Coupled Optical Velocity and Pressure Measurements in a Supersonic Flow

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Abstract *: Local non intrusive pressure and velocity measurements have been achieved on the axis of a free jet issuing from an underexpanded round nozzle. Velocity was measured with both Laser Doppler Velocimetry (LDV) and the Two Focus Velocimetry Laser (L2F). Static pressure measurements using Laser Induced iodine Fluorescence (LIF) have been coupled to.*

These measurements show the velocity and pressure oscillations due to expansion and recompression phenomena predicted in unviscid flow calculation.

1. Introduction

Two dimensional and furthermore three dimensional calculation codes provide informations which cannot be verified using classical measurement methods. In order to understand the main physical phenomena, to qualify the flows, to validate the calculation models for complex flowfield and to reduce the gap between theoretical results and experimental data, a non intrusive and fine analysis method is required. The different needs have shown the necessity:

- to more precisely the recirculation and separation zones and study the flow mixing;
- to provide measurements, especially in the field of turbomachines, in areas with moving elements as inter-blade channels.

Laser velocimetry is a non-intrusive technics for two dimentional and three dimentional velocity measurements, which required seedingof solid or liquid particles.

Laser induced fluorescence which is an optical non-intrusive method, allows for measurements of many flow parameters based on the competition of quenching and radiative decay of a molecular tracer seeded in the flow. Theroretical modelisation shows that the fluorescence signal can provide quantitative informations about static pressure in a flowfield.

The problem of static pressure and velocity measurements are especially delicate in a supersonic flow using classical probes such Pitot tube, five holes probe or hot wire, because a schock wave appears ahead of the probe.

The possibility of coupling both technics, laser velocimetry and laser induced fluorescence has been demonstrated on a free jet issuing from an underexpanded round nozzle.

2. Principles of laser induced fluorescence

Fluorescence is a spontaneous light emission caused by a radiative transition between two electronic levels of a molecule. Molecule excitation is caused by monochromatic photons from a laser source, resonant with an electronic transition. Iodine molecules have interesting fluorescence characteristics so that iodine can be used to seed the flow.

One of the molecule absorption lines correspond to the wave length of λ=514,5 nm of the argon ionised laser emission [1].

Fluorescence is one of the desactivation processes of iodine molecules from the B state to the fundamental X state, competing with the main other desactivation process which is quenching [2] *(figure 1).*

Kinetic modelisation shows that the expression of the fluorescence signal depends on pressure and temperature [3 and 4], and some molecular and optical constants :

$$S_f = C_{opt} V_c B_{12} \frac{A_{21}}{A_{21}+Q} P_{eff} f_1 X_{I_2} \frac{P}{kT} \quad (1)$$

where : Copt is the optical constant of the detection device,
Vc is the probe volume,
B_{12} and A_{21} are respectively the absorption and emission Einstein coefficients,
Q is the quenching rate proportional to $P/T^{1/2}$, with P the pressure, and T the temperature [5, 6],
f_1 is the fraction of the molecules in the absorbing state [7],
X_{I2} the seeding fraction,
k is the Boltzmann constant,
P_{eff} is the efficient power spectral density of the incident laser radiation, taking into account the overlapping of laser emission and the iodine absorption lineshape [4].

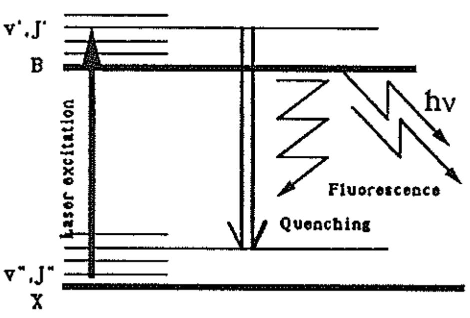

Figure 1: principle of the I_2B-X transition and excited state desactivation.

A multimode broadband argon laser was used, leading to a complex pressure and temperature dependant P_{eff} term.

