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Shock Waves

Generation of hypersonic liquid fuel jets accompanying self-combustion

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Abstract. Aerodynamic behavior of pulsed hypersonic light oil jets injected at 2 km/s and 3 km/s is presented. Auto-ignition and combustion of the fuel during the injection process were visualized. The combustion around the disintegrating jet was enhanced by liquid atomization created by the very high injection pressure as well as the interfacial instability of the hypersonic jet. The jets were injected into air at low pressure and also that premixed with helium and air. It was found that the combustion was reduced in both cases despite the higher jet speed and the increased gas pressure.

Key words: Hypersonic fuel jet, Mixing, Auto-ignition and combustion

1 Introduction

Sato et al. (1986) experimentally investigated the ignition process of fuel sprays injected into a high-pressure, high-temperature atmosphere and found that the ignition of the fuel spray started at its tip. The fuel sprays tested were in the subsonic range and the temperature of the gas atmosphere was higher than the ignition temperature of the fuel.

In a cold-air enviroment, this ignition does not take place. However, if the fuel jet moves at supersonic speed with high Mach number, the ignition may also start from the tip of the fuel jet, since the stagnation temperature is high there. The investigation of hypersonic jets has not been carried out before as it is not very easy to accelerate a fuel jet to such high speeds , and the physical process of hypersonic liquid injection is not yet clarified.

Field and Lesser (1977) observed, in their primary high-speed photography, oil jets at approximately 2 km/s and the resulting auto-ignition and combustion. Recently, the systematic study of the fuel injection in Scramjet engines, which have a typical flight speed of 2–5 km/s (see for example, Waitz et al. 1993, Yang et al. 1994, Naumann et al. 1997, and Gruber et al. 1997), has begun to provide important clues towards interpreting the mechanism of fuel mixing and combustion in hypersonic flow. The role of shock waves in the mixing and the air entrainment, which occur in the developing hypersonic shearing layers, is highlighted. In a real mixing process, the interface between the air and the liquid fuel breaks up totally. In the Scramjet engines, the shattering of droplets is accelerated immediately after the droplets leave the fuel jet surface. This acceleration in a supersonic/hypersonic flow may prevent the shearing layer and the mixing fluctuation from developing (Gruber et al. 1997, Papamoschou and Roshko 1988). In contrast, the fuel jet shattering is decelerated by the aerodynamic drag force acting on the droplets, while the jet speed itself also decreases. Therefore, a coherent structure of large-scale vortices can be formed around the jet (Brown and Roshko 1974). The fuel atomization is promoted by the vortices rolling up the fuel jet interface, and the fuel vapor concentration is increased by the high turbulence intensity in the vortices. Once the fuel vapor is ignited by being exposed to a strong shock wave formed around the tip of the jet, a flame covers the entire jet area.

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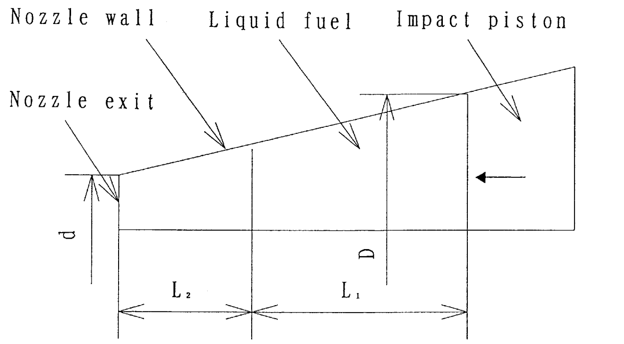

Fig. 1. Generation of a hypersonic liquid fuel jet: d, nozzle exit diameter; D impact piston diameter; L_1, liquid cylinder length; L_2, nozzle length

