Experimental Investigation of Supersonic Mixing Mechanisms of HYLTE Nozzle for DF Chemical Laser

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Abstract. Utilizing experimental techniques of Nano-particle based Planar Laser Scattering (NPLS) and schlieren photography, the flow patterns and mixing characteristics of a designed HYLTE (HYpersonic Low TEMperature) nozzle were investigated in this paper. In order to visualize the non-reacting flowfield of supersonic angled jets into a supersonic crossflow in the HYLTE nozzle, a testing section with windows was designed and manufactured. The effects of different total pressure ratio of the twin jets to the freestream and different injectants on supersonic mixing are examined. Instantaneous side- and end-view NPLS images provide transverse penetration and lateral spread information for the secondary twin jets. As an assistant method, schlieren photos display the shock patterns that exist in the HYLTE nozzle.

1. Introduction

HYLTE nozzle is an advanced nozzle concept which is widely used in DF chemical laser for its high mixing efficiency. In order to optimize the nozzle design and the laser performance, it is necessary to get a clear understanding of how the gaseous injections interact with the primary flow.

Non-intrusive visualization techniques, such as schlieren and NPLS are powerful and commonly used optical methods at present. It is considered that streamwise vortices produced by the interaction of injections and mainstream dominate and accelerate mixing. NPLS technique provides convenient conditions of the observation of streamwise vortices development of supersonic transverse injection. Schlieren photography is a convenient experimental method in non-reacting flowfield visualization, but its images are not clear enough to study the mixing mechanism in the supersonic crossflow of HYLTE nozzle.

NPLS is an advanced method for supersonic flow visualization, which is newly developed based on Particle Image Velocimetry (PIV) technology by YI Shihe and ZHAO Yuxin of National University of Defense Technology in 2005. NPLS uses nanometer TiO₂ and pulsed planar laser as tracer particles and illumination respectively, not only solving the problem of particles flow-following but also improving the Signal-to-Noise of supersonic flow imaging. Due to the good flow-following ability of nanoparticles, if the concentration distribution of particles on the inlet of flow field is uniform, the variation of particle will reflect the density variation and mixing structure of the flow field. Thus the NPLS method is appropriate for the study of transverse injection of the HYLTE nozzle in which the density and concentration gradient are rather large.

2. Experimental equipments and methods
2.1. NPLS technology

The NPLS system consists of a computer, synchronizer, CCD camera, pulse laser and nanoparticle generator, the structure of which is schematically shown in figure 1. In NPLS, the computer controls the collaboration of the components and receives the experimental images. The input and output parameters of the synchronizer are controlled by software, collaboration of other components is controlled by signal of the synchronizer. The timing diagrams of exposure of CCD and laser output of pulse laser can be adjusted according to the purpose of measurement. The laser beam is transformed to a sheet with cylindrical lens. The nanoparticle generator is driven by high pressure gas, and the output particles concentration can be adjusted precisely by the driving pressure. While measuring the flow field with NPLS, the nanoparticles are injected into and mixed with the inflow of the flow field, while the flow is established in observing widow, the synchronizer controls the laser pulse and CCD to ensure synchronization of the emission of scattering laser by nanoparticles and the exposure of CCD[1].

Figure 1. Schematic diagram of NPLS system.

The NPLS experimental system used in this paper is shown in figure 2. The synchronizer has eight output ports with temporal precision at 0.25 ns. The CCD is an interline transfer CCD equipped with micro-lens, of which the shortest frame straddle time is 200 ns, the number of CCD array is 2000 × 2000 pixels with 4096 grayscale grades. The pulse laser is a double pulse Nd:YAG laser, the wavelength of the laser is 532 nm with duration of 6 ns and 350 mJ per pulse. The location of light sheet lens, polarization angle of laser, and particle flow rate of nanoparticle generator can be adjusted according to experimental requirements.

Figure 2. Supersonic NPLS experimental system.

2.2. High speed schlieren system
The mirror-based, Z-arrangement schlieren system is used in this study, which is displayed in figure 3. The point light source is a halogen bulb. The slit sits at the focal point of the condenser lens of the lamp. Two 120-cm focal length concave mirrors are used to collimate the light through the test section and then refocus it onto a knife edge. The knife edge at the focal point of the second schlieren mirror is used to partially cut off the deflected rays for observing the schlieren effect (visualization of the density gradients). Blocking more of the light by moving the knife edge transverse to the optical axis makes the system more sensitive, showing more features of the jet. The knife edge, oriented horizontal or vertical with respect to the focused light, will emphasize the density gradients in the horizontal or vertical directions respectively[2]. The test object is imaged with a zoom lens onto a high-speed framing camera. Frame rate of the camera can be up to 120,000 frames per second (fps).

2.3. HYLTE nozzle testing section
In order to visualize the non-reacting flowfield of supersonic angled jets into a supersonic crossflow in the HYLTE nozzle, a testing section with observation windows is designed and manufactured, which is shown in figure 4. Three pieces of quartz glass are embedded in the top and side observation windows respectively for the convenience of capturing the NPLS images of centerline plane and planes in several spanwise locations. The injection angles and the secondary fluids orifice separation can be changed by replacing the forepart of the nozzle component.

