Measurement of Supersonic Injection Flowfield Using Acetone PLIF

By Hidemi TAKAHASHI,1) Mitsutomo HIROMA,2) Hiroki OSO1) and Goro MASUYA1)

1)Department of Aerospace Engineering, Tohoku University, Sendai, Japan
2)Department of Mechanical Systems Engineering, Muroran Institute of Technology, Muroran, Japan

Received November 22nd, 2007

The structure of the flowfield formed by normal sonic injection into a Mach 1.8 air stream was investigated using acetone planar laser induced fluorescence (acetone PLIF). Parametric calculation of fluorescence intensity indicates that it represents molar concentration within ±2.5% error for the present experimental conditions. For the special situation of isentropic flow without any mixing, the Mach number can be deduced from the fluorescence intensity. Mach number distribution from PLIF data agreed well with that obtained from PIV measurement. The visual images of jet trajectories obtained from acetone PLIF are compared with those obtained from Mie scattering and indicate that the acetone PLIF produces a reasonable trajectory, while Mie scattering overestimates the jet penetration.

Key Words: Acetone PLIF, Supersonic Injection, Scram Jet

Nomenclature

- $c$: velocity of light
- $C_{acetone}$: acetone molar concentration
- $dV_c$: optical collection volume
- $D$: diameter of injection port
- $E$: laser fluence
- $h$: Planck’s constant
- $J$: jet-to-free-stream momentum flux ratio
- $k$: Boltzmann constant
- $M$: Mach number
- $N_A$: Avogadro’s constant
- $P$: local pressure
- $S_f$: fluorescence intensity from acetone
- $T$: local temperature
- $\Delta y$: difference of component along $y$-axis
- $\gamma$: specific heat ratio
- $\eta_{opt}$: overall efficiency of collection optics
- $\lambda$: exciting wavelength for acetone molecule
- $\sigma$: absorption cross section
- $\phi$: quantum yield of acetone fluorescence
- $\chi_i$: mole-fraction of species $i$

Subscripts

- $f$: main flow
- $j$: jet
- ref: reference condition
- *: flow condition at injector exit

1. Introduction

Scramjet engines are expected to become the main propulsion system of space planes. In the scramjet engine, atmospheric air flows into the combustor at supersonic speed. Mixing of fuel injected into the air stream is not likely to occur quickly due to the compressibility effect or small difference in velocities of fuel and air. For this reason, it is important to enhance fuel/air mixing in order to put a scramjet engine to practical use. This kind of supersonic mixing flowfield is highly complex, unsteady, three-dimensional, and turbulent. Hence, it is necessary to understand the mechanism of fuel-air mixing. Precise measurement of this mixing should be carried out with good spatial and temporal resolutions.

Many researchers have conducted pointwise surveys such as gas sampling,1) which inserts probes into the flowfield, to investigate the injectant gas concentration distribution. This measurement technique is useful to obtain a quantitative value of concentration. However, probe insertion may change the flowfield. Moreover, the measured value is limited to only a time averaged value due to the requirement of the sampling time usually being much longer than the characteristic time scale of turbulence, especially in a high-speed flow. In the case of a reacting flow, concentration can be obtained only for stable species. Recently, non-intrusive optical measurements such as planar laser induced fluorescence (PLIF) have been developed as a very attractive means of planar concentration measurement. PLIF is a visualization technique that obtains a fluorescence signal from tracer molecules induced by a laser with a wavelength tuned in the absorption wavelength of fluorescent species. Its great advantage is to minimize intrusions into the flowfield.

