Flow Visualization of Sonic Jets Exhausting Counter to a Supersonic Free Stream Using Laser Induced Fluorescence Method

By

Shigeki TANAKA*, Koji TESHIMA**, Kazuyuki UENO***
and Michio NISHIDA***

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Summary: The flow field resulting from a sonic nose jet exhausting counter to a supersonic free stream of a Mach number of 3 was visualized by means of a laser induced fluorescence method. The experiments were conducted for various values of the ratio of counter jet total pressure to free-stream total pressure. The ratio of body diameter to jet exit diameter was taken to be 0.2 or 0.4. The results show that the structure of the opposing jets are significantly affected not only by the ratio of jet total pressure to free stream total pressure but also by the ratio of body diameter to jet exit diameter. It was also observed that at the low pressure ratios, there exists unstable flow regime. Simple analysis is applied to the prediction of the position of the free stream shock and Mach disc, and compared with the experimental result. The comparison shows a good agreement. Numerical simulation was also tried to compare with the experiments.

1. INTRODUCTION

The interaction between a jet exhausting upstream and a supersonic free stream has been studied over the years for various reasons, i.e., as a model for a retro-rocket operating in atmosphere during re-entry, as a means for pressure distribution control on forward-facing surfaces, as a means for thermal protection, and as a possible injector of gaseous fuel in a supersonic combustor. The opposing jet can reduce the pressure drag on a blunt body. Therefore, the problem of opposing jets is also very interesting with respect to the drag control of AOTV's in the entry to the atmosphere.

The opposing jets have been investigated over the years experimentally [*1–6, 9–11, 17, 20*], theoretically [*6–8, 11*] and computationally [*13–16, 19, 21*]. Typical experimental results were given by Romeo and Street [*5*], who revealed the structure of the opposing jet by means of a flow visualization method. Their flow conditions were such that a free stream Mach number was 6, opposing jet Mach numbers were 1 to 10.4 and opposing jet to free stream total pressure ratios were 0.03 to 2.5. From

* Toyobo Research Center, Toboyo Co., Ltd.
** Department of Industrial Arts Education, Kyoto University of Education.
*** Department of Aeronautical Engineering, Kyoto University.

their parametric studies, it was found that there existed two distinct categories concerning the position of a free stream shock. In one case, the free stream shock retained its basic shape, and in a second case, the shock was far removed from the body. The latter case was seen to be less steady. Finley [*11*] did parmetric studies experimentally by varying the body shape. He also developed a simplified prediction for a free stream shock, contact surface and inner shock, and mentioned that when the flow conditions are above a critical Mach number, the unsteady phenomenon appears. The unsteadiness of the opposing jet was also discussed by Karashima and Sato [*17*] based on the measured wall pressure distributions and visualized flow field. They showed three regimes for jet stability. Numerical simulation of the opposing jets were started by Hirose and Kawamura [*13*] who used FLIC method in computations. Recently, Fox [*21*] did the numerical simulation using thin-layer Navier-Stokes equations.

The present work is concerned with flow visualization of sonic jets issuing counter to a supersonic free stream and a comparison of this with computational simulation. The present flow visualization uses a laser induced fluorescence method (LIF) [*22, 23*]. In the above mentioned experimental work, the flow visualization was performed by a conventional schlieren method. Then the visualized results were the integrated results over the optical path across the flow field. On the other hand, the LIF enables us to observe the cross-sectional structure of the flow field. Another advantage of the LIF is that this method can be employed in such low density flows as the conventional schlieren and shadowgraph methods are not available. It is the objective of this paper to visualize the flow field of the opposing jets and to reveal the structure of such jets in low-density free-stream.

2. Schematic Structure of an Opposing Jet

Figure 1 shows a sonic jet expanding from an orifice at the nose of a bluff-cylindrical body counter to a supersonic free stream. The sonic jet forms the Mach disc (inner shock) and barrel shock. The jet flow encounters the oncoming stream which penetrates the bow shock (free stream shock), and then the contact surface is generated, which separates the sonic jet flow from the oncoming stream. The parameters which characterize the flow field of the opposing jet are the ratio of jet total pressure to free stream total pressure $p_{OJ}/p_{O\infty}$, a free stream Mach number M_∞ and the ratio of sonic nozle exit diameter to body diameter ratio D_J/D_B. When the total pressure ratio is low or when the jet exit to body diameter ratio is large, unsteady flow phenomena appear.