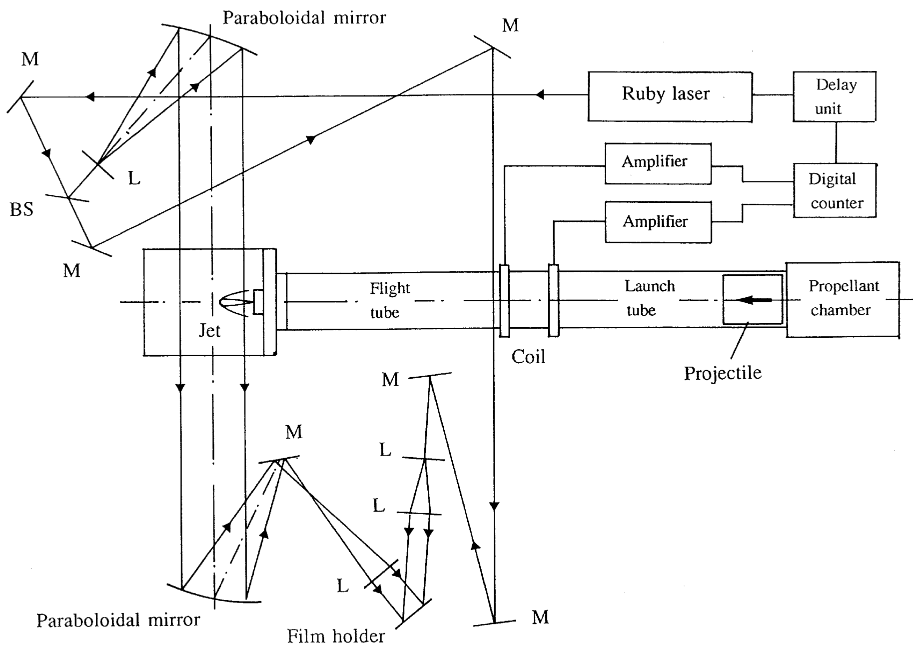

Fig. 2. The power gun system for the generation of a hypervelocity liquid jet and the double-exposure holographic interferometric setup

2 Experimental

Figure 1 shows a concept for the generation of a hypersonic liquid jet. A piston with velocity V_i impacts on the liquid cylinder of length L_1. The figure is half of the axisymmetrical geometry; the bottom horizontal line in the figure represents the axis of the nozzle. The accelerated liquid flows through the nozzle (length L_2) and then emerges from the nozzle exit (of diameter d). For a given piston geometry and weight, the velocity V_j of the jet formed at the nozzle exit depends on the ratio d/D and on L_1, L_2, V_i. See Cooley (1970), Edney (1976) and Shi et al. (1995) for details of the nozzle design. The speed of the fuel jet was measured by a time-of-flight method in which the time interval for the leading edge to cross the two laser beams, which were located with a known spacing downstream of the nozzle exit (Shi et al. 1994a, Shi et al. 1999).

The error in this measurement was found to be within ±1%. The piston was accelerated in a powder gun and impinged on a liquid-filled container (Shi et al. 1995, Shi et al. 1999). Sequencial photographs were taken by double-exposure holographic interferometry. Figure 2 shows the optical setup. A holographic ruby laser (Apollo Lasers Inc., Model 22HD, 2 J per pulse, pulse duration 25 ns) was the light source. The trigger signal to synchronize the ruby laser was obtained from the output signal of a pick-up coil, which was induced by the passage of a small magnet embedded in the plastic projectile. The jets were injected into a test chamber in which air at low pressure and pressurized helium were maintained. The injection pressure of the liquid fuel in the nozzle was created by the impact of a piston and was estimated to be about 500 MPa to 1000 MPa (Shi et al. 1999).

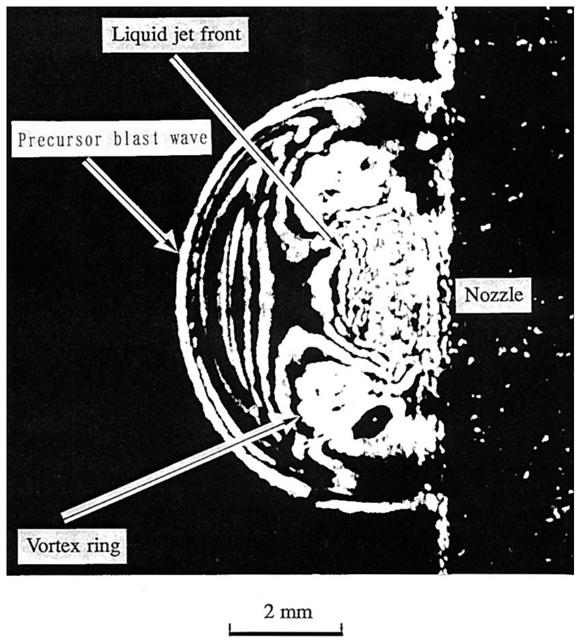

Fig. 3. The initial injection sequence of a diesel fuel jet under high injection pressure. A pair of vortex rings appeared behind a precursory blast wave. This process is similar to the discharge of a shock wave from the open end of a shock tube. The front part of the jet seemed to consist of combustion products

