representing regions with higher refractive index variation. Assuming the temperature is the main cause of the density variation, it can be inferred that regions with higher intensity are qualitatively associated with higher temperature. For the ensemble-averaged field, the intensity additionally reflects the persistence and stability of these structures over time. The displacement magnitude is reported in normalized arbitrary units, providing a relative measure of integrated density-gradient strength and enabling direct qualitative comparison between instantaneous and mean flow structures across the measurement domain.

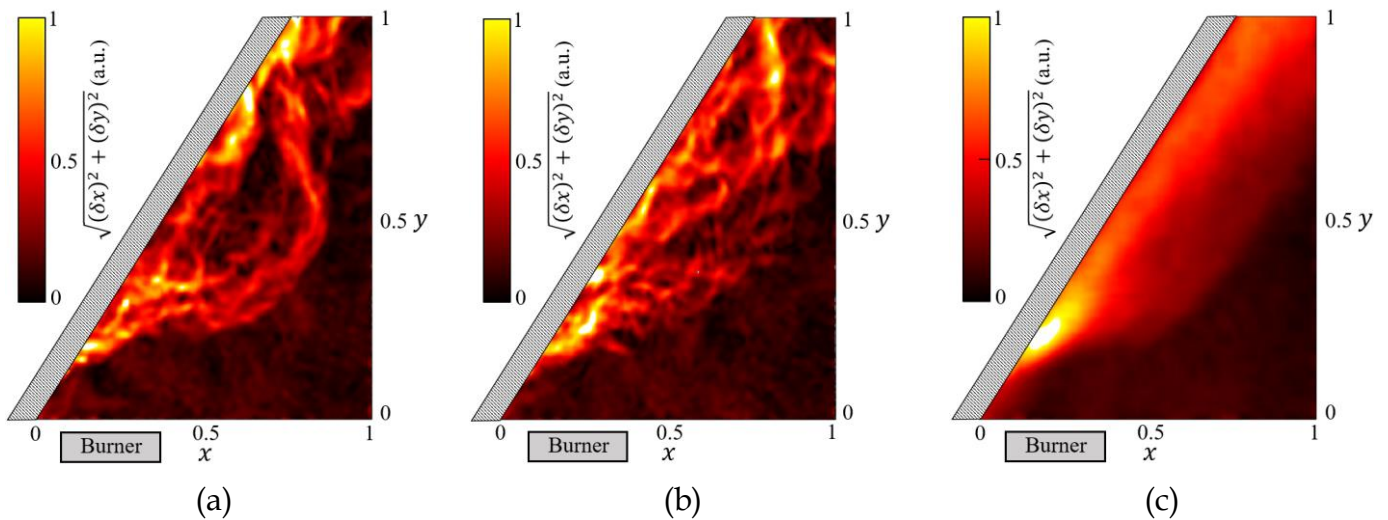


Figure. 5 Instantaneous (a), (b) and ensemble-averaged (c) of the total BOS displacement magnitude fields for equivalence ratio of $\phi = 0.8$.

