Experimental and Computational Studies of Mixing in Supersonic Flow

Ross A. Burns¹, Heeseok Koo², Noel T. Clemens³, and Venkat Raman⁴
Center for Aeromechanics Research
Department of Aerospace Engineering and Engineering Mechanics
The University of Texas at Austin
Austin, TX 78712

A preliminary combined experimental and computational investigation is conducted on the mixing characteristics of a strut-based hypermixer in a Mach 3 freestream. The hypermixing flow-field is generated by an injection pylon with expansive wedges to enhance the streamwise vorticity. Two different scalar visualization techniques are used to examine the underlying mixing processes. Planar laser scattering of condensed carbon dioxide gas is used to visualize the freestream flow, whereas two-photon planar laser-induced fluorescence (PLIF) of krypton gas is used to mark the injected jet fluid. The experimental results are compared directly to a large-eddy simulation (LES) of the same flow-field. The results obtained are complimentary because the experimental data can aid in the validation of LES models, and the simulations provide information about the thermodynamic property variations that affect the interpretation of the krypton PLIF signal.

Nomenclature

\[ A = \] Einstein A coefficient
\[ a = \] laser beam diameter
\[ d = \] injection jet diameter
\[ E_1 = \] laser pulse energy
\[ F = \] temporal profile of laser pulse
\[ h = \] hypermixer base height
\[ \hbar = \] Planck constant over \( 2\pi \)
\[ k = \] Boltzmann constant
\[ n_i = \] number density of species \( i \)
\[ n_0 = \] total number density
\[ P_o = \] stagnation pressure
\[ Q = \] electronic quenching
\[ S_f = \] fluorescence signal
\[ T_o = \] stagnation temperature
\[ \mu_i = \] reduced mass of species \( i \)
\[ \sigma_i = \] quenching cross-section of species \( i \)
\[ \hat{\sigma}^{(2)} = \] two-photon absorption cross-section
\[ \chi_i = \] mole fraction of species \( i \)

¹ Graduate Research Assistant, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin.
² Researcher, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin.
³ Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin.
⁴ Associate Professor, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin.

American Institute of Aeronautics and Astronautics
I. Introduction

At the high Mach number associated with hypersonic flight, allowing the airflow to remain supersonic within the combustor of a scramjet is essential to prevent excessive mechanical loading as well as chemical changes to the air such as dissociation that would be detrimental to combustion efficiency. At supersonic velocities, the residence times needed to accommodate proper mixing of the air and fuel would necessitate extended combustors, which are undesirable in consideration of vehicle size and weight constraints [1,2].

One mixing enhancement strategy that has shown potential for use in scramjet engines is known as a pylon or strut injector with trailing-edge ramps, also known as a hypermixer. Fuel is injected from a strut spanning the airflow in the combustor. Unlike a wall-based injector, which injects fuel transversely to the flow, the fuel introduced by the hypermixer is injected parallel or nearly parallel to the freestream and mixing is achieved by intense vorticity generated at the trailing edge of the hypermixer [3,4]. In supersonic flow, the vorticity is enhanced by the use of compressive and expansive surfaces to create strong pressure gradients.

Studies to this point have been concerned primarily with the mixing enhancement induced by the hypermixer [3-13]. Doster et al. [3,4] have performed complimentary experimental and computational studies on three primary hypermixing geometries with upstream scalar injection including a base supersonic wake, an alternating ramp mixer, and an alternating wedge mixer. The use of planar laser-induced fluorescence of nitric oxide and Raman spectroscopy allowed for visualization of the mixing processes as it progressed downstream. Results indicate enhanced mixing in the near-field with the ramp and wedge injectors, while the far-field mixing was found to be similar in all cases. Simulations performed in Fluent agreed well with the experimental data. References 5, 6, and 7 have studied the mixing characteristics of various geometries with inline fuel injection, including a supersonic base-flow wake, castellated mixers, and combinations of compressive and expansive surfaces using NO-PLIF. The mixers with compression ramps were found to have a much greater impact on the mixing due to large streamwise vorticities that increase the interfacial area between fuel-lean and fuel-rich regions. Others have considered the impact that the addition of the strut has had in terms of pressure losses within a model combustor. Gruenig et al. [8] studied four different strut geometries that included full- and partial-span struts injecting fuel at angles oblique to the flow. The four different geometries were found to have considerably different impacts on the upper and lower wall pressure distributions.

