Visualization for a Free Jet by a Laser Induced Fluorescence Method and its Structure

By

Koji TESHIMA

(January 25, 1984)

Summary: Visualized free jets by an I_2-Ar ion-laser induced fluorescence (LIF) method are shown and their features are explained qualitatively in connection with the flow properties of the flow medium and of the seeded I_2. The LIF represents the jet structure very well except for helium jets. It is shown that striped patterns of LIF in the supersonic region of the jet result from the Doppler shift of the rovibronic absorption lines of I_2 due to the flow velocity component in the direction of the laser beam and that the flow velocity can be determined from the observed inclination of the stripes. It is also shown that the intensity of the LIF depends strongly on the rotational temperature of I_2.

1. INTRODUCTION

Small size jets are important in producing hypersonic molecular beams, studies of clustering or condensation processes, and mass separation. In such flow fields, the density becomes so low that the ordinary optical interferometry can not be used, then the electron beam excitation has been used for visualization of the flow. A laser induced fluorescence (LIF) method by seeding the flow with molecules which absorbs laser light and emits bright fluorescence is convienient because of its easier handling of the device and its flexibility in moving the laser beam relative to the objective flow. Iodine molecules are easily excited to fluorescence by the 514.5 nm line of an argon ion (Ar^+) laser and this LIF method has been used for flow visualization of a free jet [*1*, *2*] and for a more complicated jet into vacuum. [*3*].

Different from the electron beam excitation, the visualized image by this method represents the state of the seeded iodine molecules not of the flow medium. Therefore, relations between these must be undersood. In this report some features of the visualized image by the I_2-Ar^+ LIF method are shown and are explained qualitatively in connection with characteristics of the argon ion laser, iodine molecules, and the free jet.

2. PRINCIPLE OF I_2-Ar^+ LIF METHOD

The 514.5 nm line of an argon ion laser, which corresponds to the transition, $4p^4D_{5/2}-4s^2P_{3/2}$, of an argon ion, includes many sharp lines distributed over a frequency width which is characterized by the Doppler broadening of the 514.5 nm line

* Department of Aeronautical Engineering, Kyoto University, Sakyo-ku, Kyoto 606

in the discharge tube. The separation of these sharp lines is determined by the dimension of the laser cavity, and is 0.0045 cm^{-1} for the laser (NEC GLS3200) presently used.

The iodine molecule has many rovibronic absorption lines in the vicinity of the 514.5 nm. At room temperature many transitions $(v'', J'')-(v', J')$ are assigned, [4, 5] while at low temperature such as in an free jet expansion, only two of them, (0, 13)−(43, 12); $P(13)$ and (0,15)−(43, 16); $R(15)$, are assigned [6, 7] due to very narrow Doppler broadening of the absorption lines. Therefore, in such a low temperature flow the strength of the LIF depends strongly on the population density of these rovibronic states.

3. Experimental Method

As shown in Fig. 1, the room temperature gas passed through an I_2-cell was expanded into a vacuum chamber through a converging conical nozzle with a 1 mm exit diameter. The vacuum chamber was pumped by a series of a mechanical booster pump (2500 m^3/hr) and a rotary pump (6500 1/min), and was kept at a pressure P_1 ranged from 13 (0.1) to 100 Pa (.76 Torr) for the stagnation pressure range of 6.65 (50)−106 kPa (800 Torr). Since the vapor pressure of iodine molecules at room temperature is about 30 Pa, concentration of the seeded I_2 in the flow medium was less than 4×10^{-3}.

The jet was irradiated by the focused (~0.3 mmϕ) laser beam at right angles with the jet axis. The laser beam was moved along the jet axis to cover the whole flow field. The fluorescence was observed from the direction at right angles with both of the jet axis and the laser beam. The observation was made by a camera through a filter (O56), which reduce intensity of the scattered light of the laser beam.

