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Visualization of Impinging Supersonic Free Jet on a Tilt Plate by LIF and PSP

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***Abstract*:** The flow field structures of low density supersonic free jets impinging on a tilt plate are studied by hybrid use of LIF (Laser Induced Fluorescence) and PSP (Pressure Sensitive Paint). The jet through an orifice flows into a low pressure chamber and impinges on the tilt plate with angle from jet axis 45, 60 or 90 degrees. A plane including the jet axis and the normal of the plate is visualized by LIF of seeded iodine molecules, scanning a laser beam along the jet axis. On the other hand, the pressure distribution on the tilt plate is visualized by PSP. In comparing the results of the two methods, the complicated shock wave system is analyzed. Deformations of the Mach disk and the barrel shock are also confirmed.

***Keywords*:** laser induced fluorescence, pressure sensitive paint, impinging supersonic free jet, tilt plate, shock wave.

1. Introduction

The attitude control of space-crafts is executed by a jet thruster issuing gas into space. There are some possibilities that the jet interacts with a solar battery panel or a part of the space-craft, affecting the attitude control. It is desirable to elucidate the flow field structure and the pressure field on the surface which interacts with the jet.

In this paper, the structure of a jet impinging on a tilt plate is studied by hybrid use of the laser induced iodine fluorescence (LIF) and pressure sensitive paint (PSP). The former visualizes the rarefied gas flows and clarifies the structures of the shock system in the jet two-dimensionally (Fujimoto and Niimi, 1988; Hiller and Hanson, 1990), while the Schlieren technique cannot be applied to the rarefied gas flows and is influenced by the three-dimensionality of the flow field. The latter makes it possible to visualize the pressure distribution on the plate continuously (Kavandi et al., 1990; McLachlan et al., 1993; Liu et al., 1997; Taghavi et al., 1999; Handa et al., 2000), unlike the pressure taps. Comparing the results obtained by LIF and PSP, the correlation between the pressure distribution and structure of the jet is clarified.

The LIF experiments are carried out by scanning of an argon-ion laser beam in a plane including the center line of the jet and the normal of the plate. Fluorescence from the iodine molecules seeded in the argon jet makes it possible to visualize the structure of the shock system.

Although the pressure on the surface has been measured using pressure taps so far, this technique cannot be applied to the surface with complicated structure and only measures discrete points on the surface. As the alternative technique, PSP has recently attracted attention on the surface pressure measurements. The PSP experiments depend on the oxygen quenching of the luminescence from luminescent molecules. In this experiment, Platinum-Octaethylporphyrin (Pt-OEP) is used as luminescent molecules and silicon-polymer as a binder. The tilt plate is covered with the paint and illuminated by UV light of 380 nm in wave length. The luminescence from the plate is acquired by a CCD camera. To increase the pressure sensitivity of the paint, pure oxygen is employed as the working fluid of the jet. The acquired signal is processed by a computer.

2. Fundamentals

2.1 Theory of LIF

Under the conditions of the experiments of the gas-dynamic interest, the dissociation of the iodine molecules can be ignored. If the broad-band fluorescence from all excited levels is collected, it can be approximated that the rotational transfer among the excited states can be neglected and the excited states are lumped into a single energy level (two-energy level model)(McDaniel, 1982). Under these assumptions, the fluorescence intensity F of the iodine molecules induced by a broad band laser is given by

$$F = C\bar{v}\frac{A_{ij}}{A_{ij}+Q}B_{ij}If_1N_{I_2} \qquad (1)$$

where C is a constant including collection efficiency and Planck constant, $\bar{v}$ the mean frequency, A_{ij} the spontaneous emission rate, B_{ij} the stimulated emission rate, Q the collision quenching rate, I the intensity of the laser beam and N_{I_2} the number density of the iodine molecule. Furthermore, f_1 denotes the fraction of the ground state population which is in resonance with the laser. Since the factor $A_{ij}/(A_{ij}+Q)$ is a function of pressure and temperature, it is impossible to determine the number density distribution only from the measurement of the fluorescence intensity distribution. However, the location of the shock wave can be determined by the radical change of the fluorescence intensity which is attributable to the sharp variation of the number density across the shock wave.

