Laser-Induced Iodine Fluorescence Applied to Confined Supersonic Mixing

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ABSTRACT

A laser-induced fluorescence (LIF) measurement system is presented and applied to the study of supersonic gas flows at low density. The LIF technique uses atomic or molecular tracers instead of microscopic particles so that particle lag effects, which are remarkable in low density flows, are avoided. The fluorescence signal of laser-excited molecules provides information about the gas velocity, temperature and pressure, since the signal depends on the spectral position of the laser radiation and the thermodynamic state of the molecules. A suitable molecule for LIF measurements is iodine which can be excited by an argon-ion laser. The argon-ion laser is used in single mode operation at 514.5 nm by inserting an etalon into the laser cavity. The etalon allows the laser to be tuned over two iodine absorption lines (Figure 1), in parallel the emitted fluorescence signal is measured and stored on a PC for further analysis. Although the optical set-up is arranged for pointwise measurements, a flowfield measurement is possible by traversing the optics. A simultaneous measurement of velocity, temperature and pressure of a supersonic free jet flowfield was presented at the 9th International Symposium on Applications of Laser Techniques to Fluid Mechanics in Lisbon (Havermann and Beylich, 1998). In this paper, an application of the iodine LIF technique to the study of mixing layer growth in confined supersonic flows is discussed. Compressible mixing layer growth is reduced considerably with increasing Mach number. An empirical relation between the convective Mach number and the growth rate was first derived for plane mixing flows from Pitot pressure data and schlieren visualisation by Papamoschou and Roshko (1988). Here, a planar test section for confined supersonic mixing was built to study ejector applications and the mixing layer growth was measured for three convective Mach numbers using the iodine LIF technique. The results are in good agreement with the empirical relation for the mixing layer growth rate.

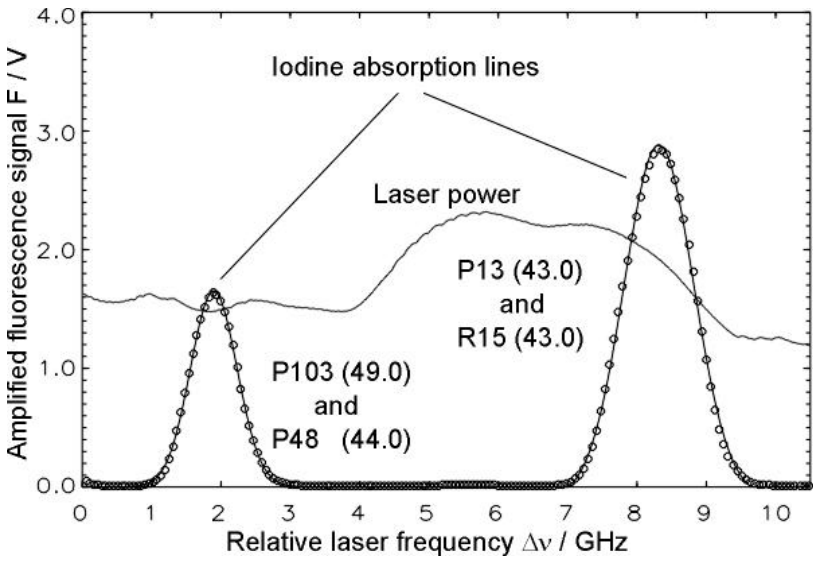

Figure 1. Measured iodine absorption spectrum by tuning a 514.5 nm single mode argon-ion laser. The absorption lines are assigned by their rotational and vibrational quantum numbers. The measured data points are fitted by a Gaussian function. The laser power used for normalisation is also recorded.

1. INTRODUCTION

Laser-based velocimetry systems like LDV or PIV rely on the scattering of light from microscopic particles which have to be added to the flow. In supersonic flows, however, high velocity gradients like shock waves or high speed shear layers are common. In these cases, particles of a finite size cannot follow the flow gradients properly what may lead to wrong measurements of flow velocities. Especially in low density flows the particle drag is reduced considerably due to low Reynolds numbers so that shock wave locations and shear layer structure are difficult to measure.

If the size of the particles is reduced to a molecular scale, however, these measurement problems can be overcome, but spectroscopic techniques have to be used to extract information about the flow from the molecules. The most promising among the spectroscopic techniques is laser-induced fluorescence (LIF), because it allows a simultaneous measurement of the flow velocity and the thermodynamic state. The best quantitative results for the study of supersonic flows were achieved by using iodine molecules as tracers (Donohue and McDaniel, 1996; Havermann and Beylich, 1998).