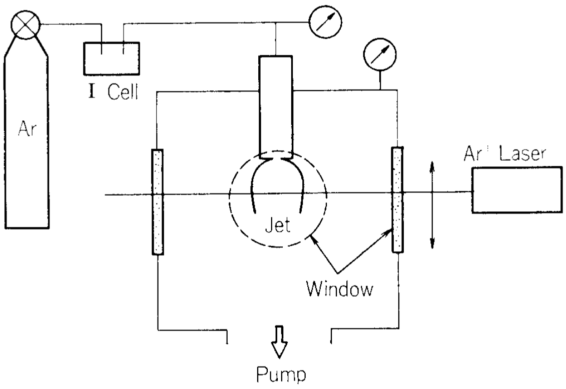

Fig. 1. Apparatus.

4. Results and Discussion

In Fig. 2 photographs of the visualized argon free jets for several stagnation pressures are shown. Some features observed from these photographs will be explained and discussed below.

1) The intensity of the LIF is strong in the regions regarded as the barrel shock,

Mach disk and jet boundary, where density and temperature increase due to decreasing the flow velocity. In Fig. 3, the free jet structure for $P_0=13.3$ kPa is compared with an equi-density pattern by a finite difference calculation of the Euler equation with artificial viscosity for $P_0/P_1=600$. The details of the calculation will be given elswhere. They agree reasonably well. The measured distance X_M of the Mach disk from the nozzle exit is compared with one calculated using the well known formula by Ashkenas and Sherman [8] in Table. Both agree fairly well. Therefore, in spite of the large mass ratio, 254/40, the LIF of the seeded I_2 in argon represents the structure of argon jets very well.

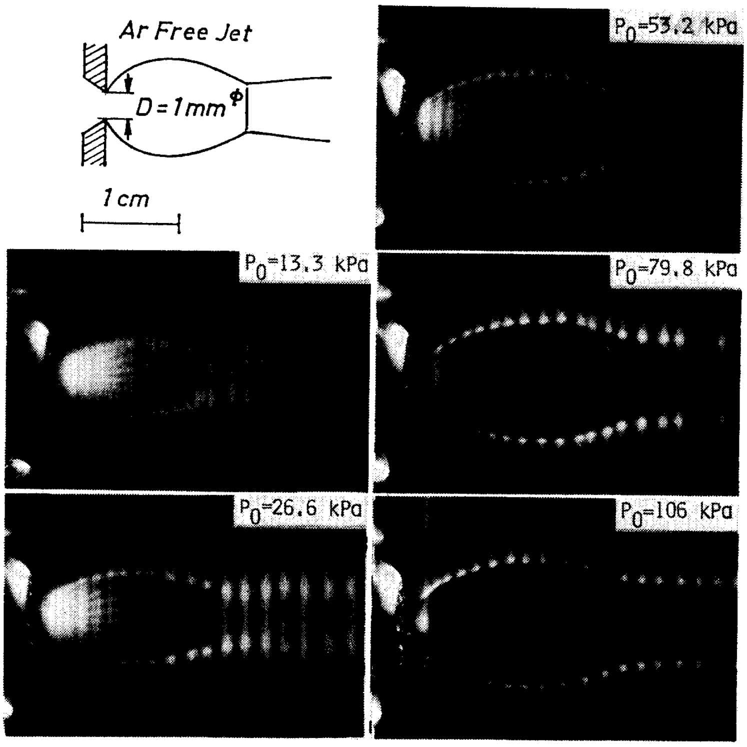

Fig. 2. Visualized free jets of argon.