2.2 Theory of PSP Based on the Oxygen Quenching

Figure 1 shows the energy transfer in the luminescence molecules and quencher (oxygen) molecules. By the illumination of light, the luminescent molecules at the ground state (S_0) are transferred to an excited singlet state. In the condensed phase, the excited molecules fall to the lowest excited singlet state S_1 by the internal conversion. From S_1, the molecules may return to the ground state S_0 with or without emission of fluorescence. Another possibility is the transfer to a triplet state T_1 by the inter-system crossing. If there is no quencher molecule, the molecules at T_1 return to the ground state with emission of phosphorescence. By the existence of the quencher molecules, there are two possibilities of quenching (Engler et al., 1992): (1) By exchange of electron between the luminescent molecule at the excited singlet state S_1 and the oxygen molecule at the ground triplet state T_0, the luminescent molecule transfers to the excited state T_1 and the oxygen molecule converts to the excited singlet state S_1; (2) By exchange of an electron between the luminescent molecule at T_1 state and the oxygen molecule at T_0 state, the luminescent molecule returns to the ground state S_0 and the oxygen molecule converts to the excited state S_1.

The rate of these quenching depends on the rate of encounters between the luminescent molecules and the oxygen molecules. When the number density of the luminescent molecules is fixed, the quenching rate depends on

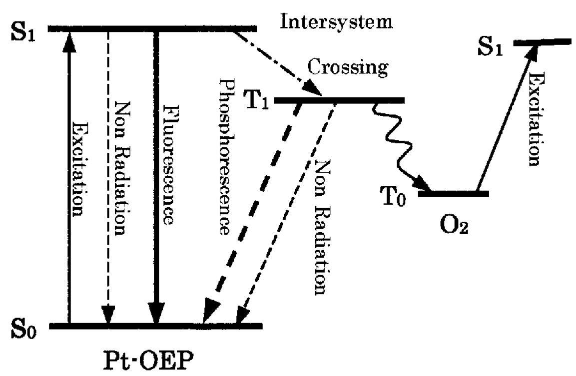

Fig. 1. Energy level diagram of luminescent molecules and oxygen.

the partial pressure of oxygen p_{O_2}. Relation between intensity of luminescence I and p_{O_2} is given by the Stern-Volmer equation:

$$\frac{I_0}{I} = 1 + K(T)p_{O_2} \tag{2}$$

where I_0 is the intensity of luminescence when p_{O_2}=0 and $K(T)$ is a constant which depends on temperature.

When the concentration of the quencher in the working fluid is r, the partial pressure p_{O_2} is expressed in terms of the total pressure p of the working fluid, which is usually measured in the aerodynamic experiments, i.e.

$$p_{O_2} = rp.$$

And Equation (2) is rewritten as

$$\frac{I}{I_0} = \frac{1}{1 + rKp}. \tag{3}$$

The dependence of the sensitivity of luminescence on the total pressure is given by

$$\left|\frac{\partial I}{\partial p}\right| = rK\left(\frac{1}{1 + rKp}\right)^2. \tag{4}$$

This shows the adequacy of the use of PSP in the low pressure range and the larger the concentration of the quencher is, the larger the pressure sensitivity is.

Figure 2 shows the experimental results for various concentrations of the quencher (oxygen) in the working fluid which is the mixture of nitrogen and oxygen. The dotted curve in Fig. 2 is the result calculated by Eq. (3) for pure oxygen (r=1). These results justify the use of pure oxygen for the low pressure gas flow from a view of the pressure sensitivity. However, since the luminescence from the Pt-OEP is also influenced by temperature, these calibration curves taken at the room temperature cannot be applied to determination of the quantitative pressure distribution unless temperature is known.

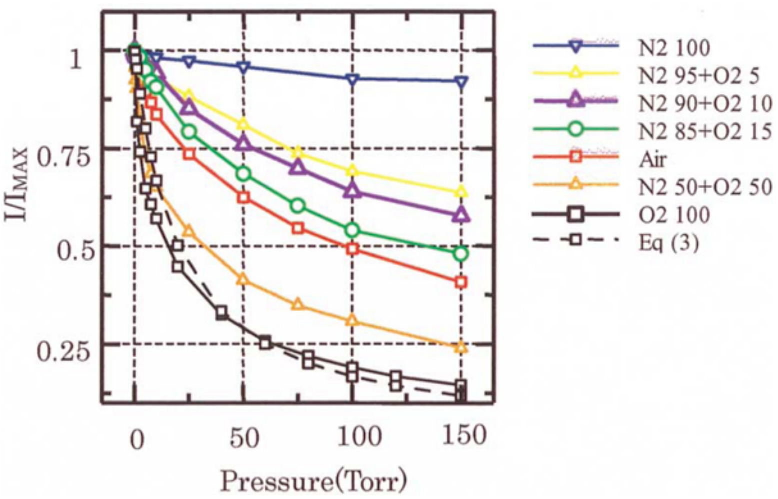

Fig. 2. Dependence of luminescence intensity on pressure for various concentration of oxygen and nitrogen.