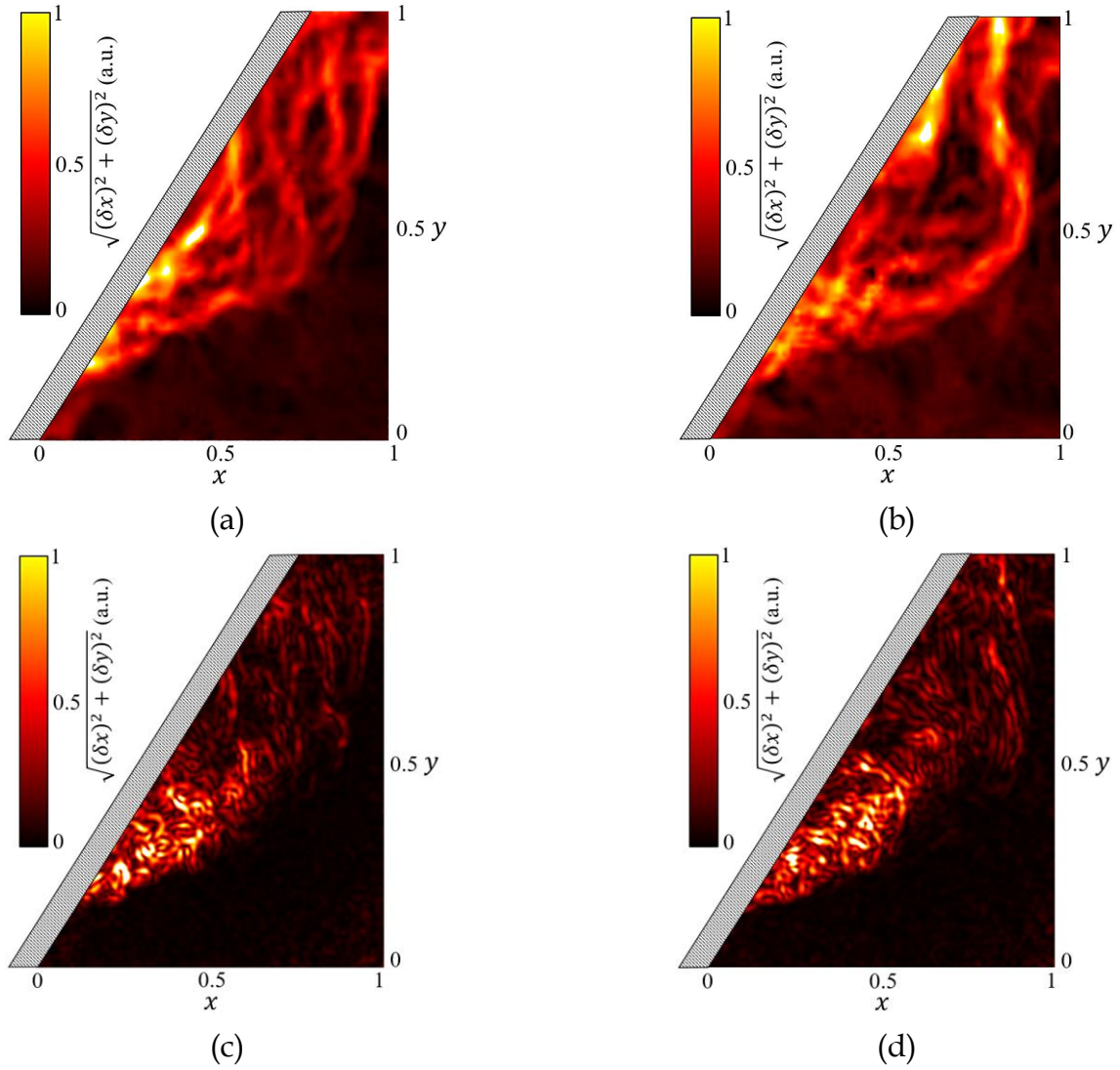


Figure. 6 Reference-based BOS (a), (b) and dynamic BOS (c), (d) of the total displacement magnitude fields for equivalence ratio of $\phi = 0.8$. (a) and (c), (b) and (d) are at the same time.

The reference-based and dynamic BOS methods are compared in Figure. 6 for instantaneous results of $\phi = 0.8$. The interrogation window size was used for both processing schemes are the same as $IW = 13$ pixels, and the temporal separation between frames in the dynamic BOS analysis was $\Delta t = 0.5$ ms. The same interrogation window size ($IW = 13$) was used for both processing schemes, and the temporal separation between frames in the dynamic BOS analysis was $\Delta t = 0.5$ ms. Figure. 6(a) and (b) indicate the instantaneous displacement-magnitude fields computed using the reference-based BOS method, where each image is correlated against a background recorded at uniform density. These fields resolve the large-scale refractive-index variations associated with the flame impingement region and the near-wall thermal field. Figure. 6(c) and (d) show the corresponding results obtained using the dynamic BOS method, in which consecutive frames are correlated. This approach highlights short-time refractive-index fluctuations and

indicates finer flow and thermal structures near the wall that are less apparent in the reference-based measurements.