The current joint study seeks to investigate the mixing characteristics of the flow downstream of the strut-based hypermixer through experimental and computational means. A hypermixer featuring a central castellation with expansive wedges was selected as it was shown to have the most significant impact on the flow-field [5-7], and poses complex interactions to challenge the LES models. Laser-based diagnostic techniques were employed to study the mixing characteristics of the field. Planar laser scattering of CO₂ gas was used to visualize freestream flow structures and enabled visualization of the entrainment of freestream fluid within the wake structure. Multiple cross-stream planes were imaged to get a sense of the three-dimensionality of the flow-field. Two-photon planar laser-induced fluorescence of krypton gas was used to visualize the injected gas as it mixed. The experimental data are compared to a large-eddy simulation (LES) of the same flow-field. The development of accurate subfilter models for complex compressible viscous flows coupled with scalar mixing is crucial to future engine design and optimization. This preliminary combined experimental-computational study has as its ultimate goal the improvement of such models and a better understanding of the mixing process.

II. Experimental Program

A. Experimental Facility

Experiments were conducted in the Mach 3 wind tunnel housed in the Flow-field Imaging Lab at The University of Texas at Austin. The wind tunnel is designed with a full-span splitter plate built into the nozzle to allow for wake formation in the test section; the splitter plate thickness, h, is 6.35 mm. The test section has cross-sectional dimensions of 50.8 mm by 50.8 mm. The tunnel is supplied by a 7 m³ storage tank held at 10 atm and exhausts to a 20 m³ vacuum tank evacuated to 60 Torr. Typical operation uses a plenum pressure (Pₚ) of 135 kPa and a stagnation temperature (T_s) of 300K. The test section has an S1-fused silica ceiling window and two acrylic side windows to provide optical access for the laser diagnostic techniques used.
B. Hypermixer Model

The hypermixer was built into a splitter plate that divides the test section of the Mach 3 wind tunnel. Interchangeable attachments to the end of the splitter plate allow for variation of the geometry being studied. Figure 1 shows the layout of the splitter plate and hypermixer model with respect to the test section. The mixer used in this study is depicted in Fig. 2. The design is a castellated base flanked by two expansion wedges with a 10° half angle.

The hypermixer was equipped with a single fuel-injection port of diameter \( d \) equal to 3.175 mm. The jet is injected downstream, parallel to the freestream direction. The jet flow rate could be pulsed by using a fast response solenoid valve with control module (Parker-Hannifin Iota One). Pulsing of the jet flow rate was desirable because in some cases krypton gas was used and pulsing enabled us to reduce the amount of this expensive gas that was used.

![Figure 1: Layout of Mach 3 test section and hypermixer model](image1.png)

C. Planar Laser Scattering (PLS)

Planar laser scattering of carbon dioxide condensate was used to visualize the freestream flow, wave structures, and the mixing of the freestream fluid with the wake or jet fluid. In this technique, CO\(_2\) gas was injected into the freestream air upstream of the plenum at a rate of 150 slpm. As the gas expanded through the supersonic nozzle, the carbon dioxide gas condensed into a fine fog, providing an excellent medium for light scattering. In regions of higher temperature, such as boundary layers or recirculation regions, the condensed fog re-evaporates, and thus no scattering occurs in these regions.

The CO\(_2\) fog was illuminated with a frequency-doubled Nd:YAG laser (Spectra-Physics PIV-400) at 532 nm. The beam was passed through standard sheet-forming optics including a 350 mm spherical lens and a -60 mm cylindrical lens before entering the test section. The sheet illuminated a field of view 50.8 mm or 4\( h \) downstream of the hypermixer. Two streamwise side-view planes were imaged: one on the centerline of the model and one 1\( d \) from the centerline. Additionally, a plan-view plane was imaged on the mid-plane of the hypermixer. Figure 3 depicts
these different fields of view. The scattered light was imaged with a back-illuminated CCD camera (PixelVision SV512V1) at 0.85 Hz using a 105 mm Nikon lens at f/2.8 for the side-views and a 50 mm Nikon lens at f/2.4 for the plan-views.

For the cases investigated with jet injection, argon gas was used as the jet fluid with a stagnation pressure of 282 Torr. Fuel was delivered in 90 millisecond bursts synced with the camera trigger. The duration of the burst was sufficient for the jet to reach a quasi-steady state by the time the laser pulse illuminated the flow.