3 Results

As pointed out by Field and Lesser (1977), the sudden acceleration of the liquid surface generates compression waves in air inside the nozzle, i.e., the air contained in the cylinder of length L_2 is compressed by a moving liquid front. The compression waves eventually form an outward-going shock wave. Figure 3 shows the shock wave emanated from the nozzle exit, which is marked as a precursory blast wave in the photograph. A ring vortex also appears at the nozzle exit. This is induced by the discontinuous velocity gradient at the nozzle corner and viscous effects. At the later stage of the injection, the precursory blast wave, which gradually attenuated with propagation, was readily overtaken by the bow shock wave formed in front of the hypersonic jet. A similar process occurs when a solid projectile overtakes the precursory blast wave released from the muzzle of a gas gun. This has been clearly simulated numerically (Takayama et al. 1997).

Figure 4a shows the injection of a light oil jet from a 2.5-mm-diameter nozzle into atmospheric air at 2 km/s. The jet is propagating from right to left. A length scale of 15 mm is given in the figure. The front part of the jet is obscured by the illumination from the combustion region. However, its boundary can be seen relatively clearly in the corresponding un-reconstructed hologram in Fig. 4b, which is equivalent to a shadowgraph. Multiple-structured bow shock waves over the hypersonic jet indicate a flow unsteadiness. As the jet moved farther downstream, the combustion became more complete. In Fig. 4c, intense radiation appears in the left part of the photograph. The right part of the photograph is a little darker but a flame layer covering the jet is clearly visible. Inclined fringes represent Mach waves produced from the irregularity of the flow in the shearing layer; these were called supersonic eddies by Papamoschou (1997). In the unreconstructed hologram in Fig. 4b, Mach waves are more clearly observable from the jaggedly shaped jet interface. The intersection angle β of the Mach waves with the jet axis in Fig. 4b is about 14°–23°, and β is about 18° in Fig. 4c. Hence the average value of β is taken as 18°. The velocity in the shear layer is estimated to be $U = 1116$ m/s from the relation $U = a/\sin\beta$, where a is the speed of sound in air. U is obviously slower than the jet velocity V_j of 2 km/s, because the droplets shattered from the liquid surface were entrained in ambient gas and eventually decelerated by aerodynamic drag forces.

A 2 km/s liquid jet is equivalent to that of Mach 5.8 at an averaged temperature of 300 K. Hence, in assuming a normal shock wave, we estimate the total temperature at the stagnation point of the jet front to be 2318 K (Anderson 1990), which is much higher than the ignition temperature of light oil, say 523 K (Sugihara 1993). The delay time for ignition, τ_i, can be calculated by the formulas proposed by Fieweger et al. (1997) and Vermeer et al. (1972), that is

$$\tau_i = 7.626 \times 10^{-9} \exp(18100K/T)\ (\mathrm{ms})\ , \qquad (1)$$

where τ_i is in ms, T is the temperature (K), and,

$$\tau_i (p/RT)^{\alpha} = \exp(A + B/T)\ (\mu\mathrm{s}), \qquad (2)$$

where τ_i is in μs, T, p, R are the temperature (K), pressure (Pa) and the gas constant of air, respectively. The constants are $\alpha = 0.86$, $A = -15.46$, $B = 23340$ K. When $T = 2318$ K, from (1) and (2), τ_i is only 18.773 ns and 23.257 ns, respectively. Therefore, it is reasonable to conclude that the fuel was ignited immediately after the jet left the nozzle exit. Figure 3 suggests that the fuel had been partially ignited inside the nozzle when the jet was still being accelerated in the path of L_2.