3. Experimental Apparatus and Method

3.1 LIF

Figure 3 shows the schematic diagram of the experimental apparatus of the LIF experiment. For flow visualization, the LIF of iodine molecules seeded in the working fluids (argon) is adopted. Iodine molecules do not disturb the flow as long as the molar fraction is low (vapor pressure of iodine is 0.2 Torr at 293K). The total flow field is visualized two-dimensionally by a laser sheet.

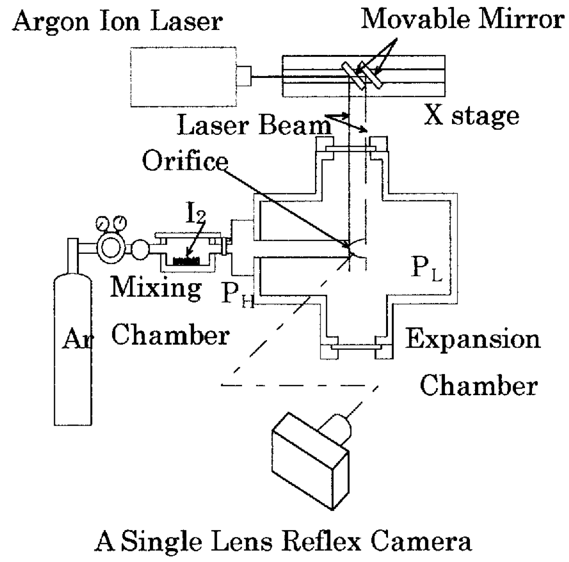

Fig. 3. Experimental apparatus of LIF.

Iodine molecules are mixed with the working fluid in the mixing chamber and the mixture is supplied into the high pressure chamber (p_h=1000 Torr), issuing into the vacuum chamber (p_l= 0.12 Torr) through an orifice of 0.3 mm in diameter. The free jet impinges on a tilt plate with an angle of 45, 60 and 90 degrees from the center line of the jet (see Fig. 11). The distance between the orifice and the plate along the center line (X_p: see Fig. 11) is set at 15, 20 and 25 mm.

An argon-ion laser beam of wave length 514.5 nm with diameter of 0.6 mm is scanned in the horizontal plane including the center line of the jet. Fluorescence of the iodine molecules makes it possible to visualize the interacting jet. A reflex camera attached with a telescope lens, a bellows to take an enlarged image on a film (ASA 400) and a sharp-cut filter to remove the laser light is set normal to the scanning plane. To make a laser sheet, the laser beam is scanned by a movable mirror set on a x-stage which is controlled by a computer. It takes about 3 minutes to scan the laser beam in the flow field, setting the exposure time of the camera for the same time.

3.2 PSP

Pt-OEP is used as the luminescent molecule which is dissolved in a layer of silicon-polymer as a binder. The surface of the tilt plate is covered by the paint and illuminated by light of 380 nm in wave length from a xenon-lamp using a narrow band-pass filter. The luminescence from the paint is acquired by a CCD camera and the signal is processed by a computer.

The error due to the non-uniformity of the paint and the non-uniform illumination is calibrated by dividing the luminescence signal of each pixel by the corresponding signal taken without flow.

The flow system is the same as that of LIF experiment except the mixture of argon and iodine is replaced by pure oxygen (Fig. 4).

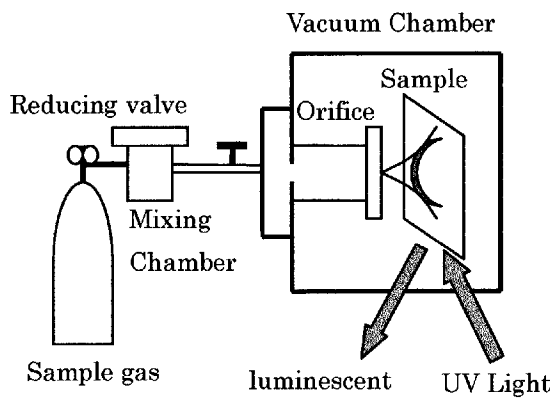

Fig. 4. Experimental apparatus of PSP.