3. Experimental Apparatus and Procedure

The LIF of iodine molecules (I_2) by an argon laser beam (λ=5.14.4nm) has applied to the flow visualization of the opposing jet in the present work. The details of this flow visualization method are described in Refs. 22 and 23. The apparatus used in the

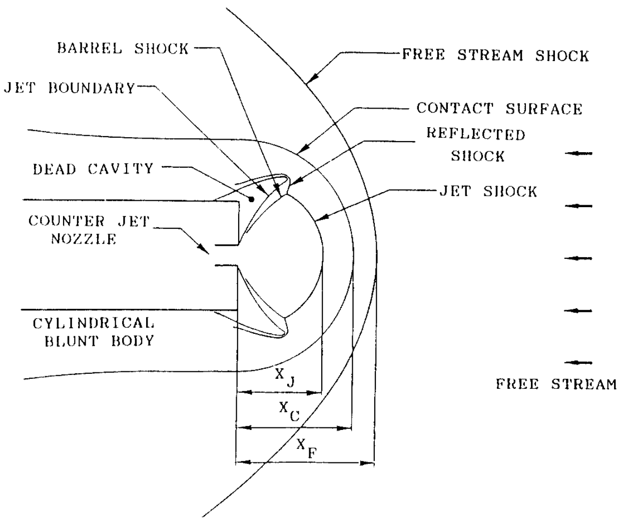

Fig. 1. Schematic Structure of an Opposing Jet.

present experiment is shown in Fig. 2. The JPL nozzle generates a free stream of a Mach number of 3. A bluff-cylindrical body (diameter D_B=2.0mm) is placed downstream of the JPL nozzle. An opposing jet issues from a sonic orifice (diameter D_J=0.4mm or 0.8mm) mounted on the upstream-facing of the body. A small amount of iodine molecules is seeded into either the free stream gas or the jet gas. The thin laser beam travels across the flow. Opened-shutter pictures of the LIF flow visualization are taken by moving the laser beam in the flow-axial direction. The detail of the nozzle and body dimensions is given in Fig. 3. Nitrogen has been used for both jets.

The typical experimental conditions are as follows:

$M_\infty=3.0$
$M_J=1.0$
$p_{OJ}=4.0\times10^4$ to 2.0×10^5 kPa
$p_{O\infty}=4.0=10^4$ kPa
$p_{OJ}/p_{O\infty}=0.41$ to 14.70
$D_J/D_B=0.2$ and 0.4

4. Experimental Results and Discussion

Typical pictures of the flow visualization are shown in Fig. 4. The flow field without an opposing jet is shown in Fig. 4(a) in which a bow shock is clearly observed. Figure 4(b) shows the case when I_2 has been seeded into the free stream gas, while Fig. 4(c) is the case when I_2 is added to the opposing jet gas. In these pictures, there is no fluorescence in lower side of the body, because the body cuts the laser beam. Figure 4(b) gives the visualization of the free stream shock and contact surface. In Fig. 4(c), the structure of the opposing jet can be well understood: the discontinuities show the contact surface and the inner shock in sequence from the right to left. In addition the

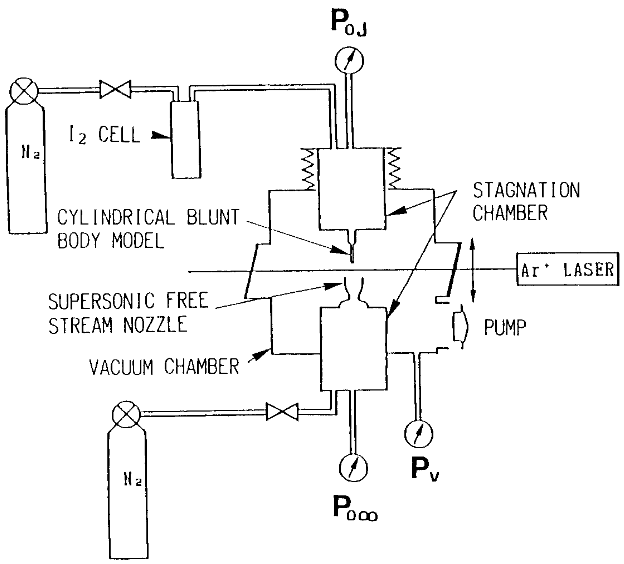

Fig. 2. Experimental Apparatus for the Laser Induced Fluorescence Method.