D. Krypton Planar Laser-Induced Fluorescence (Kr PLIF)

Planar Laser-Induced fluorescence of krypton (Kr) gas was used to visualize the mixing of the jet fluid. The technique involves the excitation of the $5p[3/2]_{3/2} \rightarrow 4p^5 1S_0$ transition of krypton. Excitation is achieved by using two-photon absorption of 214.7 nm laser light. The fluorescence signal is collected from two lines centered at 760 and 819 nm.

The 214.7 nm laser beam was created through a wave mixing process. An Nd:YAG-pumped dye laser (Lumonics HyperDye 300) was used to produce a beam at 544 nm. This dye laser operated with fluorescein 548 dye doped with sodium hydroxide in a 2:1 ratio (2 moles of NaOH for every mole of dye) to shift the peak output wavelength to a slightly higher frequency. Simultaneously, a frequency-tripled Nd:YAG laser (Spectra Physics GCR-150) was used to produce a beam at 354.7 nm. The two beams were combined in a $\beta$-barium borate ($BBO$) crystal housed in an Inrad Autotracker II. The 214.7 nm beam was separated using a fused silica Pellin-Broca prism. The beam was then passed through standard sheet forming optics including a 300 mm spherical lens and a -75 mm cylindrical lens, allowing for a relatively uniform sheet 13 mm or 2$h$ wide. Approximately 5 ml/pulse was used to excite the krypton gas.

The fuel-injection port of the hypermixer model was supplied with pure krypton gas through the same solenoid valve used in the PLS experiments described above. Two side-view (x-y) field of view were used: one that spanned the range of $x = 0$ to $2h$ and another further downstream ($x = 2h$ to $4h$). Two side-view fields of view were used: one on the spanwise centerline ($z = 0$) and the other at $z = 1d$. Figure 4 shows these fields of view. All imaging was done using a back-illuminated CCD camera (PixelVision SV512V1) with a 50 mm Canon lens at f/1.2 with two extension tubes totaling 18 mm. The camera trigger was synced with the pulsed valve.

Figure 3: Fields of view for PLS experiment; (a) Side-view and (b) plan-view

Figure 4: Fields of view for PLS experiment; (a) Side-view and (b) plan-view
III. Computational Details

A set of large-eddy simulations (LES) was performed for the same hypermixer configuration as discussed above. The mesh used along the centerline is plotted in Fig. 5(b), showing one of every four grid points, while the full three dimensional domain is depicted in Fig. 5(a). The domain consists of 384x192x226 grid points in streamwise, transverse, and span-wise directions, respectively, or 16.7 million cells. The domain spans 78.7 mm x 63.5 mm x 50.8 mm, originating 25.4 mm upstream of the injection point.

Figure 5: Computational domain; (a) full three-dimensional domain and (b) centerline mesh showing the immersed boundaries

A structured, body-fitted grid system was generated along the splitter geometry. By properly clustering grid points toward the splitter block, or in the y direction, the incoming turbulent boundary layer can evolve correctly. The geometry of the central castellation is described using the immersed boundary method [14]. The cells denoted
as green in Fig. 5(b) are defined as walls. The computational grid is clustered toward all walls and around the central injection block.

Time dependent inflow profiles obtained from a separate boundary layer simulation are used for both the upper and lower surfaces of the splitter plate and hypermixer. The thickness of the boundary layer was assumed to be 3.3 mm, which is smaller than the experimental value. A smaller value was used because the boundary layer thickness was not known at the time the simulations were done. This will be remedied in future work. For the injection, a turbulent pipe velocity profile was used, whereas the thermodynamic variables across the nozzle exit were assumed to be constant. The domain was not bounded in the upper and lower ends, and a periodic boundary condition was used in the span-wise direction. As the experimental data obtained was predominantly near the centerline of the hypermixer, the side walls were omitted as there is little expected interaction.

Details of the compressible flow LES solver used in this study are explained elsewhere [15-17]. A standard 5th-order-accurate WENO (Weighted Essentially Non-Oscillatory) scheme was used for shock capturing while the viscous terms are solved using a 4th-order central differencing method. A three-step iterative time integration scheme [17] was used where the CFL number was fixed to 0.8. Krypton species mass fraction is solved by a 3rd-order QUICK scheme. Sub-filter terms are closed by a dynamic Smagorinsky model [18]. The solver is parallelized using MPI-based domain decomposition strategy. The two simulations were performed: one with krypton injection and one without. Each simulation took approximately one day using 256 processors.