4. Experimental Results

Figures 5, 6, 7 and 8 show the original photographs obtained by the LIF (Figs.(a): see Fig. 11) and PSP (Figs. (b)) experiments for the tilt angles q=45 and 60 degrees and the distances between the orifice and the plate X_p=15 and 25 mm. It should be noted that the magnification rates of LIF and PSP images are different due to the difference of the camera position and are not taken simultaneously. And it should be also described that we use argon gas for LIF experiments and pure oxygen gas for PSP experiments. The flow field structure of a supersonic free jet for monatomic gas and diatomic gas are known to be different. However, the distance of the Mach disk from the orifice is the same for both cases, though the maximum diameter of the barrel shock is different.

(a) (b)

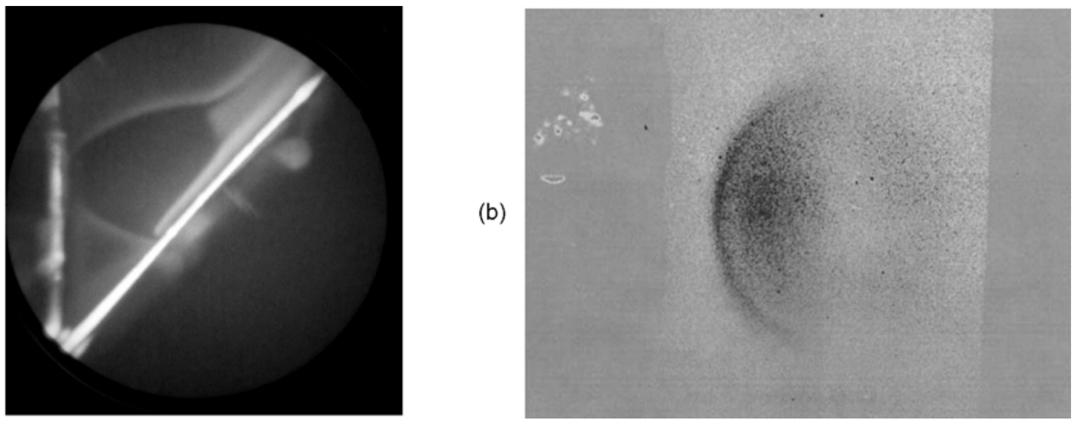

Fig. 5. (a) Flow visualization of a supersonic free jet by LIF (q=45 degrees, X_p=15 mm) (b) Visualization of pressure field on the tilt plate by PSP (q=45 degrees, X_p=15 mm)

(a) (b)

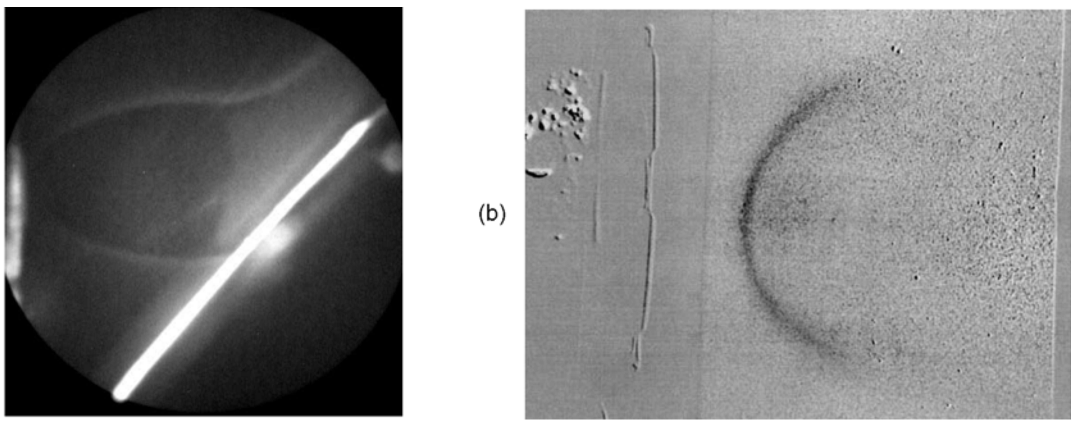

Fig. 6. (a) Flow visualization of a supersonic free jet by LIF (q=45 degrees, X_p=25 mm) (b) Visualization of pressure field on the tilt plate by PSP (q=45 degrees, X_p=25 mm)