In this study, the iodine LIF technique is used to study the structure of confined supersonic mixing flows. Such flows play an important role in several technical applications, like supersonic ejectors, SCRAMjet engines, gasdynamic lasers. It was found empirically that with increasing Mach number the growth rate of the mixing layer is reduced considerably (Papamoschou and Roshko, 1988). Small growth rates lead to long mixing chambers with large total pressure losses reducing the efficiency of the technical devices. Since the physics of supersonic mixing enhancement is not yet well clarified, a need for precise experiments exists to enlarge the database. Most experimental data for plane mixing flows were obtained using intrusive measurement techniques (Pitot tube) and qualitative flow visualisation (schlieren method, light scattering), however. Only a limited number of quantitative experiments using non-intrusive measurement techniques like LDV and PIV can be found in the literature, see Goebel and Dutton (1991) and Urban and Mungal (1998), respectively.

In this study, the iodine LIF technique is applied to study the shear layer growth in the mixing chamber of a supersonic ejector test section at three convective Mach numbers.

2. LASER-INDUCED IODINE FLUORESCENCE TECHNIQUE

The laser-induced fluorescence process can best be explained by means of Figure 2, where the potential energy of a molecule is plotted against its internuclear distance. The energetic state of a molecule consists of rotational, vibrational and electronic energy. By means of spectrally defined laser radiation (E=hν), the molecule is excited from the ground state to an upper electronic energy level which is defined by a certain rotational, vibrational and electronic state. After excitation, the molecule emits energy to return to the ground state. During this relaxation process, a part of the excitation energy is released as light emission within a time period ranging from nanoseconds to microseconds. This spontaneous emission of light is termed fluorescence. Another part of the energy is released to inner conversion between the corresponding vibrational and rotational levels. The rest of the excitation energy is conversed into radiationless processes like predissociation and inelastic collisions between the molecules (quenching).

To benefit from the narrow linewidth and high spectral power of the laser, in most LIF measurements the excitation spectroscopy technique is used. In this case, the absorption spectrum of the molecule is scanned by a tuneable laser and the fluorescence light emitted from the molecule is recorded in a broadband manner.

Among the limited number of molecules suited for gasdynamic measurements the iodine molecule has good spectroscopic properties because it has a dense absorption spectrum which partly lies in the visible. Two blended absorption lines can be excited with a single mode argon-ion laser at 514.5 nm (Figure 1). Additionally, iodine can be easily seeded into gas flows by means of crystal sublimation due to its high vapour pressure. The only disadvantage of iodine is corrosiveness which requires special protection of the experimental facilities.

The measured fluorescence signal F remains linear to the intensity of the exciting laser power as long as the saturation intensity is not exceeded. The signal can be described by (Andresen and Strube, 1994; Demtröder, 1996):

$$F = h\ N\ \ f\ B_{12}\ \ I\ \ L_n\ \frac{A_{21}}{A_{21} + Q}\ , \qquad (1)$$

where h is a constant defining the efficiency of the receiving optics and sensors, N the number density of tracer molecules, f gives the fractional population of tracer molecules in the ground state, B_{12} is the Einstein factor for induced absorption, I the laser intensity, L_v the spectral line shape function. The last factor containing the Einstein factor for spontaneous emission A_{21} and the quenching rate Q defines the fluorescence efficiency and is called Stern-Volmer-factor. The Einstein factor for induced absorption B_{12} is a measure of the vibrational and rotational line strengths (Franck-Condon and Hönl-London factors, respectively).

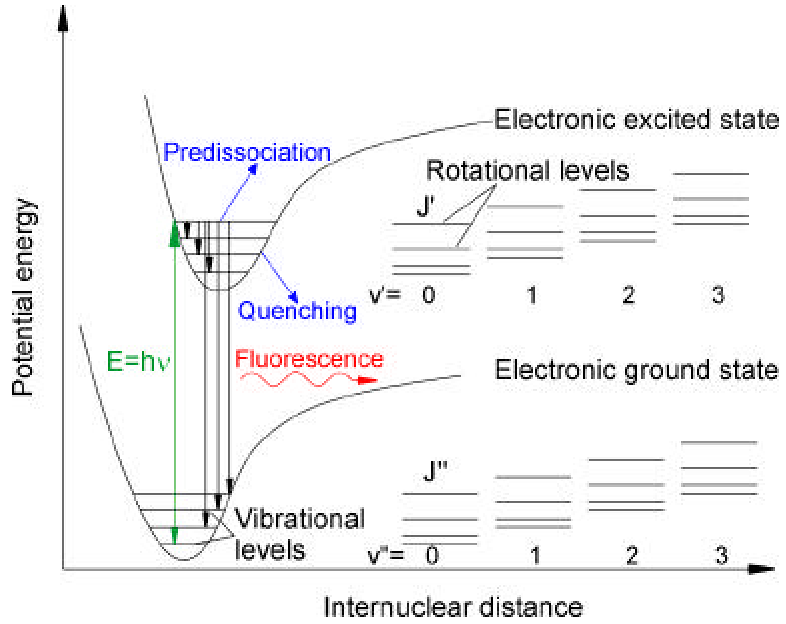

Figure 2. Excitation and relaxation processes in molecules.