The analysis of equation (1) shows that the fluorescence signal decreases when pressure increases.

3. Coupled laser velocimetry and laser induced fluorescence measurements :

Two complementary technics are used at ONERA : the laser Doppler [8] and the two focus laser velocimetry [9].

In both cases, measurements have share the same measuring volume and have been carried out simultaneously. The wave length λ = 514,5 nm, for both L2F *(figure 2)* and LDV *(figure 3)* measurements technics, has been used to induce fluorescence of iodine molecules (LIF). An achromatic lens is used to focus the broadband emission (520 nm < λ < 1000 nm) collected in the probe volume on the entrance of an optical fiber which ensures the transmission of the optical signal to a cooled As-Ga photomultiplier. The PM is then connected to a computer equiped with a photon counter. Scattered and reflected laser radiations at λ=514,5 nm or blue radiation at λ=488 nm when Laser Doppler Velocimeter is used, are blocked through a long pass filter.

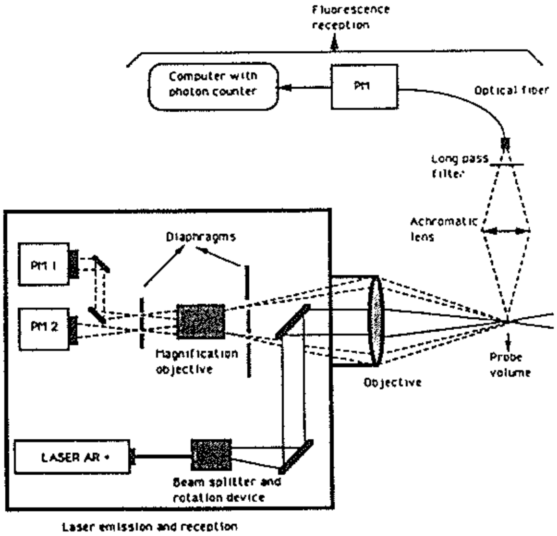

Figure 2 : principle scheme of coupled two focus laser velocimetry and laser induced fluorescence measurements.

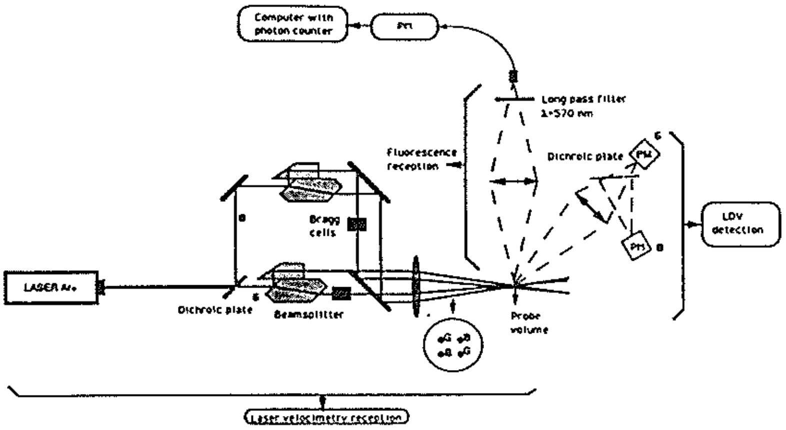

Figure 3 : principle scheme of coupled Laser Doppler Velocimetry and laser induced fluorescence measurements.

4. Experimental set up and and operating process :

Some pressure and velocity coupled measurements using respectively laser induced fluorescence and laser velocimetry have been realised on a free supersonic jet issuing from an underexpanded round nozzle. The characteristics of the nozzle were as follows :

- throat diameter : 4 mm
- exit diameter : 5 mm
- exit Mach number : 1,5
- stagnation pressure : 5,5. 10^5 Pa
- stagnation temperature : 293 K

This flowfield configuration has been chosen because inviscid flow calculations are available and because of the strong pressure and velocity variations in the jet. Pressure is varying between 2.10^4 Pa and $1,7.10^5$ Pa and velocity between 410 and 600 m/s.