IV. Results and Discussion

A. Hypermixer Wake Structure: No Jet Injection

Planar laser scattering of the CO₂ fog enables visualization of the freestream fluid in regions that remain cold enough for the CO₂ to be in the condensed phase. Figure 6(a) shows an instantaneous PLS image (x-y plane) along the centerline of the hypermixing wake. For this case there is no jet injection. The incoming boundary layer on the splitter plate is turbulent with a thickness of about 4 mm. As the flow expands over the downstream edge of the hypermixer, the shear layer merges approximately 2h downstream, at which point a recompression shock forms. The wake begins to spread again after the recompression shock a phenomenon consistent with the studies done in Refs. 5-7, in which the wake is seen to converge to a neck before spreading out again 1.5 to 2h downstream of the mixer. The structures in the shear layers – which are essentially detached boundary layers – exhibit much finer scale turbulence than the wake structures downstream of the recompression shock. The mean field is shown in Fig. 6(b).

This mean was computed with only 30 instances, which is not enough to provide a converged mean, but it nevertheless enables improved visualization of the stationary structures in the flow.
Figure 6: Comparison of the hypermixing wake without jet injection, centerline; (a) instantaneous PLS image, (b) average PLS image, (c) instantaneous density contours from simulation, and (d) average density contours from simulation

The LES shows very similar flow structures to those observed in the experiment. Figures 6(c) and 6(d) show instantaneous and average density fields for the centerline of the hypermixing wake. The reattachment point is located at the same streamwise location, $2h$ downstream of the hypermixer. A strong expansion fan forms at the edge of the mixer, indicated by the lower density, a feature not suggested by the PLS images. The weaker expansion is likely due to the thinner boundary layer that was used for the simulation. Furthermore, owing to the coarser grid used over the center block (Fig. 5(b)), the turbulence intensity was reduced and therefore the flow appears nearly laminar in the shear layers above and below the recirculation region. As discussed in Ref. 17, a boundary layer can develop appropriately only with a properly clustered grid system near walls; however, an immersed boundary method usually results in coarser meshes along the wall, therefore the method should be used with caution. To mitigate this problem, future work will focus on using high grid resolution as well as a different grid system, such as a multiblock system.

Moving off the centerline by $1d$, subtle changes begin to occur. Figure 7(a) and 7(b) show instantaneous and average PLS images, respectively, for side-view planes located at $z = 1d$, while Fig. 7(c) and 7(d) show density contours from the simulation in the same plane. It is seen in these images that the reattachment point and the foot of the recompression shock are somewhat farther upstream as compared to the centerline view. The wake also appears thinner in the far-field, which will be discussed below.
Plan view (x-z) images at the mid-plane reveal a new structure not visible in the side-views. Figures 8(a) and 8(b) show plan-view PLS in this plane, while Figs. 8(c) and 8(d) show the LES density field in the same plane. From the PLS images, it is seen that large pockets of freestream fluid have been entrained into the mid-plane. These structures are seen to grow from the edges of the central castellation of the hypermixer (at $z/h = \pm 1$). The likely cause for this structure is the strong streamwise vortices that form due to the pressure differential between the central block and the expansive wedges. These structures were observed by the simulations of Doster et al. [3,4], as well as the experiments of Gaston et al. [5-7]. Figure 9 shows Q-criterion [19] contours for the hypermixing wake; this allows for visualization of vortical structures within the flow-field. Here, the flow is seen to remain relatively quiet upstream of the central block; however, after the hypermixer has terminated, the flow-field becomes dominated with vortical structures. These vortical structures are very efficient at transporting freestream fluid closer to the centerline of the wake. As the vortices grow downstream, more and more fluid is pulled into the wake, with the vortices nearly coalescing near the end of the field of view in Fig. 8. Note also the magnitude of the vorticity caused by the presence of the shock seen in Fig. 9. This confirms the earlier assertion that the enhanced mixing seen in the side-views is caused by turbulence amplification by the recompression shock.
B. Effect of Jet Injection