The fluorescence signal described by Eq. 1 can be used for the measurement of velocity, temperature and pressure of the excited molecules. It can be assumed that the thermodynamic properties of the molecules correspond to the flow properties if the flow is in thermodynamic equilibrium, which is valid for the flows studied here.

The velocity can be measured by comparing the fluorescence signal from molecules moving with the flow to the fluorescence signal from molecules enclosed in a reference iodine cell. During laser excitation, a molecule propagating with the flow velocity v acts as a moving receiver so that the excitation laser frequency appears to be shifted for the molecule due to the Doppler effect (Figure 3).

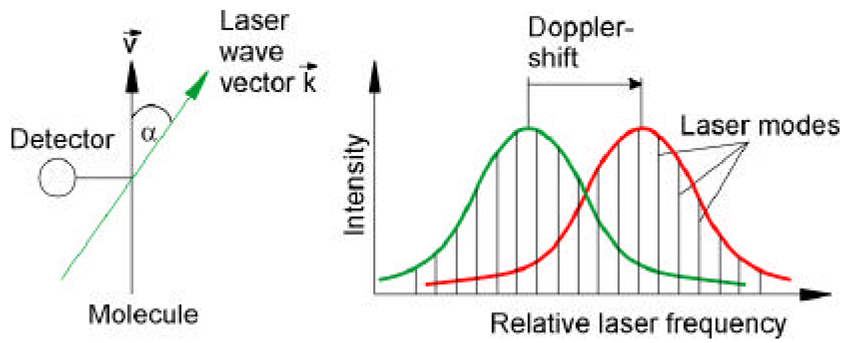

Figure 3. LIF velocity measurement using the Doppler-shifted absorption line.

The temperature can be measured by using the fluorescence signal of two absorption lines. It can be shown that the ratio of the fluorescence signals from two different absorption lines depends mainly on the fractional population and the line strengths. It is assumed that the fractional population corresponds to a Boltzmann distribution, which is a function of the temperature and the known quantum numbers of the excited transitions (two-line thermometry, see Andresen and Strube, 1994). The calculated intensity ratio for the two iodine absorption lines P13/R15 and P103/P48 (Figure 1) depends on the temperature as shown in Figure 4 (Havermann and Beylich, 1998). The intensity ratio increases at low temperatures because the fractional population of the P13/R15 absorption line doublet becomes higher than of the P103/P48 line doublet at low temperatures. This behaviour can be explained by the Boltzmann distribution function which depends on the quantum numbers and the temperature. The curve in Figure 4 shows that the sensitivity of the method is increased at temperatures below 200 K .

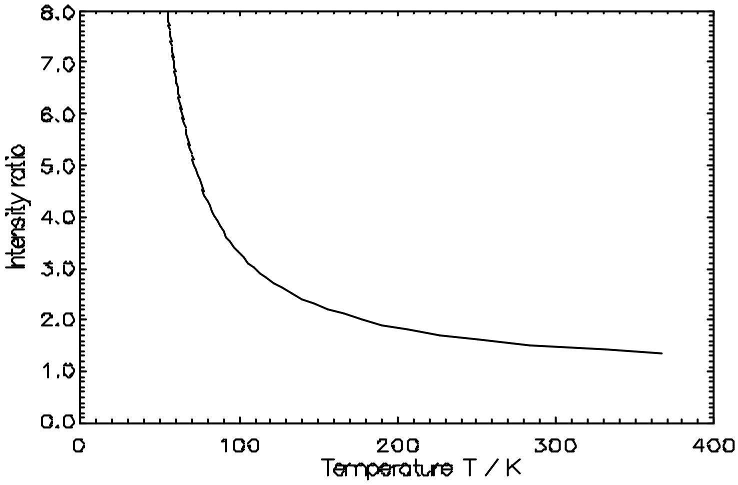

Figure 4. Calculated intensity ratio of the iodine absorption lines (P13/R15 to P103/P48) as a function of temperature.

For the pressure measurement the broadening of absorption lines is taken into account (Figure 5). The broadening of a spectral line depends on its natural lifetime, on the Doppler broadening caused by thermal motion of the molecules and on the collisional broadening due to elastic collisions between the molecules which is proportional to the number density of molecules. Using the thermodynamic equation of state the pressure can be calculated if the temperature is known. It was shown that the absorption line half width increases linearly in a pressure range between 0 and 15 kPa at a constant temperature (Havermann and Beylich, 1998). This linear pressure dependence and the other broadening effects mentioned can be included in a formula yielding the pressure from the measured absorption line half width:

$$\Delta n_W = A \frac{p}{T^{0.7}} + B\sqrt{T} + C \qquad (2)$$

The constants A,B and C were derived empirically by means of measurements conducted with a variable pressure cell. They are given in Table 1.