In order to realize these measurements, the flowfield was seeded, once with carbon particules of an average diameter of 90 nm for the velocity measurements and with a weak constant fraction of iodine molecules for pressure measurements (about 300 ppm). Iodine was seeded by passing the gas throught a reservoir containing iodine crystals maintained at constant temperature.

The velocimeter can be moved in the three directions and placed where Euler calculations are available. Collection optics of the fluorescence signal is linked with the velocimeter so that measurements of pressure and velocity are possible. The experimental set up, in the case of laser Doppler velocimeter is described on *figure 4.*

The spatial resolution, when using the laser Doppler velocimeter is 206 µm along the flow axis and 1 mm along the perpendicular axis and when using the two focus velocimeter, 218 µm along the flow axis and 1 mm along the perpendicular axis.

For the hight scattered by the particles to be maximum, the back scattering optical configuration has been chosen in LDV experimentation.

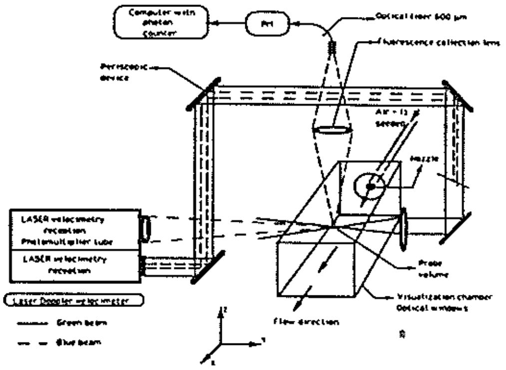

Figure 4 : experimental setup for coupled LDV and laser induced fluorescence measurements.

Because of the high level of velocity (400 to 600 m/s) a broadband (150 MHz) signal analyzer using Fast Fourier Transformation (DSA Aerometrics) has been used.

5. Laser induced fluorescence data reduction and results

Equation (1), describing the evolution of the fluorescence signal versus thermodynamical flow parameters shows a double dependance on pressure and temperature.

The influence of temperature can be removed in the case of an isentropic flow when broadband emission line at λ=514,5 nm is used. In fact, the excitation of many absorption lines which are resonnant with the laser bandwith, produce a fluorescence independant of the temperature fluctuation. Pressure can be obtain by resolving the equation of the fluorescence signal (1) with a mean temperature of 200 K.

An exploration on a distance of five throat diameters has been realised on the jet axis. The static pressure obtained using laser induced fluorescence has been compared to values from Euler calculations, because a classical intrusive technics such a Pitot tube was not available owing to the flow dimensions *(figure 5)*.

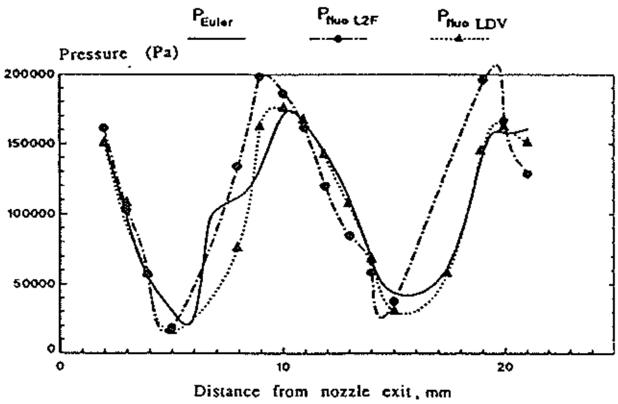

Figure 5 : comparison betwen static pressure from Euler calculation (P_{Euler}) and pressure calculated from fluorescence measurements ($P_{fluo\ LDV}$ and $P_{fluo\ L2F}$)

Pressure determination from the fluorescence signal is good in the moderate pressure gradient areas. On the other hand, in the high recompression areas, pressure determination leads to wrong results due to a lack of spatial resolution and strong temperature variations, especially around a schock wave which occurs at x=6,5 mm. In such an area, where the pressure gradient can reach $1{,}3.10^5$ Pa/mm, the spatial resolution of the collection device appears too weak compared to the main characteristics of the pressure evolution.