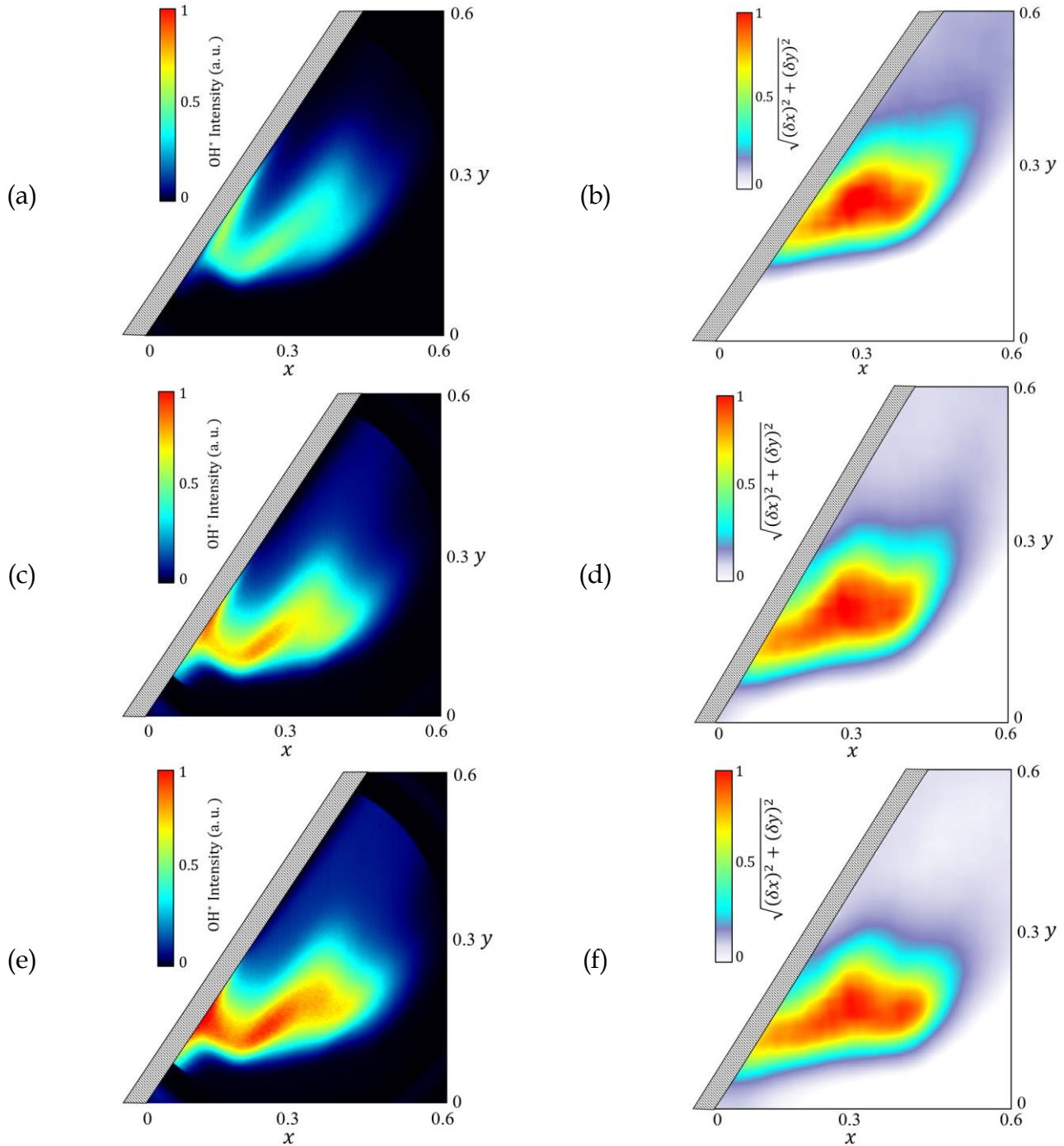


Figure. 7 Ensemble-averaged OH* chemiluminescence fields (a, c, e) and corresponding BOS displacement-magnitude fields (b, d, f) for equivalence ratios $\phi = 0.8, 0.9$, and 1.0 . For both datasets, the color scales are reported in arbitrary units normalized to maximum value across different equivalence ratios.