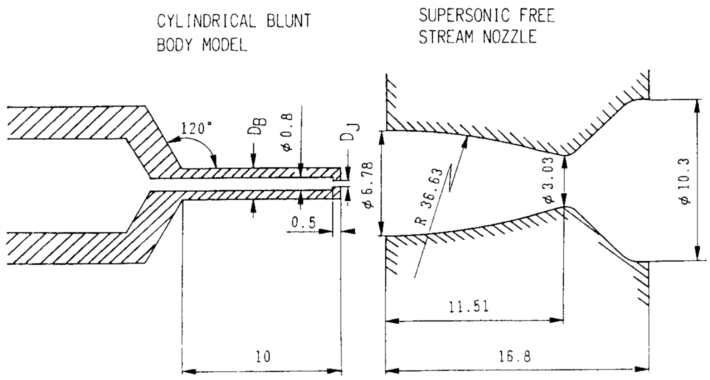

Fig. 3. Details of the JPL Nozzle and Body.

barrel shock which starts at the orifice and terminates at the inner shock is also apparent. In order to investigate the effect of the total pressure ratio upon the structure of the opposing jet, the the total pressure of the opposing jet has been varied, keeping the free-stream conditions constant. The pictures for $p_{OJ}/p_{O\infty}=0.41$ to 7.43 and $D_J/D_B=0.41$ shown in Fig. 5. In these pictures, I_2 was seeded into the opposing jet gas. In the case of $p_{OJ}/p_{O\infty}=0.84$ to 7.43, the contact surface is clearly seen, and the flow field looks very stable. On the other hand, as seen in the case of $p_{OJ}/p_{O\infty}=0.41$, the contact surface is not clear. This is presumably because the contact surface oscillates. This case falls into the unstable flow regime. The results for $D_J/D_B=0.2$ are illustrated in Fig. 6 for $p_{OJ}/p_{O\infty}=0.41$ to 14.73. The opposing jets for $p_{OJ}/p_{O\infty}=1.65$ to 14.73 seem very stable because the contact surface is very clear. In cases of low total pressure ratio such as $p_{OJ}/p_{O\infty}=0.70$ to 0.77, the contact surface is concave forwards upstream and less clear. The concave contact surface is not observed in a case of $D_J/D_B=0.4$ (Fig. 5). At $p_{OJ}/p_{O\infty}=0.41$ the contact surface moves upstream.

Figure 7 illustrates the pictures for a case when I_2 is seeded into both the free stream and opposing jet gases. In these pictures, a transmitted laser beam is reflected and returned to the flow again in order that the flow uniformly fluoresces. The conditions are $D_J/D_B=0.2$ and $p_{OJ}/p_{O\infty}=0.505$ to 4.90. The free stream shock and contact surface in Figs. 7(a) and 7(b) are fall into the unstable regime. Figures 7(c) and 7(d) are cases of stable regime.

The on-axis positions of the Mach disc, contact surface and free stream shock have been estimated from the pictures. These positions are plotted against $p_{OJ}/p_{O\infty}$ in Fig. 8 for $D_J/D_B=0.2$ and in Fig. 9 for $D_J/D_B=0.4$. The comparison of these results with simple predictions are also given in the figures. The position of the Mach disc predicted by Cassanova's theory [*12*] agrees well with the experiments. However there is no theory for predicting the position of the contact surface because it depends predominantly upon the shape of the counter jet nozzle. The solid curve for the contact surface has been obtained using a least square method for experimental data of the position of the contact surface. Assuming that the contact surface is an imaginary solid surface, and applying modified Newtonian theory to this imaginary solid surface, the position of the free stream shock is determined. As shown in the figures, this position agrees well with the experimental result.