(a) (b)

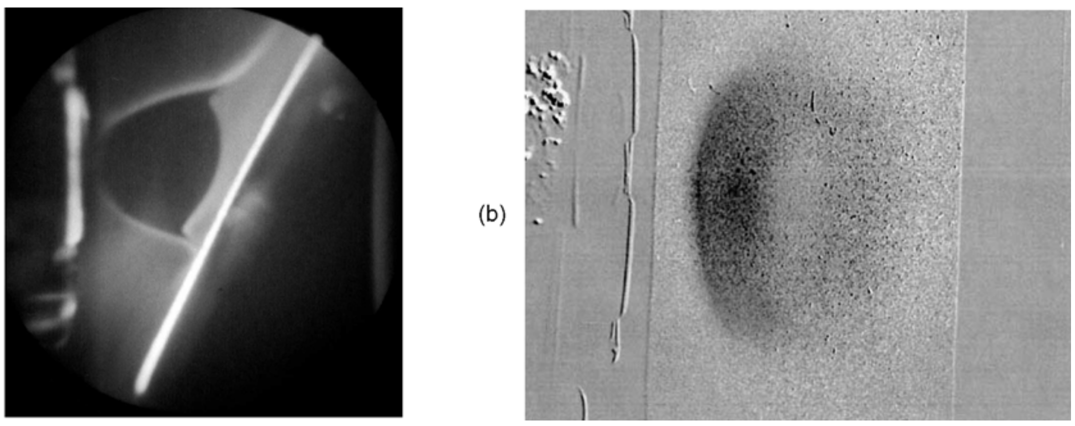

Fig. 7. (a) Flow visualization of a supersonic free jet by LIF (q=60 degrees, X_p=15 mm) (b) Visualization of pressure field on the tilt plate by PSP (q=60 degrees, X_p=15 mm)

(a) (b)

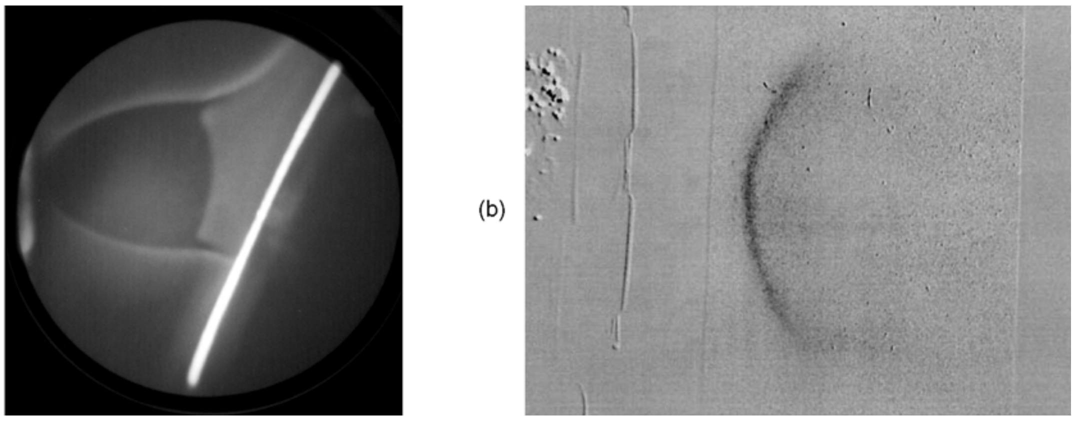

Fig. 8. (a) Flow visualization of a supersonic free jet by LIF (q=60 degrees, X_p=25 mm) (b) Visualization of pressure field on the tilt plate by PSP (q=60 degrees, X_p=25 mm)

When q=45 degrees and X_p=15 mm as shown in Fig. 5(a), there is no large displacement of the Mach disk from its original position in a free jet, but it is divided sharply into two parts: one is almost normal and the other is oblique. In this case, pressure distribution on the tilt plate shows two dark regions corresponding to higher pressure (Fig. 5(b)). The bow shape region may be caused by the impingement of the barrel and the other by high pressure behind the oblique shock. For larger X_p, the shock system of the free jet changes, as shown in Fig. 6(a). When X_p=25 mm, the Mach disk is almost not distorted from the structure of the free jet undisturbed by the tilt plate and only the high pressure region with the bow shape appears in Fig. 6(b). In the case of larger X_p, since the Mach disk is formed far from the tilt plate, the pressure behind the Mach disk may decrease gradually toward the plate, showing lower intensity of luminescence in the right hand side of the higher pressure region with the bow shape. This indicates that for q=45 degrees the shock system may change drastically at a X_p between 15 and 20 mm.