In general, the laser induced fluorescence signal depends on the thermodynamic states such as temperature and pressure as well as the mole-fraction of fluorescent species. For this reason, it is difficult to transform a fluorescence signal directly to a certain physical property when those quantities change simultaneously and independently like compressible flow with mixing.
There are several quantitative measurements with PLIF. Mole-fraction measurement conducted by Hartfield et al.\(^3\) with iodine as a tracer and temperature measurement by McMillin et al.\(^9\) with nitric oxide (NO). Hartfield et al.\(^2\) introduced a fluorescence ratio method. This method takes a ratio of two PLIF images, one for iodine seeded only into the jet flow and the other for iodine seeded into both jet and main flow. By taking a ratio of the two images of fluorescence, the dependences of pressure and temperature are canceled out so that quantitative information on the injectant mole-fraction can be obtained. McMillin et al.\(^3\) introduced another fluorescence ratio method, taking a ratio of two images obtained with two different excitation wavelengths. After some theoretical analysis on the ratio, they obtained quantitative information about temperature. The use of iodine and NO as tracers has the advantage of providing a high signal-to-noise (S/N) ratio. However, these tracers are harmful to the human body and the experimental facility, and it is quite difficult to use these fluorescent species in open-circuit tunnels. As an alternative, acetone is a candidate tracer because it is less toxic and easier to handle. Moreover, laser-induced fluorescence from acetone has an excellent S/N ratio and very high spatial and temporal resolutions.\(^4\) For an isobaric and low-velocity flowfield, many researchers have measured species concentration or temperature quantitatively by acetone PLIF.\(^5\) However, the use of acetone PLIF has not been well developed for supersonic flows, although it has been used for qualitative understanding of flow structure and turbulence mechanism because of its excellent spatial and temporal resolutions.\(^6\)

There appears to have been no study in which physical properties are directly and quantitatively evaluated from the LIF signal obtained by seeding tracers into either the jet or main flow. Achieving such a quantitative evaluation would provide great advantages for understanding the mechanism of mixing in the scramjet combustor.

This study focuses on qualitative understanding of the three-dimensional distributions of gas injected transversely into a supersonic main stream and quantitative evaluation by acetone PLIF with seeding of acetone only into the jet. To obtain a quantitative understanding of the diffusion mechanism, we conducted a theoretical analysis of fluorescence signal under various flow conditions and compared acetone PLIF with Mie scattering\(^7\) regarding the spatial distribution of the jet. Consequently, instantaneous features of injectant jet behavior governing the supersonic fuel/air mixing were clarified.

2. Experimental Apparatus and Techniques

2.1. Supersonic wind tunnel and test section

A schematic of the present experiment apparatus is shown in Fig. 1. A suction-type supersonic wind tunnel was used. Atmospheric unheated air was inhaled into a vacuum tank through a two-dimensional contoured nozzle and a test section. The vacuum tank has volume of 8 m\(^3\) and was evacuated to about 5 kPa before each test run. A bubbling container was set in the injectant feeding line to supply vaporized acetone into dry air as a tracer for LIF measurement. The injectant was pressurized dry air fed from an air cylinder. The mole-fraction of seeded acetone was assumed to be saturated at room temperature, that is, approximately 20%. For PIV or Mie scattering measurement, we used droplets of dioctyl sebacate produced with Laskin nozzles in a mist generator as a tracer. The droplet diameters were approximately 1 \(\mu\)m.\(^8\)

The test section was a rectangular duct, 30-mm wide, 30-mm high, and 330-mm long. The nominal Mach number of the air stream was 1.8. A 2.5-mm diameter sonic transverse injector was located on the centerline of the tunnel wall. Quartz glass windows on three walls provided optical access to enable LIF measurement.

This report uses the Cartesian coordinate system. The origin is located at the intersection point of the centerline of the wall and the injector axis. The streamwise axis is \(x\), the transverse axis is \(y\), and the spanwise axis is \(z\).

2.2. Laser measurement system

Figure 2 illustrates the laser measurement system. The light source for inducing acetone is the fourth harmonic radiation from a Q-switch pulsed Nd:YAG laser with a wavelength of 266 nm and energy of 70 mJ/pulse. The laser beam was expanded to a two-dimensional sheet 30 mm wide and 0.5 mm thick. This was used by six mirrors, two positive cylindrical lenses (\(f = 200\) mm), and one negative cylindrical...
cal lens \((f = -20\, \text{mm})\) so that the flowfield could be measured with parallel light. Given these laser sheet characteristics, the 70 mJ pulse energy was well below the saturation level of acetone fluorescence. Mirrors were used to orient the sheet in the streamwise vertical \((x-y)\) and spanwise vertical \((x-z)\) planes.