Table 1. Constants used in Eq. 2.

A	B	C
2.49 $K^{0.7}$ GHz/kPa	0.021 GHz/$K^{0.5}$	0.8 GHz

Elastic collisions between the molecules not only cause line broadening, but also a frequency shift of absorption lines. This is called collisional impact shift and must be subtracted from the measured frequency shift to obtain the pure Doppler shift for the velocity calculation. An empirically obtained relation (Donohue and McDaniel, 1996) was used:

$$\Delta n_I = D\frac{p}{T^{0.7}} \tag{3}$$

with D= −0.39 $K^{0.7}$ GHz/kPa.

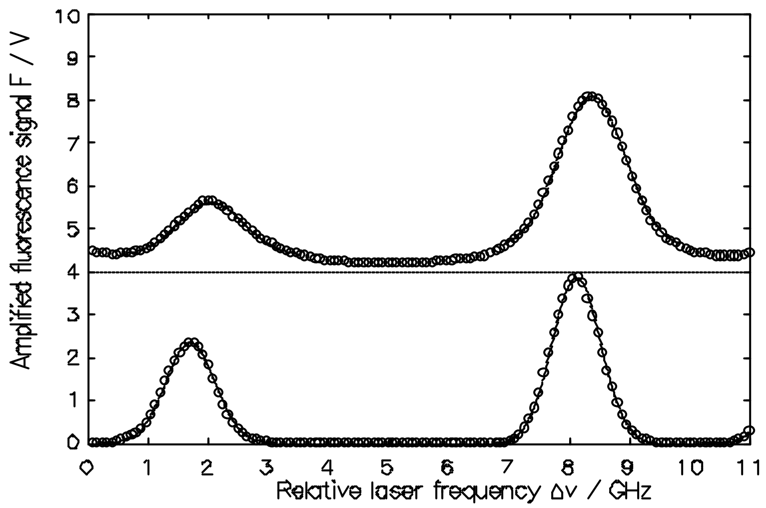

Figure 5. Iodine LIF spectrum measured at two different pressures: 7 kPa (upper) and 0.04 kPa (lower).

The experimental set-up of the iodine LIF system is shown in Figure 6. Iodine molecules are seeded into the air flow by means of convection. The excitation source consists of a 15 W argon-ion laser which is operated single mode by using an intracavity etalon. The etalon acts as a frequency filter and transmits only one of the many longitudinal modes oscillating in the laser cavity. The laser linewidth is thereby reduced from 10 GHz to less than 20 MHz and the etalon allows the specific selection of one single mode within the laser gain profile. The etalon is tuned by tilting which changes slightly its free spectral range. A spectrum analyser in combination with a Fabry-Perot interferometer (FPI) visualises the tuning of the laser modes on an oscilloscope.

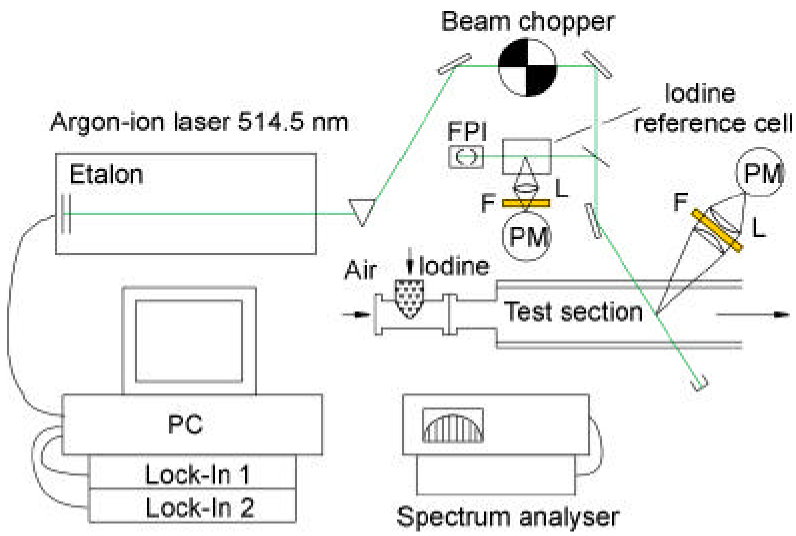

Figure 6. Set-up of the iodine LIF measurement system.
(F: Filter, L: Lens, FPI: Fabry-Perot interferometer, PM: Photomultiplier)