When q=60 degrees, as shown in Fig. 7(a) and 7(b), the shock system of the free jet does not change drastically as an increase in X_p. Comparing with the shock system for q=45 degrees, the Mach disk changes to a bow shape and the discontinuous bend of the Mach disk (see Fig. 5(a)) disappears. As for the case of X_p=25 mm, there is no distortion of the Mach disk. In the PSP image of Fig. 7(b) for X_p=15 mm, the image of the high pressure region is darker than that of Fig. 5(b) for q=45 degrees, showing stronger interaction. It may be inferred from Fig. 7(a) that the darkness strongly depends on the distance between the Mach disk and the tilt plate. This means that the shorter the distance is, the higher the pressure on the tilt plate is. This can be also confirmed from Figs. 8(a) and 8(b) for X_p=25 mm, in which the distance of the Mach disk and the tilt plate is relatively larger and only high pressure region with bow shape can be found.

When q=90 degrees, for both X_p=15 mm and 25 mm, the jet flows symmetrically with respect to the center line as shown in Figs. 9 and 10. The photograph of the pressure field for the case of q=90 degrees is not taken because of the geometrical limitation of the illumination and detection system.

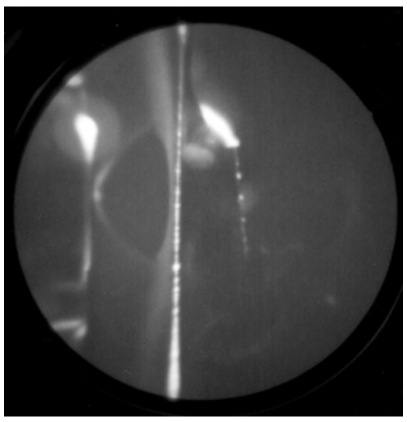

Fig. 9. Flow visualization of a supersonic free jet by LIF (q=90 degrees, X_p=15 mm)

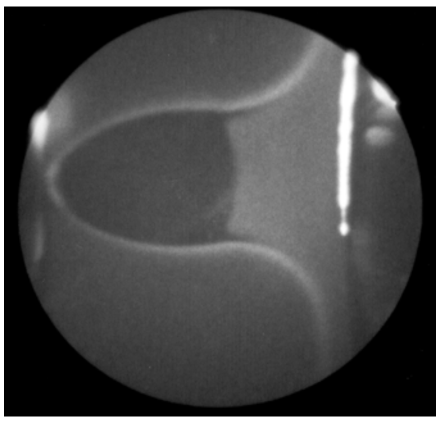

Fig. 10. Flow visualization of a supersonic free jet by LIF (q=90 degrees, X_p=25 mm)

In all (a)s of Figs. 5 to 8, we can see the bright line along the surface of the tilt plate. This may be caused by the scattered laser beam on the plate, because the laser beam passes through the optical filter in the case of the long exposure time (about 3 minutes).

As shown in Fig.11, the distance of the shock from the orifice along the jet axis (X_M) is proportional to the distance between the orifice and the plate (X_p). It is also found that the proportional constants of any tilt angles are the same irrespective of tilt angle (q).