It was seen from both the experimental and computational data that the presence of the hypermixer enhances turbulence within the wake because of the strong streamwise vortices that emanate from the central castellation and the recompression shock that forms within the wake, consistent with previous work as noted above [3-7]. However, the main purpose of the study is to understand how gas injected from the base will mix with the downstream flow-field. Figures 10(a) and 10(b) show instantaneous and average PLS fields along the centerline, while 10(c) and 10(d) show LES density contours. The density contours from the simulation allow the jet to be visualized, but the jet is rendered black in the PLS because the jet fluid is not seeded with CO₂. It is seen here that the jet has had little impact on the flow-field seen through the PLS (compare to figures 6(a) and 6(b)). The LES reveals that the jet is highly underexpanded and the jet seems to have a larger impact on the flow-field than in the experiments; this point will be discussed shortly. Furthermore, in the simulation, the addition of the jet has caused the wake to become far more turbulent, on par with the turbulent structures seen in the experiments. Additionally, a secondary shock forms on top of the barrel shock as the flow is forced to turn up immediately following the hypermixer; however, this secondary shock is not apparent in the PLS images.
Figure 10: Comparison of the hypermixing flow-field with jet injection, centerline; (a) instantaneous PLS image, (b) average PLS image, (c) instantaneous density contours from simulation, and (d) average density contours

Figure 11 shows plan-view images of the mid-plane of the mixer like those seen in Fig. 8. The experimental results show, as in the side-views, no particular effect on the flow-field by the jet. The simulation on the other hand shows that the streamwise vortices that are present begin interacting with the jet around $1.75h$ downstream of the mixer. This is further confirmed by Fig. 12 below, showing isosurfaces of mixture fraction. The jet stays fairly self-contained until $x = 1.75h$, at which point mixing begins occurring around the jet boundaries.

To investigate experimentally the mixing of the jet fluid, krypton gas was used as the jet fluid and the krypton was visualized by using two-photon PLIF. Only one downstream station was imaged with Kr PLIF. Instantaneous and average fields along the centerline are shown in Fig. 13.
Figure 11: Plan-view comparison of hypermixing flow-field with jet injection; (a) instantaneous PLS image, (b) average PLS image, (c) instantaneous density contours from simulation, and (d) average density contours from simulation

Figure 12: Isosurfaces of mixture fraction colored by density
Figure 13: Kr PLIF images of jet within hypermixing flow-field, centerline; (a) instantaneous and (b) 15-frame mean image. The dark vertical line at x/h=0.4 is due to a burn mark in the laser-access window.

In agreement with the LES, the jet present in the experiments is underexpanded; however, it is more weakly underexpanded as evidenced by the Mach disk standoff distance that is approximately 1h (or 2d) versus the 2h (or 4d) for the simulation. This difference explains why the flow-field appears less influenced by the presence of the jet in the experiments as compared to the simulation. Nonetheless, it is seen that the jet maintains its structure until roughly 1.75h downstream as seen in the simulation as well. This suggests that the primary mechanism for the initial jet breakdown isn’t necessarily the streamwise vortices, but rather the presence of the recompression shock. Indeed, this same phenomena was observed by Fox et al. [7], who noted that the injected jets appear to narrow in the neck of the wake before beginning to spread.

A look at a different plane 1d off center, seen in Fig. 14, shows that the krypton has indeed migrated out of the jet in the downstream view. The maximum radius that the barrel shock attains is roughly 0.8d, so the images taken 1d out of plane should miss the jet completely in the near-field. This is consistent with the images seen in Fig. 14(a) and 14(b), in which the PLIF signals are barely detectable.

Figure 14: KrPLIF images of jet within hypermixing flow-field, 1d off centerline; (a) instantaneous and (b) 15-frame mean image

Figure 15 shows a composite of mean krypton PLIF and PLS images. The barrel shock from the jet sits entirely within the broadest part of the wake downstream of the hypermixer. Mixing then begins to occur as the recompression shock forms, followed by a rapid decrease in signal as the krypton mixes with the rest of the fluid in the wake.
C. Interpretation of Fluorescence Signal