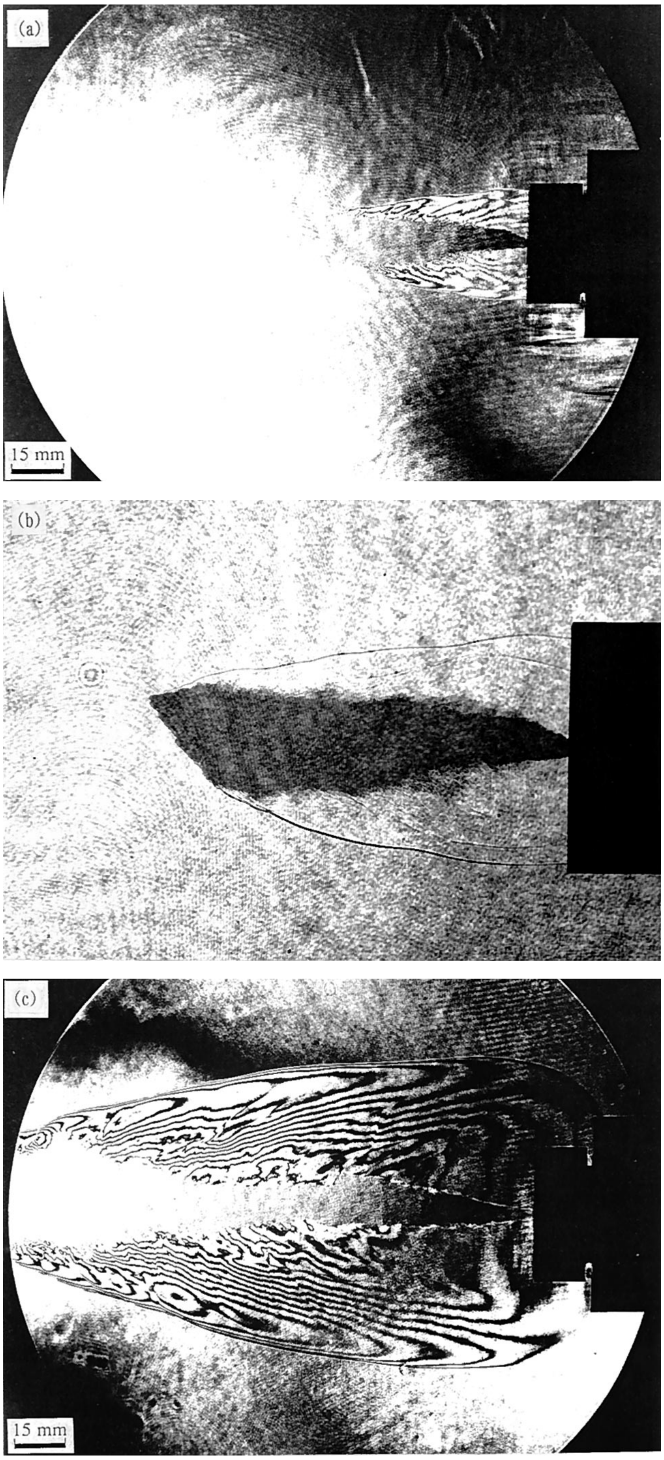

Fig. 4. **a**: Interferogram of a 2 km/s diesel fuel jet injected from a 2.5-mm-diameter nozzle at 0.1 MPa in air. **b**: Unreconstructed hologram of the 2 km/s diesel fuel jet injected from a 2.5-mm-diameter nozzle **c**: Interferogram of 2 km/s diesel fuel jet from a 2.5-mm-diameter nozzle at 0.1 MPa in air

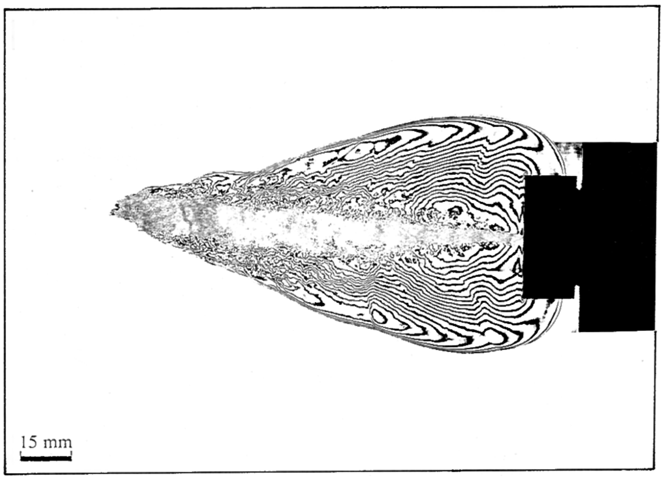

Fig. 5. Interferogram of 3 km/s diesel fuel jet from a 1.0-mm-diameter nozzle at 0.1 MPa in air