Figure. 7 compares ensemble-averaged flame structures obtained from OH* chemiluminescence imaging with corresponding averaged BOS displacement-magnitude fields, for equivalence ratios of $\phi = 0.8, 0.9$, and 1.0 . The OH* results, shown in Figure. 7(a), (c), and (e), depict the spatial distribution of mean reaction-zone luminosity as the flame impinges on and develops along the inclined wall. Across all three equivalence ratios, the flame brush becomes wider with increasing equivalence ratio. In addition, the flame shifts upstream along the inclined plate at higher equivalence ratios. With increasing equivalence ratio from $\phi = 0.8$ to $\phi = 1.0$, the primary change is an increase in OH* signal intensity, reflecting higher heat-release levels rather than a modification of the flame shape or position.

The corresponding BOS ensemble-averaged displacement magnitude fields, shown in Figure. 7(b), (d), and (f), capture the mean refractive-index gradients generated by the combined effects of thermal expansion and hot-gas transport within the flame-wall interaction layer. A direct comparison between the OH* chemiluminescence fields and the corresponding BOS displacement-magnitude fields shows good agreement in the overall shape and location of the flame-wall interaction region. In the OH* images, the highest signal intensity is concentrated close to the wall, with a clear peak at the center of the intensity profile. The BOS results exhibit a similar spatial distribution, with the strongest displacement further from the wall located in the central part of the same overall structure. Across equivalence ratio, similar to OH* signal, the BOS fields shifts upstream along the inclined plate with increasing equivalence ratio. However, the intensity variation is not significant across these three equivalence ratios.

Figure. 8 compares the ensemble-averaged OH* chemiluminescence and BOS displacement-magnitude fields for the $\phi = 0.8$ condition. The iso-contours extracted from the OH* field (Figure. 8(a)) and the BOS field (Figure. 8(b)) reveal several common spatial features, including the general location of the flame-wall interaction region and the orientation of the dominant structure along the inclined wall. The contour overlay in Figure. 8(c) shows partial overlap between the two diagnostics, while also highlighting differences in their spatial extent and distribution. As can be observed, BOS contours occupy a larger area and extend farther from the wall than the corresponding OH* contours. This trend is quantified in Table 1, where the area ratio defined as $(A_{OH^*}/A_{BOS})_{I^*=s^*=0.3}$ is 0.50, indicating that the BOS-defined structures extend over a larger spatial region than the corresponding OH* contours. This behavior is expected because the two techniques respond to different physical quantities. Whereas OH* chemiluminescence is primarily associated with the reaction zone, BOS reflects refractive-index gradients arising from density variations throughout the optical path, including both the reacting region and the surrounding hot-gas field.

The normalized cross-correlation map shown in Figure. 8(d) exhibits a maximum correlation coefficient near zero spatial offset, indicating that the dominant structures identified by the two diagnostics are spatially related. However, the finite width of the correlation peak and the differences observed in the contour comparison suggest that the BOS response is not limited to the regions of peak chemiluminescence and captures additional thermofluid structures outside the reaction zone.