The LES is potentially very useful for helping us to understand how to interpret the Kr PLIF signal. The signal is proportional to the krypton concentration, but has an additional dependence on the thermodynamic properties owing to variations in the electronic quenching rate. Specifically, the two-photon fluorescence signal follows,

$$S_f = D \left( \frac{E_l}{a} \right)^2 \frac{A_{21}}{A + Q} \frac{\sigma^{(2)} n_i}{4 \pi^2 (\hbar \omega)^2} \int_{-\infty}^{\infty} F^2(t) dt$$

derived from a two-level model for electronic transitions assuming the absorption process does not reach saturation [20]. Here $E_l/a$ is the laser fluence, $n_i$ is the species number density, $A_{21}$ is the Einstein A coefficient for the fluorescence transition, $A$ is the transition rate that includes all possible decay paths from the two-photon excited state, $Q$ is the electronic quenching rate, $\sigma^{(2)}$ is the two-photon absorption cross-section, $F$ is the temporal profile of the excitation source, $\omega$ is the excitation frequency, and $D$ is a calibration constant containing all parameters involved in the optical detection system. For details on the calculation of the absorption cross-section, refer to [20].

Eq. (1) shows that the fluorescence signal is directly proportional to the number density of the fluorescing species, the excitation energy squared, and the fluorescence yield $A_{21}/(A+Q)$. For the transition of krypton used, $A$ and $A_{21}$ take on a value of 39.4MHz. The quenching rate $Q$ is given by

$$Q = n_o \sum_{I=1}^{N} \chi_i \langle v_i \rangle \sigma_I$$

(2)

where $\langle v_i \rangle$ is the mean relative speed, given by $\langle v_i \rangle = \sqrt{8kT/\pi \mu_i}$, $\mu_i$ is the reduced mass, $\sigma_I$ is the quenching cross-section, and the sum is over all species that collide with krypton. In the limit that all quenching cross-sections are constant, then Q is proportional to $P/\sqrt{T} \sum_{i=1}^{N} \sigma_I \chi_i / \sqrt{\mu_i}$.

The LES is useful for investigating the variations in signal due to variations in the local thermodynamic conditions. Consider Fig. 16, which shows a theoretical conversion of the LES data to PLIF signal following Eq. (1). This image features many of the same intensity structures seen in the actual experimental data.
We can use the LES to separate the number density from the fluorescence yield effects. For example, Fig. 17 shows the Kr concentration (or number density), and this image gives a very different picture of the mixing as compared to the fluorescence signal of Fig. 16. The fluorescence signal comprises a much smaller range of intensity values as compared to the Kr number density itself.

This difference indicates that there is a considerable effect on the signal due to the fluorescence yield. To investigate this further, Fig. 18 shows an image of the fluorescence yield as computed from the LES thermodynamic data. All quenching cross-sections were assumed to be constant. Figure 18 shows that the region immediately downstream of the trailing edge exhibits abrupt changes in the fluorescence yield, which would make it difficult to interpret the PLIF signal without more information about the flow-field. In contrast, in the region downstream of the Mach disk, the fluorescence yield remains relatively constant, i.e. variations in the pressure and temperature fluctuations are small compared to those seen in the shock structures. In this case the PLIF signal will be proportional to the mole fraction (or number density). This is encouraging for using Kr PLIF as a quantitative mixing diagnostic, since the combustion takes place well downstream of the mixer, and so it is in this region that quantitative measures of mixing are needed.
V. Conclusions

A preliminary study of a simple strut-based hypermixer in a Mach 3 flow was made using laser diagnostics and LES. The hypermixer had a castellated bluff trailing edge with tapered expansion wedges on either side. Gas could be injected through a single injection port located at the spanwise centerline of the mixer. The flow-field with and without jet injection was visualized by using planar laser scattering from a CO$_2$ fog. The hypermixer without jet injection was seen to enhance mixing by production of vorticity both through shock structures and through strong streamwise vortices emanating from the geometry. Addition of the fuel injection could potentially modulate the flow-field if the mass flowrate is high enough as seen in the computational study. Krypton PLIF was used as a passive scalar in the experiments to track the mixing process occurring within the flow-field. At the location of the recompression shock, the under-expanded injection jet was seen to exhibit intense mixing by large-scale turbulent structures. The simulation data were used to investigate local density and quenching effects on the fluorescence signal. It was observed that the krypton PLIF signal exhibits strong variations within the initial barrel shock structure owing to the large variations in thermodynamic conditions, but the density and quenching effects were relatively small in the wake region downstream of the recompression shock. This latter observation suggests that Kr PLIF could be useful as a quantitative measure of mixing because in this region it will be primarily sensitive to the Kr mole fraction.

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