The fluorescence images were recorded using a digital charge-coupled device (CCD) camera system with an image intensifier unit and a micro-Nikkor 50 mm, \(f/2.8\) lens. Operation of these devices was synchronized by a pulse generator. A band pass filter (passband: \(390 \pm 100\, \text{nm}\)) was attached in front of the camera lens to cut stray light. MATLAB\textsuperscript{®} 7.1 was used as post-processing software.

2.3. Analysis of acetone fluorescence signal

We analyzed the fluorescence signal to clarify the quantitative relationship between the acetone fluorescence signal and other physical quantities. The fluorescence signal from acetone, which has a broadband spectrum, is a function of excitation laser fluence, absorption cross-section of tracer molecules, efficiency of collection optics, and fluorescence quantum yield. Considering these factors and assuming that laser intensity is much lower than the saturation level,\textsuperscript{9) the acetone fluorescence signal \(S_t\) is expressed as

\[
S_t = \eta_{opt} \frac{E}{hc/\lambda} dV_c \cdot \frac{\chi_{acetone} P}{kT} \sigma(\lambda, T) \phi(\lambda, T, P) \tag{1}
\]

Here, the absorption cross-section \(\sigma\) is experimentally demonstrated as constant for the pressure and temperature of this study.\textsuperscript{10) We used the multi-decay model to calculate the fluorescence quantum yield \(\phi\) because it produces better agreement with experimental data and can quantitatively explain thermodynamic dependences on the fluorescence signal.\textsuperscript{11) Calculated results are described below.

First, we present a general interpretation of the fluorescence signal. The molar weight of the mixed gas composed of acetone and air changes with the mixed acetone mole-fraction. Taking this into consideration and combining the equation of state, we can rewrite Eq. (1) as

\[
S_t = \eta_{opt} \frac{E}{hc/\lambda} dV_c \cdot N_A \cdot \sigma(\lambda, T) \cdot \phi(\lambda, P, T) \cdot C_{acetone} \tag{2}
\]

The graph in Fig. 3 plots the relationship between the fluorescence signal and acetone molar concentration calculated based on Eq. (2). The calculation conditions in this experiment were 0% to 20% acetone mole-fraction, 150 K to 230 K temperature, and 0.05 to 0.35 atm pressure. All calculated values were normalized by the reference value derived from the case of \(P_{opt} = 0.35\, \text{atm}, T_{ref} = 230\, \text{K},\) \(\chi_{ref} = 20\%\). Clearly the graph shows that the fluorescence signal is proportional to acetone molar concentration. Four lines covering almost all conditions in the flowfield of the present experiment agree with each other within 2.5%. In other words, acetone molar concentration can be derived quantitatively from an acetone PLIF image within approximately \(\pm 2.5\%\) error, even if local temperature, pressure, and acetone mole-fraction change independently.

Second, we present the special case of isentropic flow with uniform stagnation temperature and mole-fraction. Combining the isentropic relationship and the assumption of constant mole-fraction results in the following equation for fluorescence signal as a function of Mach number.

\[
S_t = \eta_{opt} \frac{E}{hc/\lambda} dV_c \cdot N_A \cdot \sigma(\lambda, T) \cdot \phi(M) \cdot \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma - 1}} \tag{3}
\]

Figure 4 plots Mach number against calculated fluorescence signal on a semi-log scale. The Mach number plotted here ranges from 0 to 3.0, and the fluorescence signal was normalized by the reference value at stagnation. In this case, clearly there is a one-to-one correspondence between Mach number and fluorescence signal.

3. Results and Discussions

3.1. PLIF visualization on center plane of duct

Figure 5 is a Schlieren photograph of the typical flowfield with an injection condition of \(J = 1.7 \pm 0.05\). Figure 6 is an image visualized by acetone PLIF on the center plane of the duct under the same experimental conditions. It is the mean
structure of the flowfield obtained by taking an average of 30 instantaneous shots after stray background noise was subtracted and non-uniformity of the laser sheet intensity distribution was corrected for each image. Fluctuation of each laser pulse is believed to be removed by taking an average. The axis scale was normalized by using an injector diameter ($D = 2.5 \text{ mm}$). The gray scale level represents the acetone molar concentration normalized by the value at the injector exit.