6. Laser velocimetry data reduction

Experimental results *(figure 6)* obtained from the LDV and L2F are almost the identical in the areas with positive velocity gradient and a schift of about 4% can be observed when flow deceleration occurs.

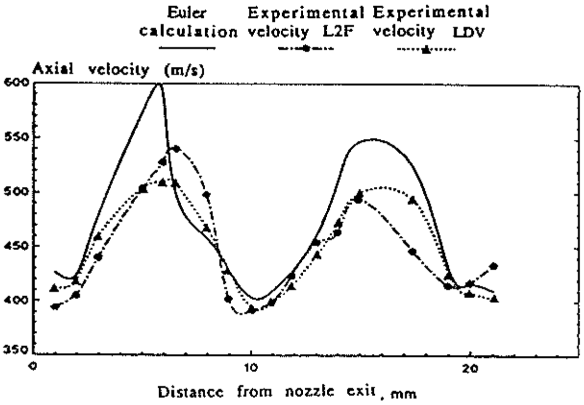

Figure 6 : comparison between theoretical Euler velocity and velocity measurements from two focus laser (experimental velocity L2F) and laser Doppler (experimental velocity LDV) velocimeter.

Both the lack of spatal resolution and some velocity lags of the particles, which probably exists in spite of the very small granulometry, can explain the differencies between theoretical and experimental results.

7. Future developments of laser induced fluorescence experiments

The interpretation of the temperature dependence of the fluorescence signal can be improved, using a narrow bandwith dye laser tuned on the center of an absorption line, which Boltzmann population fraction is temperature insensitive.

A plot of Boltzmann fractions for a few energetic rotationnal levels J" of the absorbing state as a function of temperature is given in *figure 8*. For example, the level J" =76 is almost independant of the temperature in the range of 175K to 275K.

For an optimised choice of the absorption line, the fluorescence signal is inversely proportional to pressure and fairly independant of temperature.

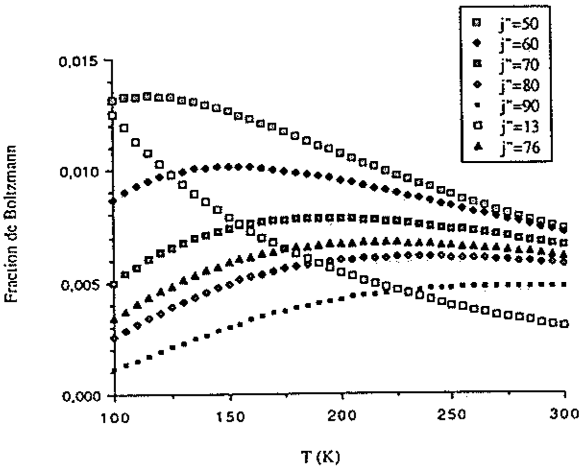

Figure 8: Evolution of Boltzmann fraction of the iodine absorbing state for different energtic levels J" versus temperature.

8. Conclusion

This paper demonstrated that the determination of the static pressure using laser induced fluorescence can easily coupled with laser velocimetry measurements. The compatibility between the two seeding technics, carbon particles and iodine molecules, has been defined.

The LIF measurements in this typical small supersonic underexpanded jet flow are in good agreement with the numerical calculations, except in areas of strong pressure gradients. An improvement of a the spatial resolution of the collection device can probably solve this problem.

The possibility of using carbon particles for laser velocimetry measurements has been demonstrated for both velocimeters but it involves the use of a signal analyser with a weak signal to noise ratio and a very broad pass band in the case of LDV.

A future development of this experimentation could be a direct determination of the velocity using a laser induced fluorescence with a detection of a Doppler schift.

These non intrusive coupled optical technics could have a development in cascades and turbomachines facilities.

9. References

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