It has been noticed that a reduction of the nozzle exit diameter enhances atomization of a hypersonic liquid jet (Shi et al. 1994b). This fact is commonly understood in diesel engines. However, a better atomization with smaller diameter droplets of the spray caused the coherent large structure of vortices to form more easily around the hypersonic liquid jet. These vortices will perturb the liquid surface to promote the fragmentation of the liquid. Meanwhile, the shock-induced mixing of the baroclinic effect $\nabla\rho \times \nabla p$ provides an additional effect in breaking up the liquid jet (Kuhl et al. 1992). Here ρ and p are the density and pressure of the flow, respectively. The light oil jet released from a 1.5-mm-diameter nozzle at 3 km/s is a typical example as shown in Fig. 5. The central white area corresponds to the zone of the combusting jet core which was formed through mixing with air. Between the jet core and fringes, there is a vortex layer which forms a shroud enclosing the central core of the jet, similar to the cocoon formed in supersonic astrophysical jets (Norman et al. 1982, Smarr et al. 1984).

Figures 6a and 6b show injections of 2 km/s light oil jets into air at 3.24 kPa (absolute). The strength of the bow shock wave and the combustion are obviously reduced.

Smoke produced by combustion after the injection in the test chamber was revealed to be more dilute than that in 0.1 MPa in ambient air. In other words, the combustion occurred only partially at such low pressures due to the lower oxygen concentration. In Fig. 6a, although a flame layer is visible around the jet, the contrast between the flame and the jet is not high due to the weak shock wave and weak combustion at lean oxygen concentration.

Figures 7 and 8 show sequencial interferograms of a 2 km/s light oil jet in a helium/air mixture at 0.1 MPa and 0.4 MPa respectively. The test chamber was evacuated first down to 20 kPa, then helium was supplied to it at 0.1 MPa. The chamber contained therefore a pre-mixed helium/air mixture. Since the sound speed of helium is about 1.0 km/s under standard conditions, which is three times higher than that of air, the Mach number of the jet

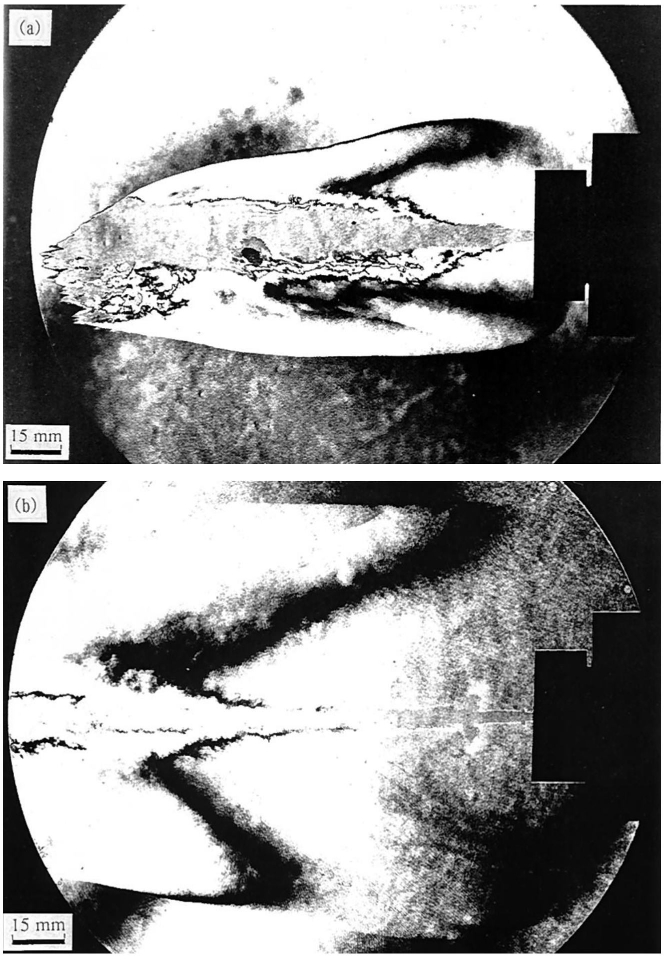

Fig. 6a,b. Interferogram of 2 km/s diesel fuel jet from a 2.5 mm diameter nozzle. Chamber pressure and gas: 3.26 MPa air

Fig. 7. Interferogram of 2 km/s diesel fuel jet from a 2.5 mm diameter nozzle. Chamber pressure and gas: 0.1 MPa in helium/air