A comparison of Figs. 5 and 6 clearly demonstrates that the flow structures such as Mach disk, barrel shock wave, jet boundary, and Prandtl-Meyer expansion region are clearly visualized by the acetone PLIF image. The locations of the Mach disk in the Schlieren and PLIF images agree well. Figure 6 clearly indicates a gradual change of fluorescence intensity with density change in the expansion region just above the injector orifice, and sudden increase in intensity behind the Mach disk and around the barrel shock wave where the density increases due to compression. It is also obvious that fluorescence intensity decreases gradually along the main flow direction as mixing progresses.

Figure 7(a) shows the Mach number distribution derived by Eq. (3) and Fig. 4 in the Prandtl-Meyer expansion region surrounded by a barrel shock wave and a Mach disk framed by a white box in Fig. 6. Figure 7(b) plots the Mach number distribution obtained from PIV measurement under the same experimental conditions. Note that there is no PIV data near the wall ($y \leq 1 \text{ mm}$) owing to the huge error caused by reflected light from the wall. The two distributions agree well, but the distribution obtained by PIV has a slightly smaller value than that obtained by PLIF due to the limited ability of PIV tracer particles to follow the flow. The tracer particles seem unable to closely follow an acceleration of flow as strong and significant as 200 m/s in a small distance of 2 to 3 mm. Furthermore, there is an overall uncertainty of 6.5% in PIV measurement. Therefore, taking this error into account, the Mach number distribution obtained from the fluorescence signal is quantitatively reliable in the Prandtl-Meyer expansion region.

3.2. PLIF visualization on plane normal to center plane

The following discusses cross-sectional acetone PLIF images in the $y-z$ plane shown in Fig. 8. In this figure, the seven planes in the region of $0 \leq x/D \leq 12$ are displayed with a streamwise separation of $2D$. Each image is an average of 30 instantaneous shots after the background noise was subtracted and the laser sheet non-uniformity was corrected. The maximum intensity in each plane decays rapidly as it travels downstream, as can be seen in Fig. 6. Hence, if all the planes in the same intensity range are shown, it would be almost impossible to see the fluorescence distribution in the planes far downstream from the injector. To avoid this undesirable effect, the intensity range of each
plane in Fig. 8 was normalized by the maximum intensity in each plane. Therefore, each image roughly corresponds to the relative jet concentration distribution.

The evolution of PLIF images in Fig. 8 shows that the jet is first stretched toward the spanwise direction ($x/D = 2$), and then both tips of the jet roll down toward the lower wall ($x/D = 4–6$) and the jet diffuses into the main stream ($x/D = 8–12$). The spanwise direction width of the jet is almost constant in the region of $x/D = 6$. In other words, the main air stream rolled up around the jet core along the center line so that injectant was divided into two parts and finally changed its shape to a pair of counter rotating vortexes that had a peak on each side. Consequently, the time-averaged development of the injectant jet can be seen by acetone PLIF images.

Figure 9 shows some examples of instantaneous PLIF images in the plane of $x/D = 6$ captured at intervals of 200 ms. Hence, there is no sequential relationship from one image to the next. The intensity range of each plane was normalized by the maximum intensity in each image in the same way as in Fig. 8. Although there is an image relatively similar to the averaged one, the shape of the LIF image changes greatly over time. By comparing with Fig. 8, the well-known mean structure obtained by conventional gas sampling or time averaged computational fluid dynamics (CFD) consists of a vigorously varying instantaneous jet distribution.

### 3.3. Comparison of PLIF and Mie scattering

Mie scattering has been widely used to investigate jet penetration and spanwise spreading. As mentioned previously, Mie scattering is an imaging technique that imposes scattered light from tracer particles. Since the tracer is not a molecule but a particle, this technique may be affected by the velocity lag of tracer particles. Thus, probably there will be differences in jet trajectories obtained by acetone PLIF and Mie scattering under the same experimental conditions. Hence, we compared the two trajectories to confirm this.