5. Numerical Results and Comparison with Experimental Results

In order to compare with the experimental results, numerical calculations were

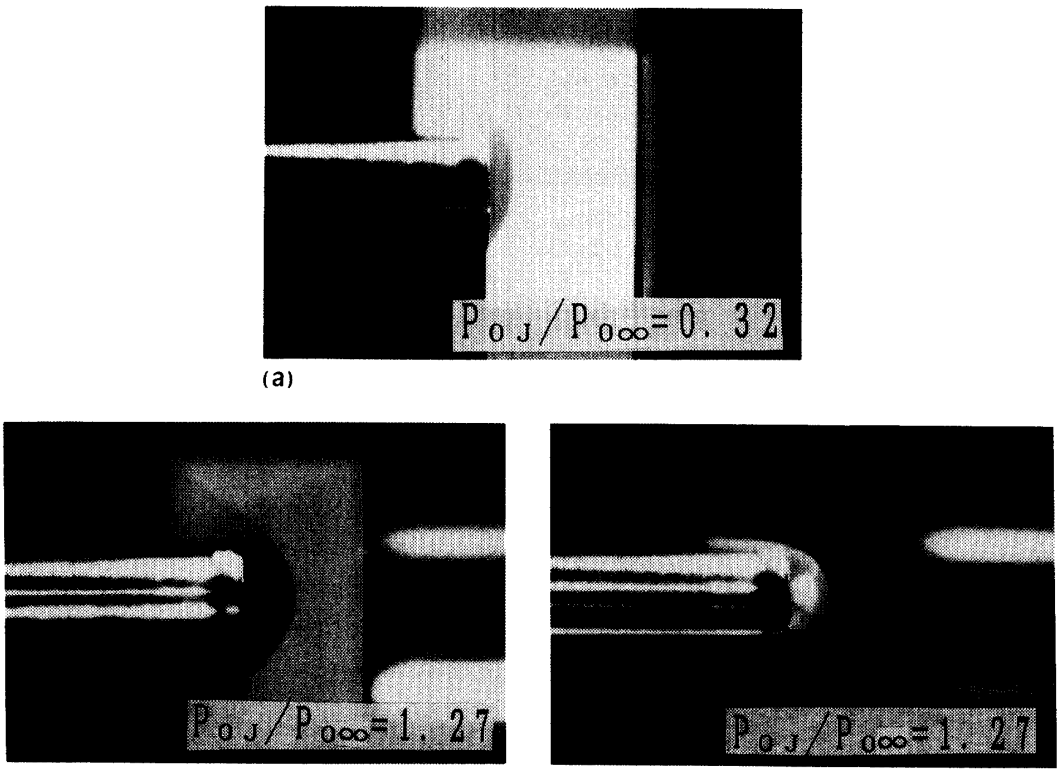

Fig. 4. LIF Flow Visualization.