![Schlieren system](image)

**Figure 3.** Schlieren system.

![HYLTE nozzle testing model](image)

**Figure 4.** HYLTE nozzle testing model.

Gas feeding and pressure measuring orifices are placed at the bottom of the testing section. The diffuser is installed at the end of the testing section which connects with vacuum tank and provides...
equivalent pressure between them. As for cold experiment, gaseous nitrogen or helium is used to simulate the jet fluids of secondary nozzle, while the crossflow of primary nozzle is always nitrogen. Because secondary jets are 0.3mm in diameter, the tiny gaseous flow is dominated by mass flow controller (MFC).

3. Results and discussions
By visualizing the supersonic transverse injection flowfield in the HYLTE nozzle, streamwise and spanwise images of NPLS are taken, the flow structures of these twin supersonic secondary injections are identifiable. Owing to the block effect of the first injector to the main flow, the second injector has a stronger injection and deeper penetration than the former injector. For the Mach number of the mainstream is a little too high (Mach 4-5), shear-induced mixing is poor\(^3\), the mixing layer tends to become stable, as a result, some large-scale structures of the flowfield have been restrained.

![Figure 5. Instantaneous side-view NPLS images.](image1)

![Figure 6. Instantaneous end-view NPLS images.](image2)

Figure 5 presents instantaneous side-view NPLS images which offer a view of the jet/crossflow interaction at the spanwise centerline of the twin injectors. From case 1 to case 3, there is a increase in total pressure of the primary flow progressively, while the pressure values of secondary jets are the same. The penetration of secondary injections is depressed obviously with the increasing crossflow pressure. Results also show that the mixing quality is greatly enhanced by jet surface stretching and entraining the crossflow fluid continuously, which is clearly visualized in figure 5(c). That is to say, higher momentum jets entrain less crossflow fluid than lower momentum jets. Case 3 and case 4 are designed to operate at the same condition, while case 4 is supplied with helium to the secondary injections. Because of the smaller molecular weight of helium, the jets penetrate farther vertically in case 4 than in case 3.

The cross-sectional structure of the twin jets is observed in figure 6. The image plane moves downstream from the base to 2mm, 8mm, 14mm and 20mm respectively, the near-field development
of the jet/crossflow interaction may be examined. Counter-rotating vortex pairs emerge near the base, which is very close to the injectors. The jet cross sections change from ellipse-shaped to kidney-shaped consequently. Further downstream the two jets attract each other and start to merge, at the same time, the strength of the counter-rotating vortices becomes weaker.

As can be seen from figure 7, two curved-shaped bow shock waves appear in the vicinity of the twin injectors. The injected gases act as obstructions to the freestream and thus produce interaction bow shock waves upstream of the injector locations. In addition, it is pointed that angled injection will result in weaker bow shock than normal injection\[4\], that is why the injector bow shock waves in all obtained schlieren images are not strong enough. The shock waves coming from the HYLTE throat and from the joint of base and wall have been marked together. It is obvious that the shock inclination angle from the neck depends on the nozzle’s expansion degree\[5\].

**Figure 7.** Schlieren photos of flow:
1–Shock waves from the nozzle throat; 2–first injector bow shock; 3–second injector bow shock; 4–shock wave from the joint of base with wall.

**Figure 8.** Partial enlarged view of Schlieren images: 5–Barrel shock.

From figure 7, we can see the whole system but not the details of shock waves presented to the flow in HYLTE nozzle. Figure 8 displays the partial enlarged view of schlieren images. The difference between case 5 and case 6 is the injection pressure. The increasing pressure (case 6) makes the jet momentum larger which would increase the oblique angle of the bow shock waves. This means that the total pressure losses created from the injectors may increase with the momentum flux ratios and mass fluxes at which the injectors are operated due to increased blockage effects. Furthermore, the barrel shock could be discerned downstream of the first injector bow shock\[6, 7\]. Another barrel shock behind the second injector bow shock and Mach disks are not visible in schlieren images for low resolution.

4. Conclusion
In order to visualize the supersonic flow field of transverse injection in the HYLTE nozzle, NPLS and schlieren photography was used in this paper. The objective was to examine the influence of different total pressure ratio of the twin jets to the freestream and different injectants may exert on the flow structure and mixing. It is clarified that in consequence of the shielding effect of the front jet, the rear jet penetrated further into the mainstream. The mixing characteristics of these tandem jets were dominated by the contact surface stretching, entraining and counter-rotating vortices generated beside the jets.

As for HYLTE nozzle, mixing enhancement is mostly characterized for the variation of several flow control and geometrical parameters including the effective jet-to-crossflow velocity ratio, jet injection angle and secondary fluids orifice separation. Further research should focus on examining the
impact of the secondary fluids injection angle and orifice separation on the mixing mechanism of transverse injection in HYLTE nozzle.

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