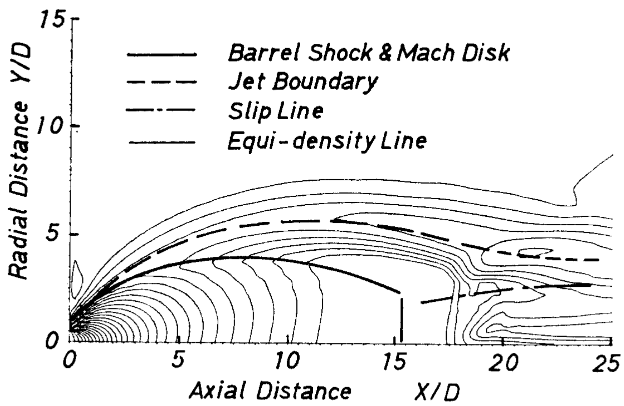

Fig. 3. Comparison of the visualized jet structure with an equi-density pattern calculated by finite a difference method.

Comparison of locations of Mach disk

P_0 (kPa)	P_1 (Pa)	P_0/P_1	X_M/D	
			Measured	$0.67\ (P_0/P_1)^{0.5}$
13.3	22.6	588	15.3	16.3
26.6	31.9	833	18.0	19.3
53.2	57.2	930	20.4	20.4
79.8	77.1	1030	20.9	21.6
106	101	1050	21.3	21.7

2) For lower stagnation pressures, the LIF inside the jet is wider than outer region where the LIF comes from the residual iodine molecules in the vacuum chamber. This is due to the flowing excited states of I_2 during their relatively long life time (~2.2 μsec). Therefore, for a sufficiently narrow laser beam, the velocity of the flow can be determined by characteristic decay curves of the LIF. [2] However, as increasing the stagnation pressure, the width becomes narrower and is almost the same as the outer one for $P_0=106$ kPa. This is due to the collisional de-excitation of the upper state of I_2. This fact makes the quantitative measurement of the properties for high density flow very difficult.

3) In the supersonic flow region surrounded by the barrel shock and the Mach disk, the strength of the LIF is not continuous; the absorption does not take place uniformly along the laser beam. This discontinuous strength of the LIF forms a striped pattern in this region. As described in Sec. 2, the absorption lines of I_2 concerned with the LIF in this region are P(13) and R(15) and they become so narrow due to low translational temperature of I_2 that even with a slight frequency difference (~0.045 cm^{-1}) between these lines and the laser lines iodine molecules do not absorb the laser lines. However, due to Doppler shift resulted from the velocity component of the flowing I_2 to the direction of the laser beam, frequency of one of the laser lines coincides with this shifted absorption lines. Since amount of the Doppler shift is determined by flow velocity and the angle between the flow direction and the laser beam, and since there are many lines separated by 0.0045 cm^{-1} in frequency, then there exists many points along a laser beam where the Doppler shifted absorption lines coincide with the laser lines. These discrete LIF form the stream lines. Since the flow velocity in this region already reaches its maximum value, then the stream lines are straight and form a radialy striped pattern. From the inclination of the stream line to the laser beam we can calculate the flow velocity to be $5.7\pm0.3 \times10^4$ cm/sec, which is nearly equal to the adiabatic flow limit. Hence, the LIF method is a sensitive tool for measurement of flow velocity in a low temperature rarefied flow. In other regions of the jet the LIF becomes continuous because of high temperature and low speed of the flow.

4) With increasing the stagnation pressure the striped pattern becomes weak and almost disappears for $P_0=106$ kPa. Since density decreases along each stream line in proportional to the inverse square of distance from the nozzle, then this rapid decrease in strength of the LIF with increasing P_0 is not due only to increasing effect

of the collisional de-excitation. If P(13) and R(15) are the only absorption lines, the strength of the LIF is proportional to the population density of the rotational $J''=13$ and 15 of $v''=0$. In Fig. 4, the ratio of the population in these states to the population in the vibrationally ground state, in which all the iodine molecules can be assumed to populate for such low temperature condition, is plotted as a function of rotational temperature T_r. The ratio increases with decreasing T_r and has a maximum at 11.5 K and decreases with further decreasing T_r. The rotational temperature of iodine molecule diluted with argon along the jet axis was calculated using isentropic flow properties of a source flow expansion of argon and a relaxation equation for the rotational energy of iodine molecule. The results are shown in Fig. 5. In the figure the parameter Z_r is the collision number, [9] whose value is order 1, P_0D is taken in Torr·cm and T_t is the isentropic translational temperature. In the present experiment the value of P_0D ranges from 10 to 80, then the rotational temperature becomes lower than 10 K in the most part of the flow field and decreases with increasing the stagnation pressure. Therefore, the decreasing in strength of the