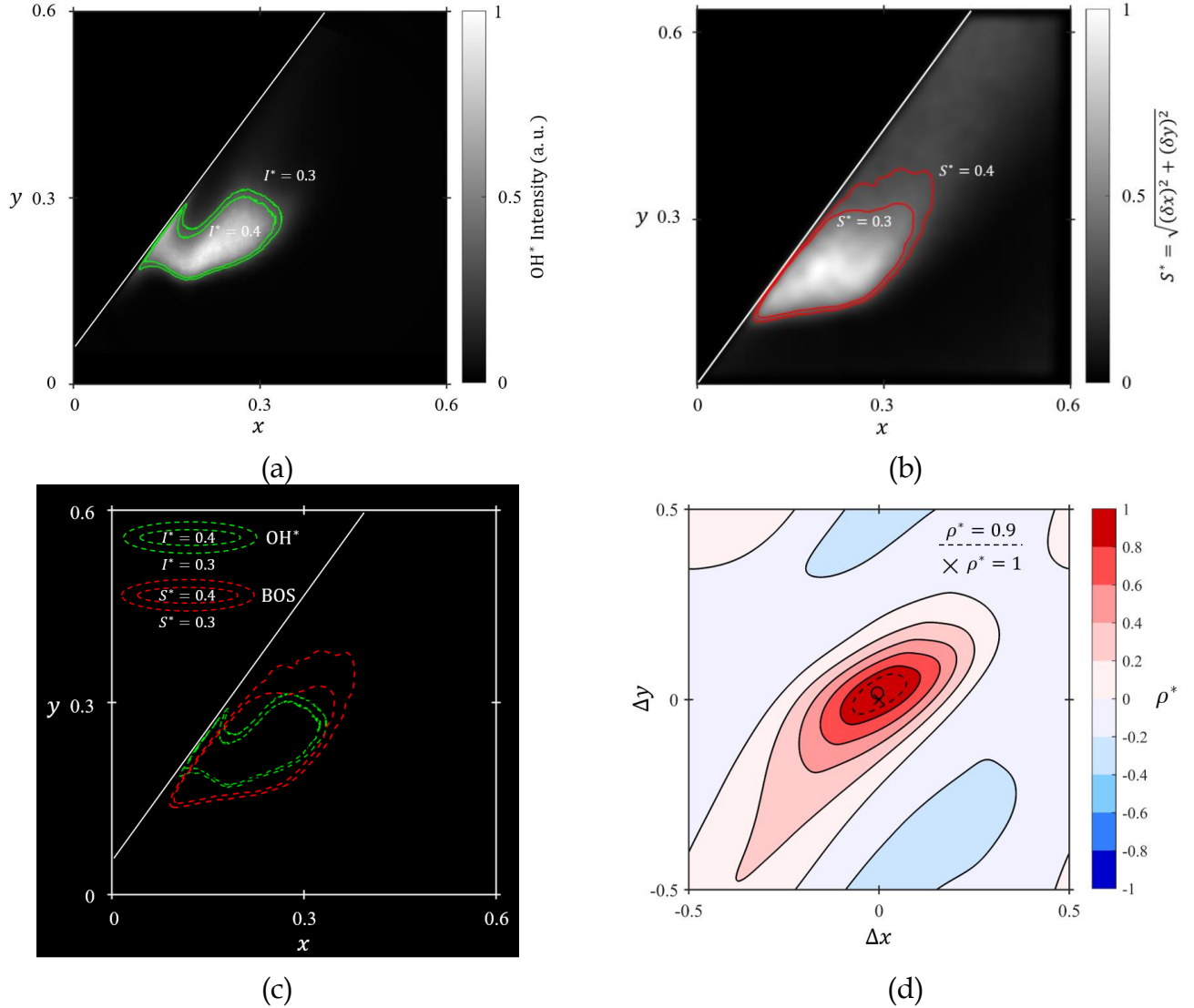


Figure. 8 (a) Ensemble-averaged OH* chemiluminescence field for equivalence ratios $\phi = 0.8$ with iso-contours of $I^* = 0.3$ and 0.4 highlighted on the map. (b) corresponding BOS displacement-magnitude field with iso-contours of $s^* = 0.3$ and 0.4 highlighted in the map. (c) Overlap of the iso-contours for OH* chemiluminescence and BOS displacement-magnitude. (d) Cross-correlation map of the two signals, i.e., OH* and BOS.