The laser beam is chopped for lock-in amplification and directed under a defined and known angle into the flowfield. A small part of the laser beam is split off and directed to the iodine reference cell. The measuring volume in the reference cell and in the flow (V~0.3 mm³) are imaged by a lens system on the pinhole of the corresponding photomultipliers. A long pass glass filter (cut-off wavelength 530 nm) is used to block the scattered green laser light so that only the yellow fluorescence light from the excited iodine molecules is transmitted. During the etalon tuning the fluorescence signals in the flow and in the reference iodine cell are measured simultaneously by two separated photomultipliers. The detector signals are then amplified using two lock-in amplifiers which ensure a low-noise signal gain. The analog amplifier output is further digitised by an AD-card (12 bit, 60 kHz), the data processing and storage are done with a Pentium 100-MHz PC.
Experiments conducted with supersonic free jets showed that the velocity can be measured from low subsonic values of less than 100 m/s up to high supersonic velocities of 700 m/s and more with an uncertainty of ±30 m/s. The temperature measurement is possible for temperatures lower than 300 K with an uncertainty of ±10 K, whereas pressure measurements are possible in the range from 0.5 to 15 kPa (±0.5 kPa) (Havermann and Beylich, 1998).

3. EXPERIMENTAL FACILITIES

A low density wind tunnel running with ambient air was used for the experiments. Test sections can be connected to several vacuum pumping systems grouped around a large vacuum tank (28 m³ volume). For the present experiments, a water ring vacuum pump which could run continuously at vacuum pressures down to 5 kPa was used. This kind of vacuum pump has further proven to withstand iodine corrosion sufficiently well.
A test section for supersonic ejector studies was constructed and specially designed for optical measurements, see Figure 7. The rectangular cross section allowed the mounting of plane glass windows necessary for optical visualisation and measurement techniques. For global and fast flow visualisation a high sensitive schlieren optics was built up. Additionally, the measurement of wall and Pitot pressures was provided (Havermann and Beylich, 1997).
The primary mass flow $\dot{m}_1$ is accelerated by a half-symmetric Laval nozzle to a supersonic velocity. Different nozzle blocks can be mounted to obtain exit Mach numbers between 1.8 and 2.7. The secondary mass flow $\dot{m}_2$ can be varied between 0.3 and 5.5 g/s and enters the test section from the top. After that it is slightly accelerated to a low subsonic speed before flowing into the mixing chamber where both flows are mixed. The mixing chamber has a constant area, for the present experiments the height and length were set to 17 mm and 250 mm, respectively. A stepping motor driven traversing mechanism is used to choose the location of measurement; the optics are moved in the horizontal direction, whereas the test section is moved in the vertical direction. The mechanism is controlled by a PC so that measurements of extended flowfields with high spatial accuracy (±0.08 mm) are possible.

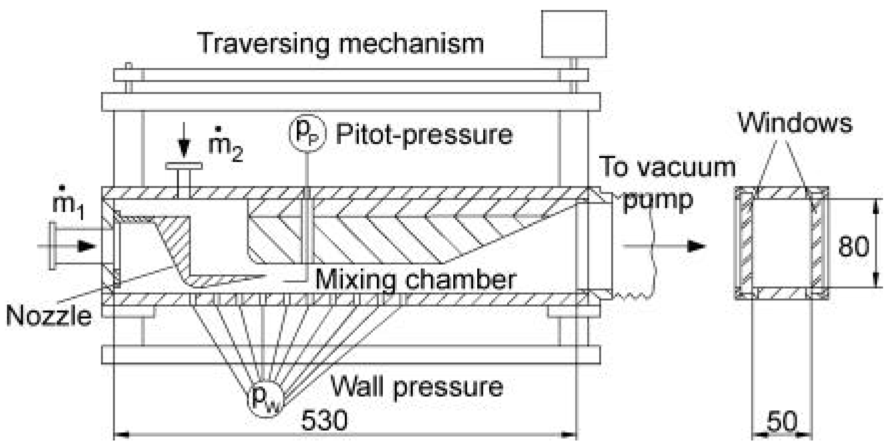

Figure 7. Supersonic ejector test section. All dimensions are expressed in mm.

4. EXPERIMENTAL RESULTS

Three different secondary mass flows were chosen to study the mixing layer growth at three different secondary Mach numbers. The experimental input conditions are reported in Table 2. The mixing layer growth corresponds to the shear layer growth if macroscopic mixing is considered, i.e. mixing without chemical reactions.

Table 2. Experimental conditions. ($\dot{m}$: mass flow, p_0 : stagnation pressure, M: Mach number, u: velocity)

		$\dot{m}_1$	$\dot{m}_2$		
		Nozzle	No. 1	No. 2	No. 3
$\dot{m}$	g/s	27.0	0.7	2.3	5.5
p_0	kPa	100	3.7	4.9	6.9
M	-	2.7	0.1	0.2	0.4
u	m/s	593	30	76	135