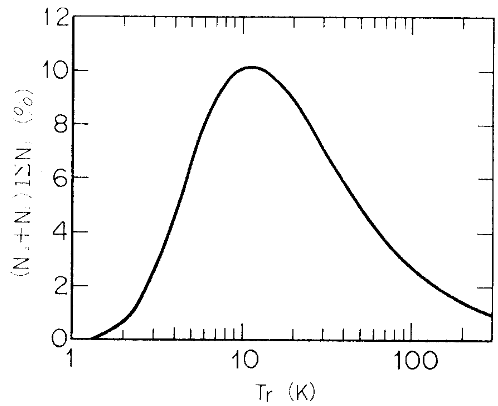

Fig. 4. Population ratio of the rotational states concerned with the LIF to the vibrationally ground state as a functional temperature.

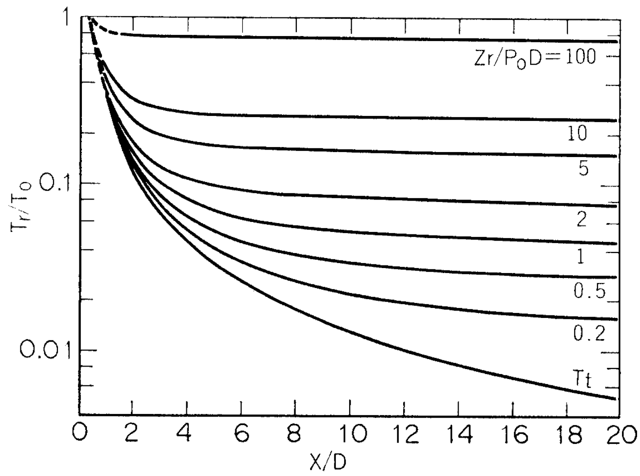

Fig. 5. Relaxation of rotational temperature along jet axis.

LIF is due to decrease in the relative population density of the rotational levels 13 and 15, followed by decreasing of the rotational temperature.

In Figs. 6 to 9, visualized free jets of several gases are shown. These photographs were taken with a continuously moving laser beam along the jet axis.

He (Fig. 6): Due to the large mass ratio (254/4) the LIF does not represent well the jet structure, especially in the vicinity of the nozzle exit, and for lower stagnation pressures. The striped pattern is dense, reflecting the larger flow velocity than for argon jet. The strength of the LIF is not symmetric across the axis; the upper part of the jet is much brighter than the lower. Since the power of the laser line decreases with frequency distance from its center, iodine molecules in the upper part absorb the