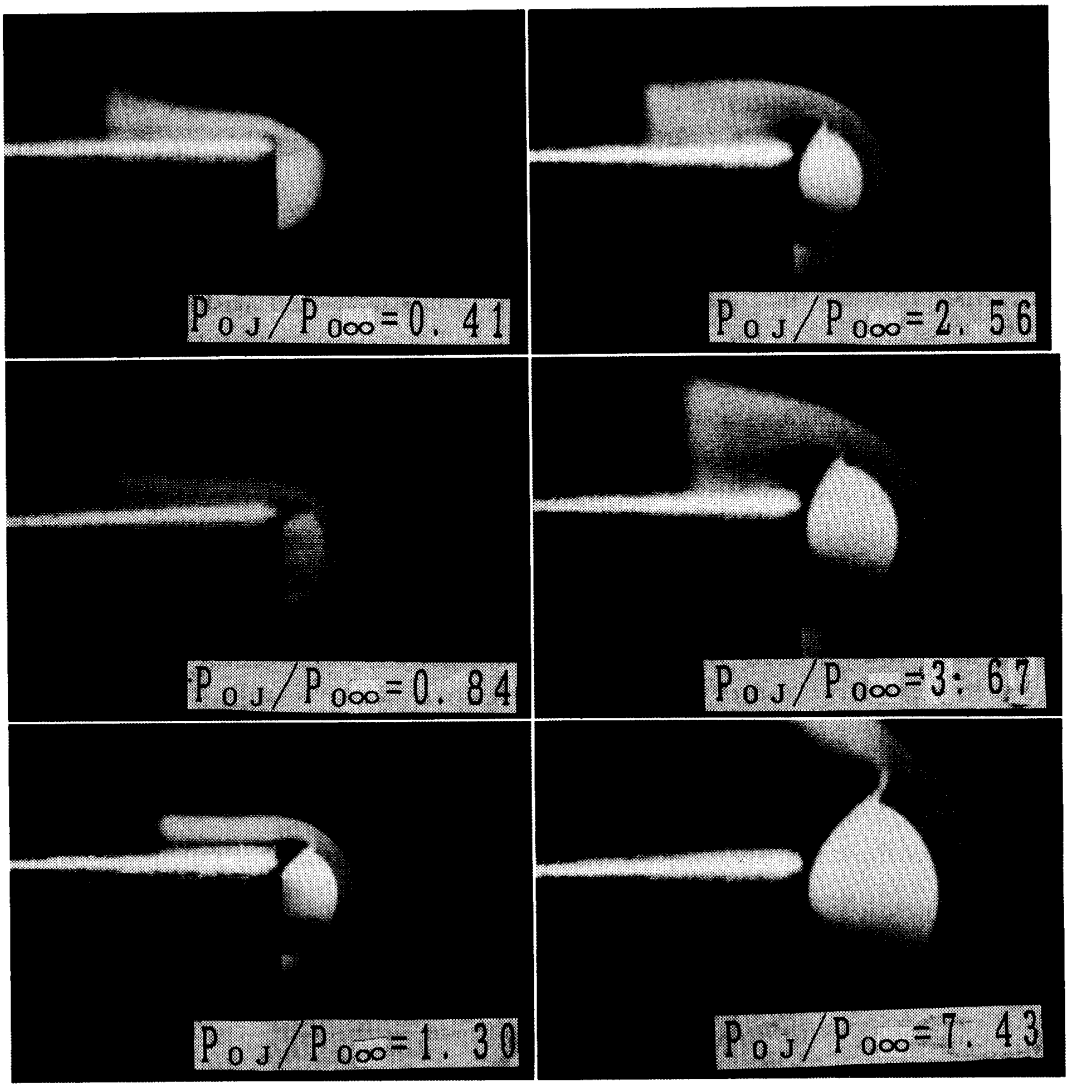

Fig. 5. LIF Flow Visualization for Various Values of $P_{OJ}/P_{O\infty}$ and D_J/D_B=0.4.

carried out using Piecewise Linear Method(PLM) [*24*]. The basic equations to be solved are Euler equations. The same conditions as the experimental conditions are employed as the numerical boundary conditions, and the initial conditions are given by an impulsive start for a opposing jet. The computational domain is divided into 200×100 grids with $\Delta(x/D_J)=\Delta(r/D_J)=0.05$.

Figure 10 shows the comparison of the experimental and numerical locations of the Mach disc, contact surface and free stream shock at a few total pressure ratios, for D_J/D_B=0.2. The bars mean the width of numerical variation in time. The numerical Mach disc position is fairly well agrees with the experimental one. However, the numerical results of the contact surface and free stream shock fall below the experimental result. According to the experimental result shown in Fig. 8, the range of $p_{OJ}/p_{O\infty}$ represented in Fig. 10 is in a stable regime. Nevertheless, the numerical results show the time variation in the position of the three discontinuitites. It will be expected to obtain the stable solutions by including real viscosity terms in the basic