The LIF system was used to measure the complete one dimensional velocity distribution in the mixing chamber starting at 7 mm from the nozzle exit in steps of 10 mm in the streamwise direction and from 1 to 16 mm in 1 mm steps in the transverse direction. In total, 400 points were measured for each secondary mass flow configuration, which took about one hour and a half per run.
To obtain the correct velocity from the Doppler shift of the absorption line, the pressure shift had to be accounted for (Eq. 3). Therefore, also the temperature and pressure were measured and calculated from the fluorescence data according to the corresponding models.
Additionally, spark illuminated schlieren pictures were taken. They show the formation of the turbulent mixing layer and can be compared with the measured velocity distribution. The measured velocity distribution and the schlieren pictures for the three secondary mass flows are shown in Figure 8. The spatial development of the mixing layers can be clearly seen in the velocity distributions. The data for mass flow no. 1 show high velocities at the top of the mixing chamber, however. They can probably be explained by a leakage in the test section, since there is no physical explanation for this phenomenon.
The mixing layer growth rate was obtained from the streamwise evolution of the shear layer thickness. The shear layer thickness *b* was calculated for each streamwise location according to the definitions given in Eq. 4 and Figure 9:

$$u_1 - 0.1\Delta u \leq u \leq u_2 + 0.1\Delta u \quad (4)$$

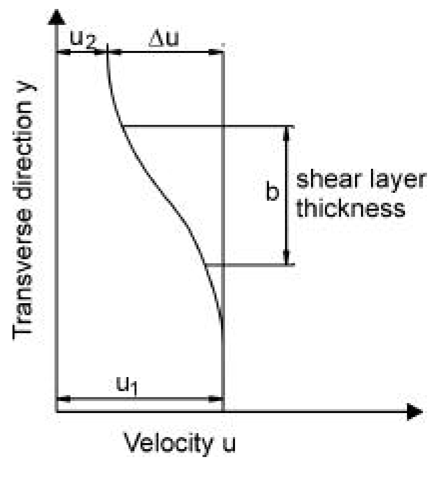

Figure 9. Definition of shear layer thickness.