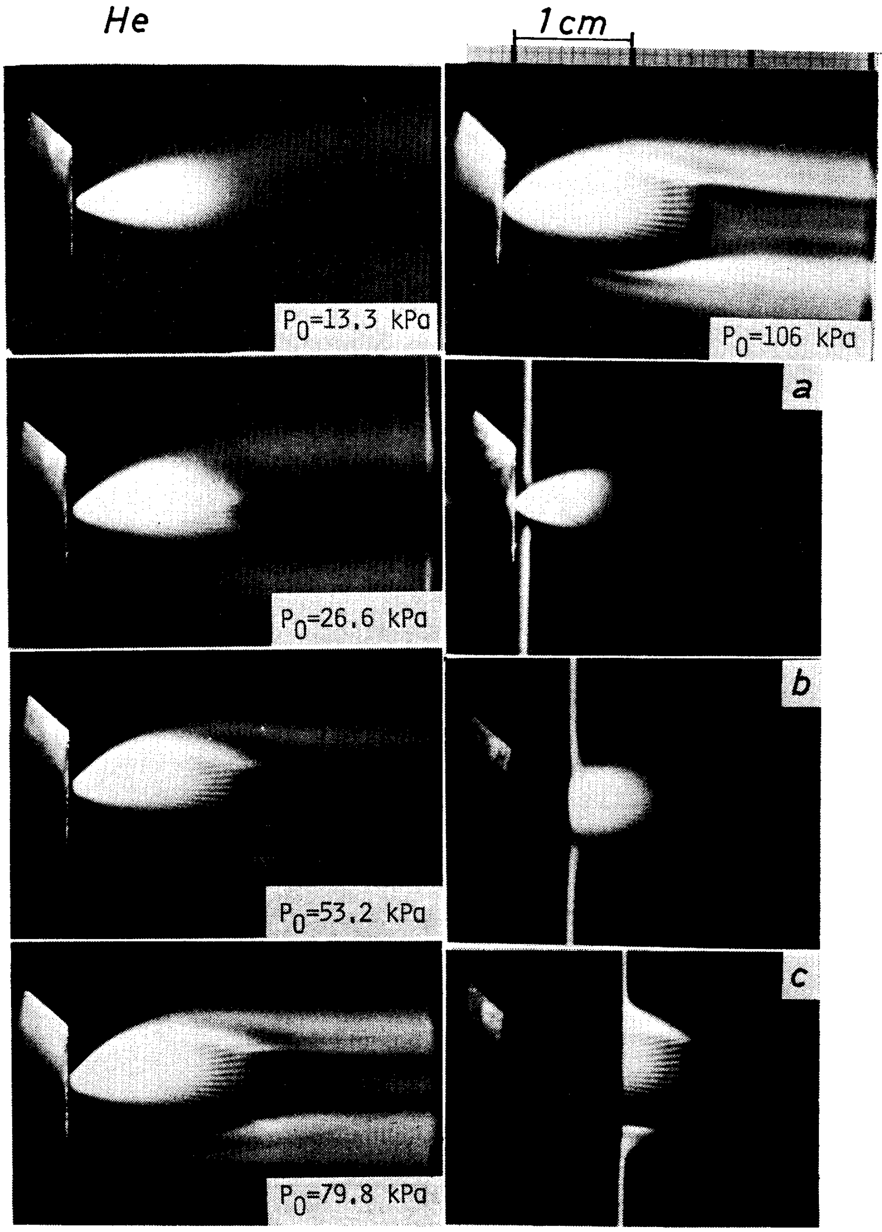

Fig. 6. Visualized free jets of helium.

laser lines close to the center, while they absorb weak laser lines far from the center in the lower part of the jet. Because the laser beam comes from upper to lower, the frequency center of 514.5 nm line coincides with the I_2 absorption lines P(13) and R(15) shifted to a higher frequency by some amount. Widening of the LIF due to high speed flowing is so evident as shown in the figure (right; a, b, c).

N_2 (Fig. 7): The striped pattern can be observed. The location of the Mach disk is not clear compared with argon jet.

CO_2 (Fig. 8): The striped pattern cannot be seen for jets with P_0 larger than 53.2 kPa. It might be possible that condensation effects increases with P_0 and the resulted temperature increase yields the continuous absorption of the laser lines.