Figure 11 shows the jet trajectories obtained from acetone PLIF and Mie scattering at the same jet-to-freestream momentum flux ratio. These trajectories are maximum intensity tracks in mean images averaged over 150 instantaneous shots on the center plane of the duct. These trajectories can be considered as one guideline for jet penetration height. However, we should remember that the maximum intensities in the region of $y/D \geq 0.5$ are more affected by the expansion and shock waves around the injector exit so that the values in this region cannot be used as jet penetration height.

Acetone PLIF and Mie scattering clearly produce different trajectory heights even for the same injection conditions. Mie scattering has a higher trajectory than acetone PLIF due to the difference in the ability of tracers to follow the flow. The tracer particles for Mie scattering experience a velocity lag when subjected to rapid deceleration, especially along the transverse direction caused by passing through the Mach disk and, as a result, travel a different path.

A Schlieren photograph shows large, pulse-like deviations around $x/D = 10$, and thereafter the flow disturbance is caused by the incidence of the reflected bow shock wave in the jet regime. Such deviations are also seen in the acetone PLIF result, although the extent is relatively small so that the effect of shock incidence is less significant in PLIF than in Mie scattering for obtaining the jet trajectory.
Figure 12 compares the jet trajectories obtained by acetone PLIF and Mie scattering with jet stream lines obtained from the PIV measurement based on Mie scattering. In this case, the jet-to-freestream momentum flux ratio was $J = 1.7$. The trajectories were smoothed by taking a traveling average with neighboring points within $\pm 0.5D$ of each point to smooth pulse-like deviations and to understand the rough trend of jet penetration behavior. The mean difference of jet penetration heights of acetone PLIF and Mie scattering in the region of $6 \leq x/D \leq 15$ was approximately $0.6D$. This indicates that the penetration height obtained from Mie scattering is approximately 20% overestimated relative to that of acetone PLIF in that region. The penetration height of the PLIF is close to the lowest streamline of the PIV measurement.

Figures 13(a) and (b) plot the jet trajectories obtained from acetone PLIF (a) and Mie scattering (b) for $J = 1.5, 1.7, 1.9,$ and $2.1$. Despite rather small differences in the jet-to-freestream momentum flux ratio, the penetration heights vary distinctly with $J$ for acetone PLIF. In contrast, those of Mie scattering are nearly unable to show dependence on $J$. This comparison indicates that the acetone PLIF traces fluid behavior well and accurately obtaining structural change in flowfield caused by small changes in injecting conditions. However, the change in flowfield could not be captured accurately by Mie scattering due to the lag in tracer particles. Consequently, clearly acetone PLIF is better for capturing detailed and exact mechanisms of highly complex flowfields such as the supersonic injection flowfield. In addition, only 30 images were required to obtain an averaged image such as Fig. 11 for acetone PLIF. In contrast, Mie scattering requires many more images due to a larger deviation in the scattering signal. Therefore, we conclude that acetone PLIF also has significant advantages over Mie scattering in post-processing.

Based on the above, acetone PLIF is more useful than Mie scattering for understanding the detailed supersonic injection flowfield.

4. Conclusion

We examined the flow structure produced by transverse sonic injection into a Mach 1.8 main stream for four jet-to-freestream momentum flux ratios using the acetone PLIF technique. The jet trajectories obtained from the acetone PLIF were compared to those from Mie scattering. The laser-induced fluorescence from acetone was also analyzed theoretically, and the following conclusions were drawn.

1. The signal of laser-induced fluorescence from acetone can be interpreted as the molar concentration of acetone within $\pm 2.5\%$ error, although it is affected by local temperature, pressure, and acetone mole-fraction.
2. The Mach number distribution is derived quantitatively from an acetone PLIF image where isentropic conditions and a constant mole-fraction can be assumed.
3. Flow visualization by acetone PLIF follows the flow better than visualization by Mie scattering. The former enables precise detection of differences in flow structures with small changes in flow conditions.
4. The instantaneous structure of a mixing flowfield can be visualized with excellent resolution by acetone PLIF. Instantaneous structures are quite different from the mean structure. Therefore, a mixing mechanism should be discussed taking into account both the mean structure and the instantaneous structure.

References

4) Lozano, A., Yip, B. and Hanson, R. K.: Acetone: A Tracer for Conce-