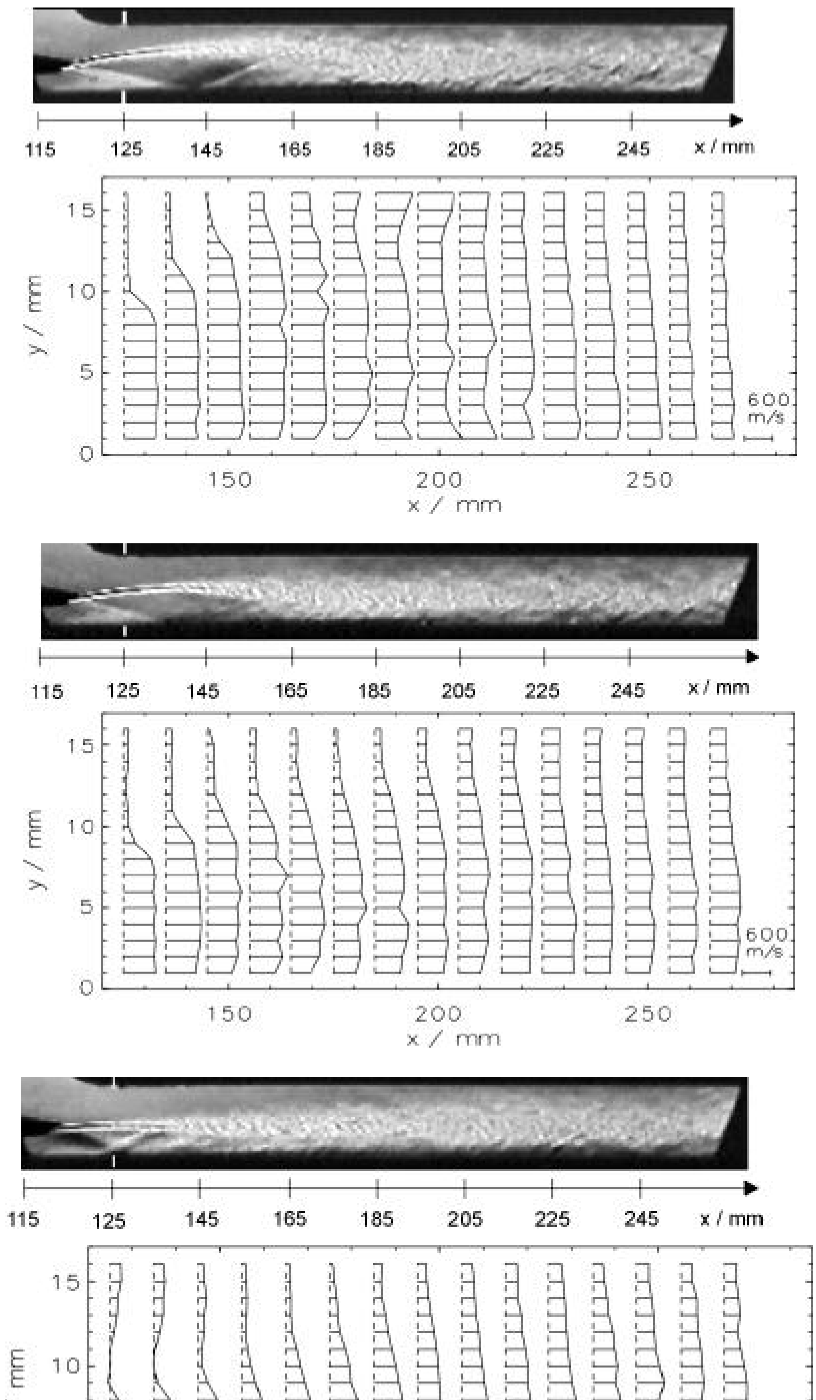

Figure 8. Schlieren pictures of the mixing chamber and corresponding one dimensional velocity distributions measured by the LIF system for secondary mass flows no. 1; 2 and 3 (from top to bottom).

The calculated shear layer thickness for each streamwise location is plotted in Figure 10 for the corresponding secondary mass flows. The datapoints were least-square fitted by a straight line, the worst datapoints were omitted, which was useful especially for secondary mass flow no. 1.

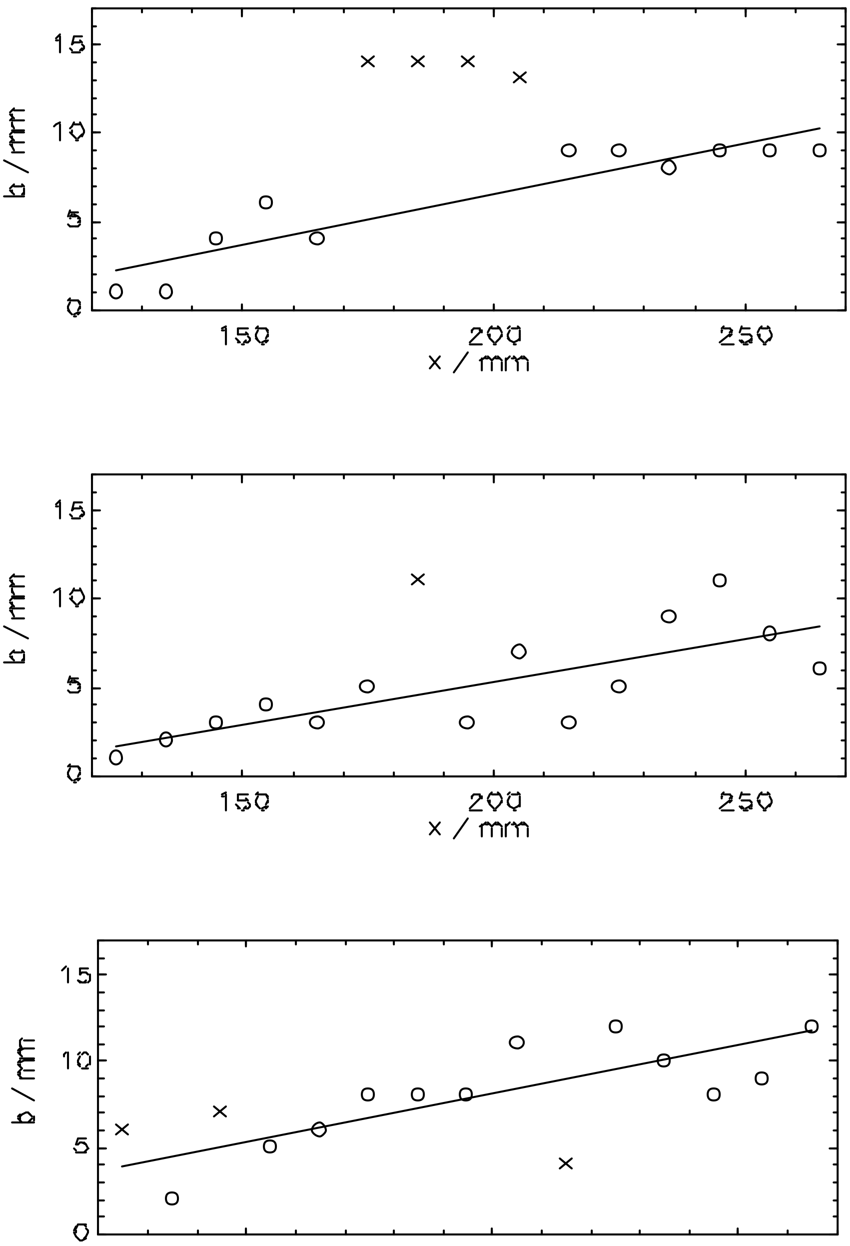

Figure 10. Streamwise evolution of the shear layer thickness in the mixing chamber. The datapoints were fitted by a straight line and the worst datapoints (crosses) were omitted for the fit. (Secondary mass flows no. 1; 2 and 3 from top to bottom).