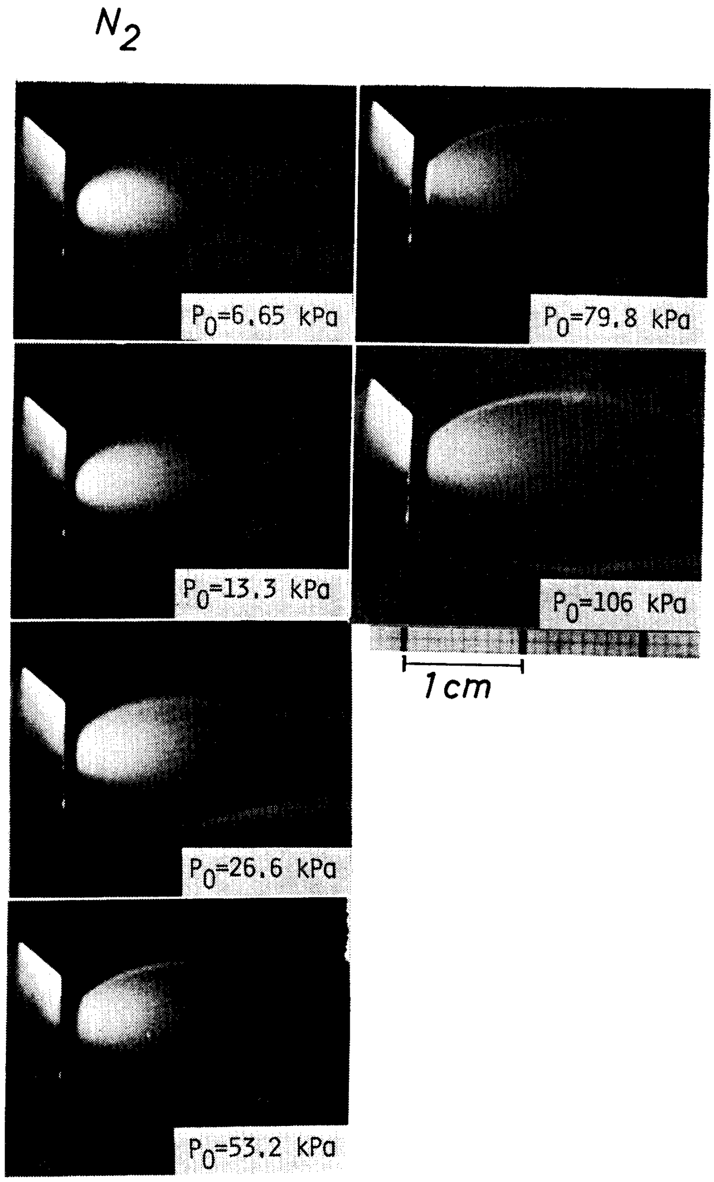

Fig. 7. Visualized free jets of nitrogen.

SF_6 (Fig. 9): No strips can be seen. This might be due to a large amount of the internal energy transfered into translational which precludes lowering the temperature sufficiently enough to cause the discontinuous absorption.

The diameter of the barrel shock increases with decreasing of the value of specific heats-ratio of the gas, as observed in an early study [10] by the schlieren method.