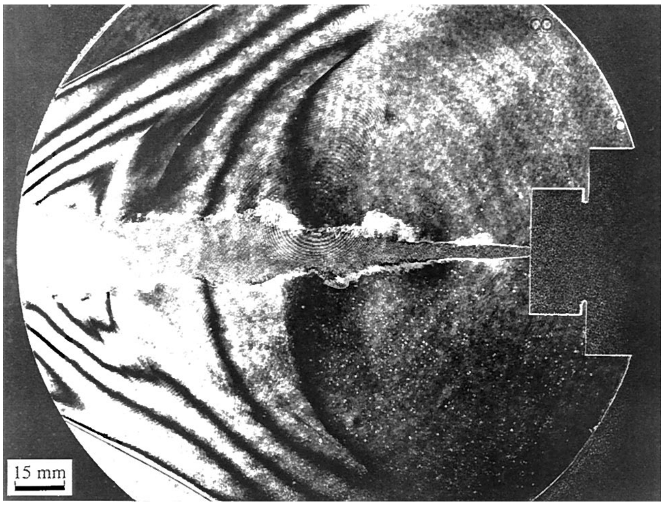

Fig. 8. Interferogram of 2 km/s diesel fuel jet from a 2.5 mm diameter nozzle. Chamber pressure and gas: 0.4 MPa helium/air

in this mixture is about 1.8. This mixture not only represents the effect of inert gas on the combustion but also demonstrates the effect of temperature by simply enhancing the sound speed of the test gas. It was found that the combustion is definitely controlled as expected, as seen from the flame surrounding the jet shown in Fig. 7. If the combustion occurs, it does so only at the very edge of the mixing layer. Light blue smoke, indicating evaporated unburnt fuel, was found in the test chamber after injection. The radially expanding ball-shaped jet near the nozzle exit shown in Fig. 7 is believed to be caused by bubble collapse. Figure 8 shows the injection of a 2 km/s oil jet in helium at 0.4 MPa. Again the test chamber was evacuated down to 20 kPa and the helium was fed in at that elevated pressure. That mixture consists of mainly inert buffer gas. The jet shape and the flame layer surrounding it in the right part of the picture appear to be no different from the jet seen in Fig. 7. Although the increase of gas density increases the fringes behind the leading shock wave and causes the combustion illumination of the left part of the jet shown in Fig. 8, the smoke check after the injection shows that the smoke density is not much different from that in Fig. 7. This may suggest that it is necessary to produce a gas enviroment at a pressure higher than 1.5 MPa for the high-pressure injection experiment (see Mayer 1994, Reitz and Bracco 1982).

4 Concluding remarks

This paper presents the result of the injection of hypersonic light oil jets. The sequence of the jet formation, disintergration of jet interface and initiation of combustion edges were visualized with double exposure holographic interferometry. The result shows that the injection process is very similar to fuel injection in diesel engines, but the velocity of diesel fuel spray into engine cylinders never reaches a value close to 2 km/s to 3 km/s, so the shear layer of the jet boundary has not played any important role.

The present experiment also shows a similar trend but is actually different from the mixing process of liquid hydrogen with hypersonic gas flow in Scramjet engines because the shattering of the liquid jet in this case experiences a deceleration process. It is considered that the deceleration may provide chances for (1) the development of a coherent large vortex structure around the central core of the liquid jet, (2) further mixing and vortex formation and evolution due to the baroclinic mechanism in compressible flow. The experimental technique proposed in this experiment stems from that of water jet cutting technology (Field and Lesser 1977, Cooley 1970, Edney 1976), although visualization has never been tried with double exposure holographic interferometry. However, after a series of investigations it is suggested that the present experimental method can be extended to more generalized supersonic aerodynamic studies. One of the aims of the present fuel injection into a low-pressure environment and helium-enriched air mixture is to observe the effect of combustion on the formation and development of a supersonic shear layer. This is because the numerical simulation of astrophysical jets has shown that the behavior of the "cocoon" surrounding a hot jet is significantly different from that around a cold jet. This is not a goal of this work but remains one of the issues to be examined in the future.

With the tests using helium/air mixtures, although the poorer combustion may be due to the poor ignition because of the lower shock Mach number, it may also be partially influenced by the lean oxygen concentration at 20 kPa. Further work of measuring residual oxygen levels may help to clarify any differences in combustion. It has been found that the illumination of the burning jet is intense enough to apply it to light source.

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