The shear layer growth rates for the three measured Mach number combinations were compared to a relation which was derived empirically from measurements in plane shear layers (Papamoschou and Roshko, 1988). This relation is based on the ratio of the compressible mixing layer growth rate normalised to an imaginary incompressible mixing layer growth rate that has the same velocity and density ratios of the two mixing streams. An appropriate similarity parameter for a compressible shear layer is the convective Mach number calculated for each stream. The convective Mach number describes the velocity of the coherent structures in the mixing layer. Since there are still some doubts about the existence of coherent structures in supersonic mixing layers, it has become customary to use an average convective Mach number M_c, which is defined as the difference between the two flow velocities u_1 and u_2 divided by the sum of their speeds of sound, a_1 and a_2:

$$M_c = \frac{u_1 - u_2}{a_1 + a_2} \tag{5}$$

The convective Mach numbers in this study were 1.0; 0.92 and 0.82 for the secondary mass flows no. 1; 2 and 3, respectively.
An appropriate equation describing the relationship between the average convective Mach number, the compressible shear layer growth rate $(db/dx)_{com}$ and the corresponding growth rate of the assumed incompressible mixing layer $(db/dx)_{inc}$ was given by Dimotakis (1991) as a fit to several experimental data from plane shear layers:

$$\frac{(db/dx)_{com}}{(db/dx)_{inc}} = 0.2 + 0.8\exp(-3M_c^{\ 2}) \tag{6}$$

The incompressible shear layer growth rate can be calculated according to Brown and Roshko (1974) using the velocity ratio r and the density ratio s of the two flows:

$$\left(\frac{db}{dx}\right)_{inc} = c\frac{(1-r)(1+\sqrt{s})}{1+r\sqrt{s}} \tag{7}$$

The plot of Eq. 6 shows that for convective Mach numbers above one the growth rate of a compressible mixing layer is reduced to only 20 % of the corresponding incompressible layer (Figure 11).

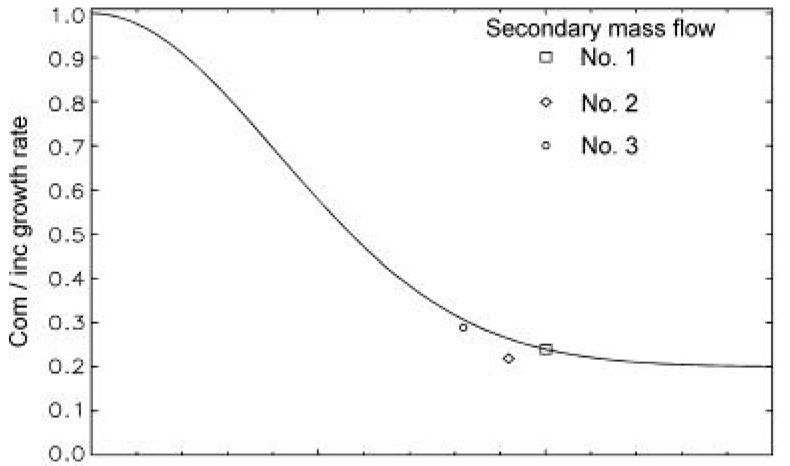

Figure 11. Comparison of the empirical curve for the plane free shear layer with the three measured growth rate ratios at convective Mach numbers of 0.82; 0.92 and 1.0.

The experimental results from this study were compared to Eq. 6 and they are included in Figure 11. A good agreement with the empirical relation (Eq. 6) can be seen.

5. CONCLUDING REMARKS

An iodine LIF measurement system and the corresponding theoretical background were presented. The system was built up and used to study supersonic gas flows at low density. It is difficult to obtain reliable measurements in such flows using particle-based laser velocimeters because of reduced particle drag. Additionally, the iodine LIF technique allows not only a measurement of the flow velocity, but also of the thermodynamic variables of state due to molecular physics. It was shown before that velocities can be measured with an uncertainty of ±30 m/s. The range of temperature measurements goes from 50 K to 300 K with an uncertainty of ±10 K and the pressure can be measured between 0.5 and 15 kPa with an uncertainty of ±0.5 kPa.
In this paper, the iodine LIF system was used to study the mixing layer growth in a supersonic ejector test section. Two mass flows were mixed in a mixing chamber of a constant area. The primary mass flow was supersonic and entrained a subsonic secondary mass flow. The one dimensional velocity distribution was measured in the mixing chamber using the iodine LIF system for three velocity ratios. Additionally, schlieren pictures were taken for qualitative comparison.
A suitable similarity parameter for compressible shear layer growth is the convective Mach number, which was varied between 0.82 and 1.0. The shear layer growth rate was calculated from the velocity distribution in the mixing chamber and further compared with an empirical relation. A good agreement between this relation and the measured growth rate was observed. This shows that the iodine LIF system works accurately in complex flowfields so that it is well suited to study mixing enhancement techniques.

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