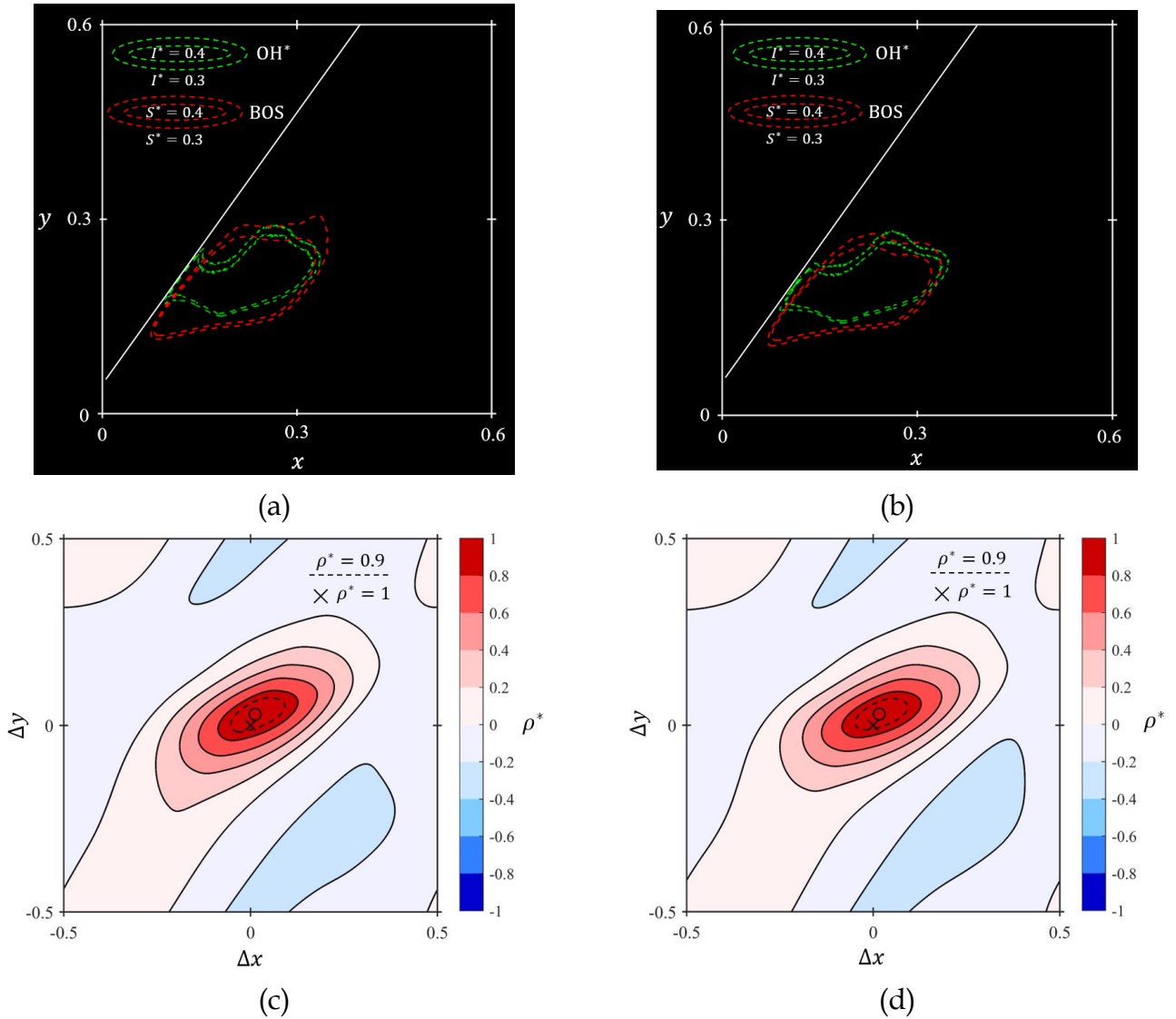


Figure. 9 (a), (b) Overlap of the iso-contours for OH* chemiluminescence and BOS displacement-magnitude for equivalence ratios of $\phi = 0.9$ and 1.0 , respectively. (d) Cross-correlation map of the two signals, i.e., OH* and BOS for equivalence ratios of $\phi = 0.9$ and 1.0 , respectively.

The same analysis was repeated for the $\phi = 0.9$ and 1.0 cases, and the results are presented in Figure. 9. Similar to the $\phi = 0.8$ condition, the contour overlays reveal comparable overall shapes and orientations between the OH* and BOS fields, while the BOS contours consistently enclose a larger region than the corresponding OH* contours. The cross-correlation maps shown in Figure. 9(c) and (d) exhibit distributions similar to those observed in Figure. 8(d), with the correlation maximum located close to zero spatial offset. The peak correlation coefficients reported in Table 1 remain high for all equivalence ratios, increasing from 82.9 % for $\phi = 0.8$, indicating a strong spatial correspondence between the dominant structures identified by the two diagnostics. At the same time, the area ratios reported in Table 1 confirm that the BOS-derived structures consistently occupy a larger spatial region than the corresponding OH* contours. Taken together, the contour

comparison, area-ratio analysis, and cross-correlation results indicate that although OH* chemiluminescence and BOS displacement magnitude originate from different physical mechanisms, both diagnostics capture related large-scale features of the flame-wall interaction while emphasizing different regions of the reacting flow field.