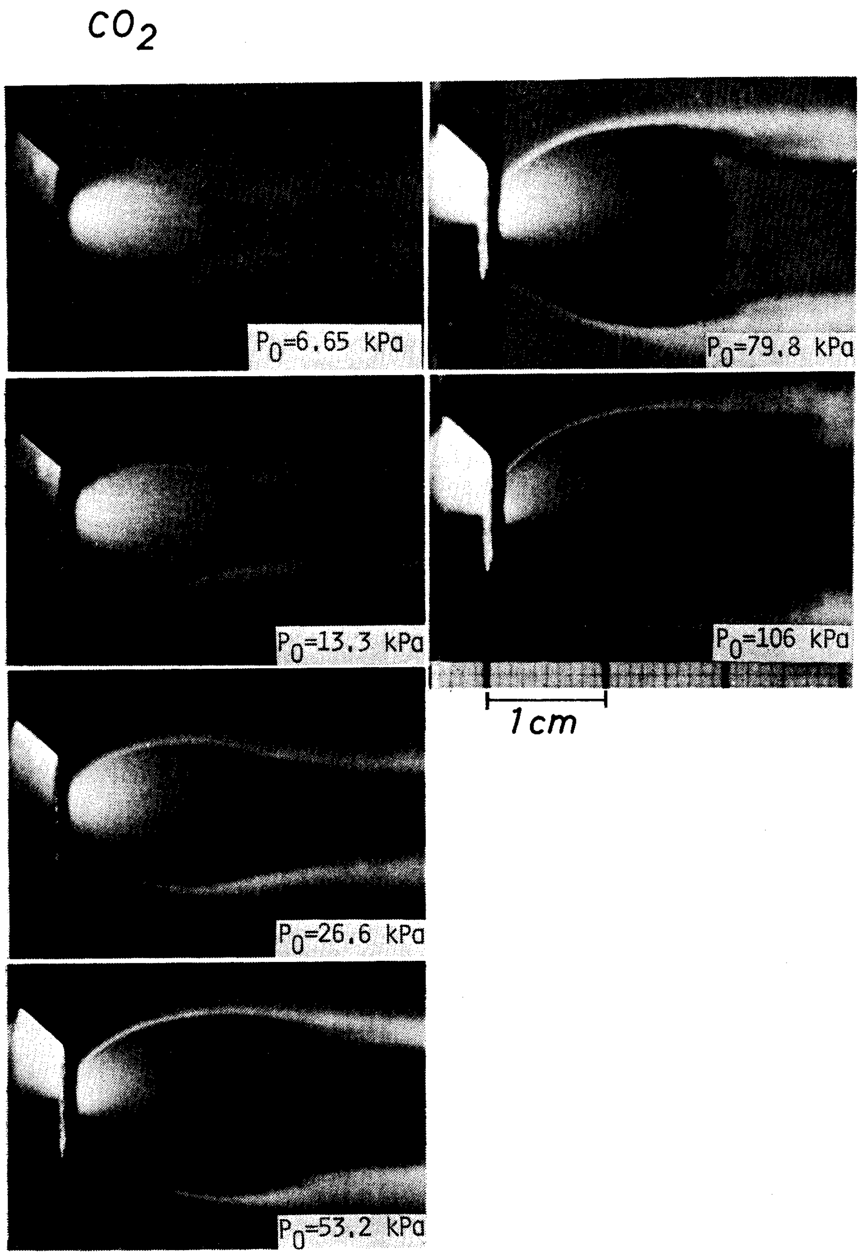

Fig. 8. Visualized free jets of carbon dioxide.