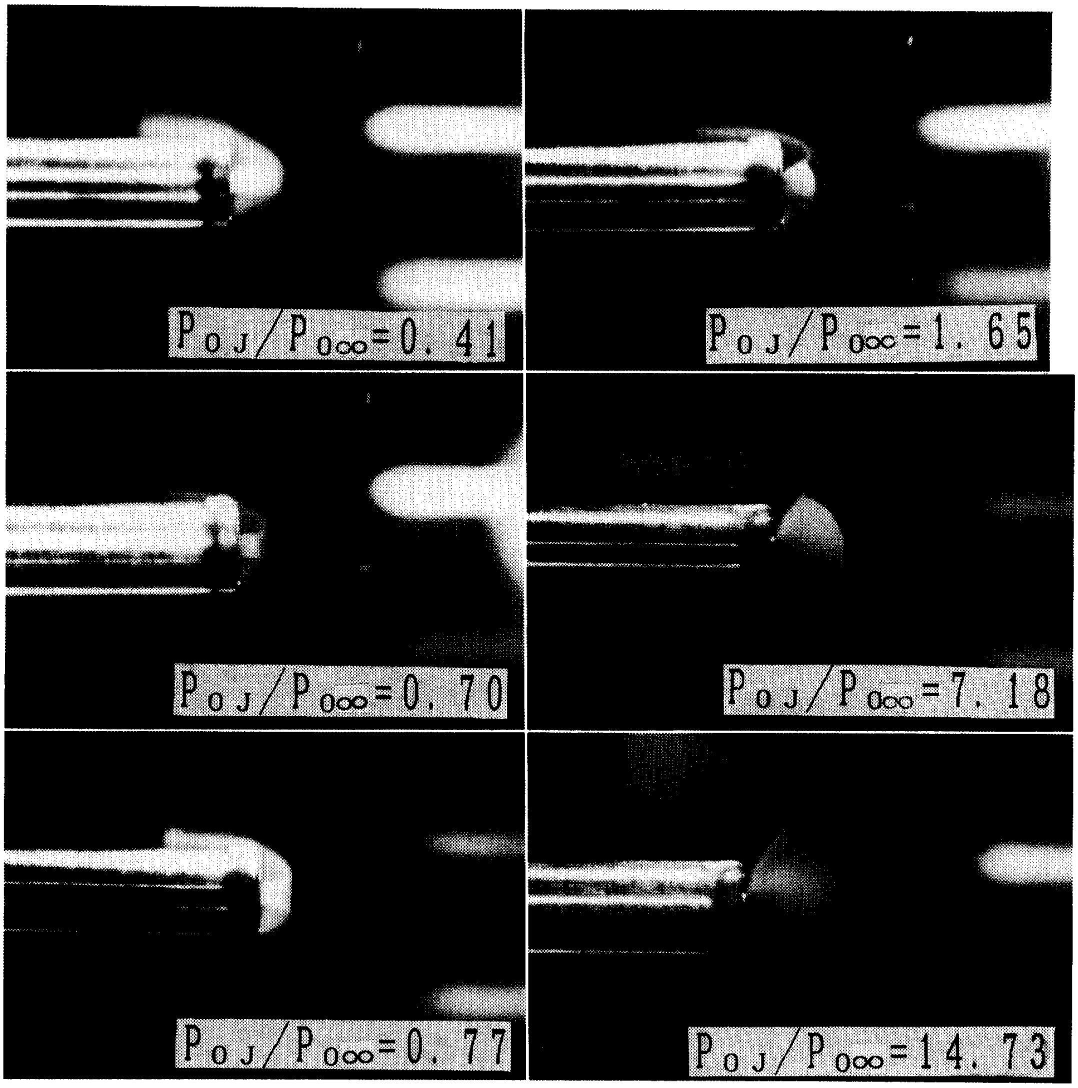

Fig. 6. LIF Flow Visualization for various values of $P_{OJ}/P_{O\infty}$ and $D_J/D_B=0.2$.

equations. The computations using the real viscosity are our future problem.

6. Concluding Remarks

In the present study, the LIF was applied to flow visualization of a sonic jet exhausting counter to a supersonic free stream in order to reveal the detail of the opposing jet structure. In addition, numerical calculation was carried out to compare with experimental results. The principal conclusions which may be drawn from this investigation are summarized as follows:

(1) It is proved that the on-axis structure of sonic jets exhausting counter to a supersonic free stream can be visualized with an LIF method.

(2) The contact surface is clear for large pressure ratios, while it is unclear for small pressure ratios which presumably means unstable flow phenomenon.