Table. 1 Croos-correlation peak and Area ratio of the OH* over BOS for three different equivalence ratios.

	$\phi = 0.8$	$\phi = 0.9$	$\phi = 1.0$
$\rho^* = \rho(BOS, OH^*)$ (%)	82.9	83.6	84.3
$A^* = (A_{OH^*}/A_{BOS})_{I^*=s^*=0.3}$	0.50	0.63	0.75

The correlation between the OH* and BOS fields is consistent with previous combustion-oriented BOS investigations reported earlier. In the study of laminar Bunsen flames, Cakir et al. (2025) demonstrated that BOS captures the overall flame structure while extending beyond the chemiluminescence-defined reaction zone due to its sensitivity to the surrounding heated-gas region and secondary thermal structures like hot-product convection regions. Similarly, Tasmany et al. (2024) showed that BOS-type measurements strongly correlate with flame heat-release dynamics while simultaneously responding to turbulent thermal convection and refractive-index fluctuations outside the localized combustion zone. The present results follow the same trend. Despite the fundamentally different physical origin of the two diagnostics, the high cross-correlation coefficients exceeding 80 % together with the near-zero displacement of the correlation peak indicate that the dominant large-scale flame structures identified by BOS and OH* remain spatially aligned. At the same time, the consistently larger BOS-defined area suggests that the BOS signal extends beyond the primary heat-release layer and includes additional thermofluid structures associated with hot-product transport, turbulent mixing, thermal diffusion, and wall-influenced gradients generated during flame-wall interaction. The effect becomes more pronounced at $\phi = 0.8$, where the flame operates closer to the lean extinction limit and is therefore more prone to local quenching, intermittent heat release, and turbulent fluctuations. Under these conditions, the difference between the BOS and OH* areas becomes larger, resulting in a smaller area ratio, A_{OH^*}/A_{BOS} . As the equivalence ratio increases toward stoichiometric conditions, the BOS and OH* areas become progressively closer, leading to an increase in the area ratio from 0.50 to 0.75 and suggesting a reduction in fluctuation-driven thermal spreading and a stronger confinement of the thermal field around the stabilized reaction zone. A similar trend is also observed in the cross-correlation analysis, where the peak correlation coefficient increases slightly from 82.9 % to 84.3 % with increasing the equivalence ratio, indicating that the BOS and OH* structures become marginally closer in shape and spatial distribution, although the increase remains relatively small.

5. Conclusions

This study presented an application of high-speed Background-Oriented Schlieren (BOS) to investigate flame-wall interaction in a combustor-liner-like configuration consisting of a turbulent swirling natural-gas flame impinging on an internally cooled inclined wall. Reference-based and dynamic BOS processing were employed to visualize the refractive-index gradients associated with flame impingement and hot-gas stream within the near-wall region. The measurements demonstrated the capability of BOS to resolve both the mean thermal structures and the transient density-gradient fluctuations present in the flame-wall interaction zone under high-temperature reacting-flow conditions. Comparison of the two processing approaches showed that dynamic BOS highlighted short-time refractive-index fluctuations and finer-scale structures, while reference-based BOS provided a clearer representation of the mean thermal field. Comparison with OH* chemiluminescence revealed that, although the two diagnostics are sensitive to different physical quantities, they captured related large-scale features of the flame-wall interaction region and exhibited high peak spatial correlation coefficients ranging from 0.80 to 0.85 across the investigated equivalence-ratio range. At the same time, BOS consistently identified a larger spatial extent than OH* chemiluminescence, reflecting its sensitivity to density and temperature gradients throughout the thermal field rather than solely to the reaction zone.

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