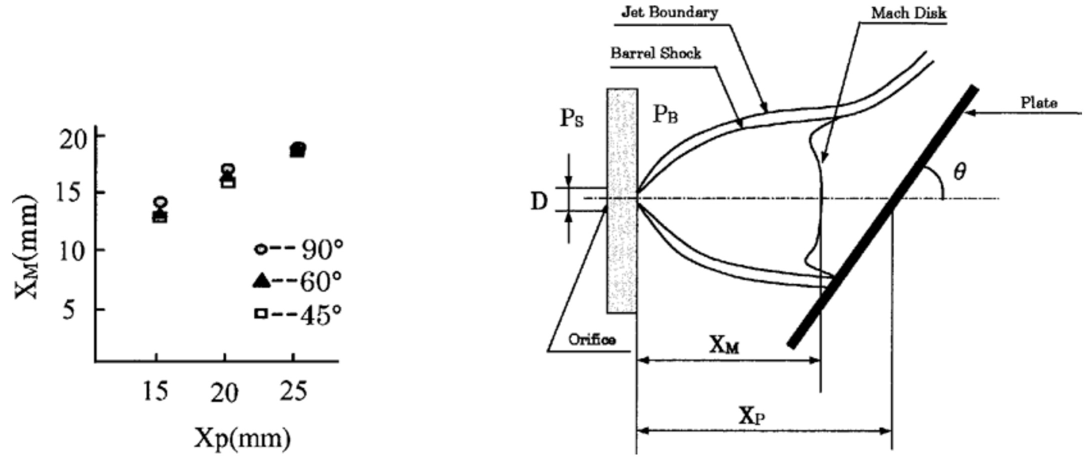

Fig. 11. Relation between X_M and X_p and the flow field structure.

5. Concluding Remarks

Structure of the shock wave system in a jet impinging on a tilt plate and pressure distribution on the plate are studied by a hybrid use of LIF and PSP for several combinations of the tilt angles q and the distances between the orifice and the plate X_p. By comparison of these two methods, existence of high pressure region is explained in terms of the structure of the barrel shock and the Mach disk. The following conclusions are obtained:

(1) Use of pure oxygen as a working fluid in the low pressure range is effective to strengthen the pressure sensitivity of PSP.

(2) When q=45 degrees and smaller X_p, the shock wave system inside the supersonic free jet consists of barrel shock, Mach disk and oblique shock. For larger X_p, however, the Mach disk is almost not distorted from the structure of the free jet undisturbed by the tilt plate.

(3) For q=60 and 90 degrees, the shock wave system of the supersonic free jet keeps the same structure as the undisturbed supersonic free jet in the range of X_p in our experiments.

(4) Pressure distribution on the tilt plate due to the impingement of a jet depends on the position of the plate relative to the position of the Mach disk in a free jet. When the plate is placed in front of the Mach disk, the high pressure region is generated by the impingement of the barrel shock and high pressure behind the oblique shock. When the plate is placed behind the Mach disk, the high pressure region becomes a semi-circle due to the impingement of the barrel shock.

Acknowledgments

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References

Engler, R. H., Hartmann, K., Troyanovski, I. and Vollan, A., Description and Assessment of a New Optical Pressure Measurement System (OPMS), Demonstrated in the High Speed Wind Tunnel of DLR in Goettingen, Deutche Forschunganstalt fuer Luft- und Raumfahrt (1992).

Fujimoto, T. and Niimi, T., Three Dimensional Structures of Interacting Freejets, Rarefied Gas Dynamics, Space related Studies, AIAA (1988), 391-406.

Handa, T., Miyazato, Y., Masuda, M and Matsuo, K., Experimental Investigation on Luminescent Characteristics of Fast Responding Pressure Sensitive Paint, Proceedings of PSFVIP, PF087(1999).

Hiller, B. and Hanson, R. K., Properties of the Iodine Molecule Relevant to Laser-induced Fluorescence Experiments in Gas Flows, Experiments in Fluids, 10 (1990), 1-11.

Kavandi, J. Callis, J., Gouterman, M., Khalil, G., Wright, D., Green, E., Burus, D. and Mclachlan, B., Luminescent Barometry in Wind Tunnels, Rev. Sci. Instrum., 61-11 (1990), 3340-3347.

Liu, T., Campbell, B. T., Buruns, S. P. and Sullivan, J. P., Temperature- and Pressure-sensitive Luminescent Paints in Aerodynamics, Appl. Mech. Rev., 50-4 (1997), 225-246.

McDaniel, J. C., Investigation of Laser-induced Fluorescence for the Measurement of Density in Compressible Flows, PhD Thesis, Stanford University (1982).

McLachlan, B.G. Kavandi, J.L., Callis, J.B., Gouterman, M. Green, E., Khalil, G. and Burus, D., Surface Pressure Field Mapping Using Luminescent Coatings, Experiments in Fluids, 14 (1993), 33-41.

Taghavi, R., Raman, G. and Bencic, T., Pressure Sensitive Paint Demonstrates Relationship between Ejector Wall Pressure and Aerodynamic Performance, Experiments in Fluids, 26 (1999), 481-487.

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