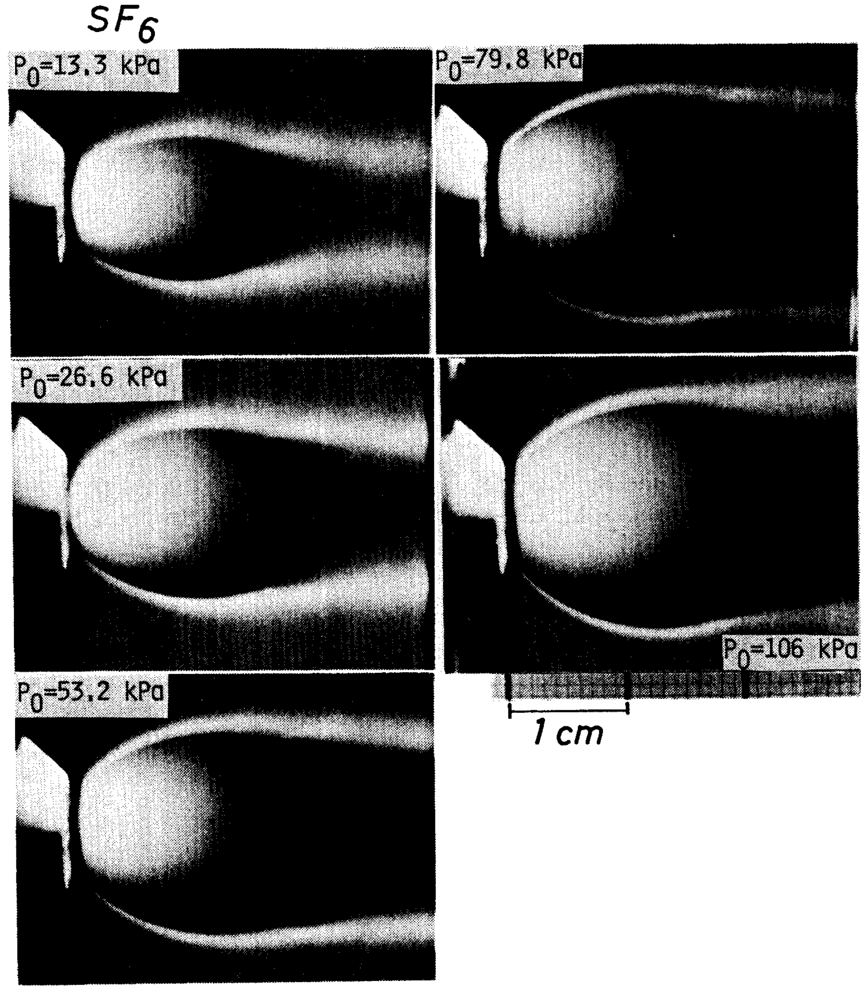

Fig. 9. Visualized free jets of sulfer hexafluoride.

5. Conclusions

A summary of the results is shown below.

1) The visualized free jet by the I_2-A_r^+ LIF method can be explained qualitatively in connection with the properties of the flow medium and of the seeded iodine molecules.

2) In spite of the large mass ratios, the LIF of the heavy I_2 can represent approximately the free jet structure of the flow medium except for helium.

3) The flow velocity in the supersonic region can be obtained very accurately from the measured inclination of the striped pattern of the LIF.

4) A qualitative feature of the rotational temperature of iodine molecule in argon free jets is demonstrated.

5) For more quantitative measurements of temperature and density, further informations about the mass separation, temperature dependence of the absorption coefficient of I_2, probability of collisional de-excitation of the excited I_2 and rotational relaxation rate of I_2 will be needed.

The author would like to express his appreciation to Profs. T. Fujimoto, M. Kawasaki and N. Ibuki for their valuable suggestions and discussions. He is also much indepted to H. Kobayashi for his help in numerical calculation of the free jet structure, and to H. Nakatsuji for his assistance in performing the experiments.

The numerical calculation of the free jet by the finite difference method was performed at the Computer Center of Institute for Molecular Science.

REFERENCES

[*1*] W. J. Hiller and J. Hägele, 2nd Int. Symp. on Flow Visualization, p. 427 (1980).
[*2*] T. Fujimoto, M. Usami and A. Matsubara, to be published in J. Japan Soc. Mech. Engr. (in Japanese).
[*3*] N. L. Rapagnai and S. J. Davis, AIAA J. **17**, 1402 (1979).
[*4*] J. B. Koffend, R. Bacis and R. W. Field, J. Mol. Spectrosc., **77**, 202 (1979).
[*5*] J. Chevaleyre, J. P. Perrot, J. M. Chastan, S. Valignat and M. Broyer, Chem. Phys., **67**, 59 (1982).
[*6*] D. J. Ruben, S. G. Kukolich, L. A. Hackel, D. G. Youmans and S. Ezekiel, Chem. Phys. Let., **22**, 326 (1973).
[*7*] K. Sakurai, private communication.
[*8*] H. Ashkenas and F. S. Sherman, Rarefied Gas Dynamics, ed. J. H. deLeew, Academic Press, 1966, p. 84.
[*9*] R. J. Gallagher and J. B. Fenn, J. Chem. Phys., **60**, 3487 (1974).
[*10*] K. Bier and B. Schmidt, Z. Angew. Phys., *13*, 493 (1961).