(3) At $D_J/D_B=0.2$, the contact surface is concave towards upstream for small

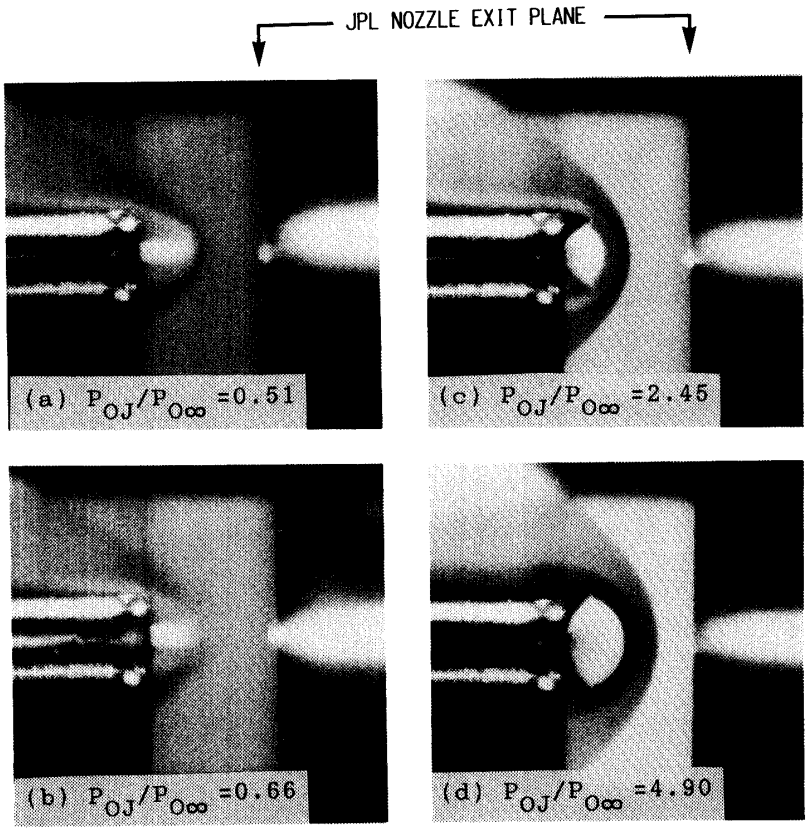

Fig. 7. LIF Flow Visualization, $D_J/D_B=0.2$.

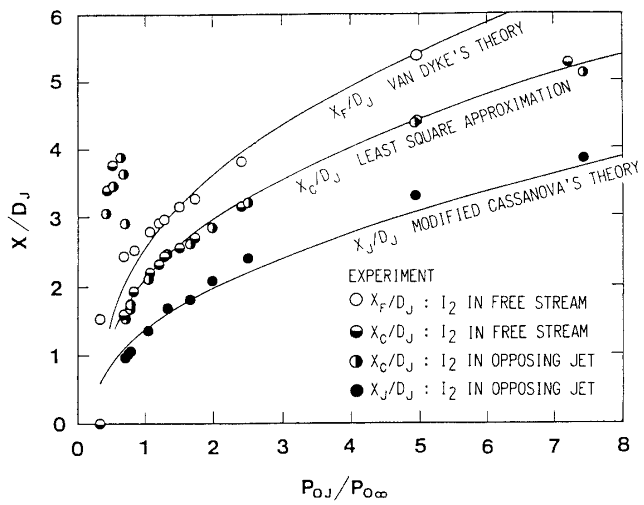

Fig. 8. Variation of the Positions of the Mach disc, Contact Surface and Free Stream Shock for Total Pressure Ratio in a Case of $D_J/D_B=0.2$.

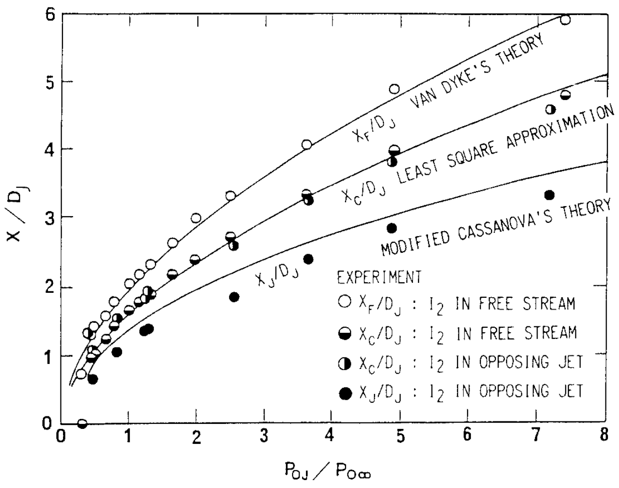

Fig. 9. Variation of the Positions of the Mach Disc, Contact Surface and Free Stream Shock for Total Pressure Ratio in a Case of $D_J/D_B=0.4$.

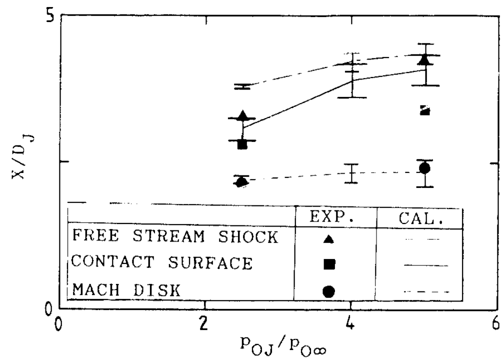

Fig. 10. Comparison of Numerical Results with Experimental Results ($D_J/D_B=0.2$).

pressure ratios.

(4) Unstable regime of opposing jets was observed in small total pressure ratio. In this unstable regime, the contact surface is seen to oscillate.

(5) Comparison of numerical calculations with experiments were tried. A fairly good agreement was obtained in Mach disc position, while the numerical results of the contact surface and free stream shock were below the experimental results.

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