EXPERIMENTS AND NUMERICAL SIMULATIONS ON THE MID-TERM EVOLUTION OF HYPERSONIC JETS

MARCO BELAN[1], SERGIO DE PONTE[1], SILVANO MASSAGLIA[2]
and DANIELA TORDELLA[3]
[1]*Dipartimento di Ingegneria Aeronautica e Spaziale, Politecnico di Milano, Italy;*
E-mail: belan@aero.polimi.it
[2]*Dipartimento di Fisica Generale, Universitá di Torino, Italy*
[3]*Dipartimento di Ingegneria Aeronautica e Spaziale, Politecnico di Torino, Italy*

Abstract. The experiment described here is focussed to the observation of underexpanded, hypersonic turbulent jets. The experiment is relevant to a few aspects concerning the dynamics of astrophysical phenomena such as the Herbig-Haro jets and to the interaction between the large-scale vortices and the system of shocks that determine the spreading and entrainment properties of highly compressible free-flows. A number of orifice jets with a ratio between the stagnation pressure and the ambient pressure of the order 10^3–10^4 have been studied by changing the stagnation/ambient density ratio. This has been realized using dissimilar gases in the jet and in the ambient medium: by using He, Ar and air the stagnation/ambient density ratio can be changed by one order of magnitude while keeping fixed the pressure ratio. It has been possible to visualize the near and mid-term evolution of the jets and measure the axial and transversal density distributions. A comparison relevant to the shock waves configuration in between the nozzle exit and the first Mach's disk is shown for an air in air laboratory jet and its numerical simulation.

Keywords: astrophysical jet, hypersonic jet, compressible mixing, entrainment

1. Introduction

Experimental simulations of hypersonic jets in conditions that intend to mimic some aspects of the Herbig-Haro jets have been carried out by means of intense lasers (e.g. Farley et al., 1999; Stone et al., 2000) and by a Z-pinch machine (Lebedev et al., 2002), while the time-evolution of a low Mach number jet, that reproduces some features of extragalactic radio jets of Fanaroff-Riley I sources, has been discussed by Raga et al. (2001). The experiment results we present here are still preliminary as far as the application to YSO jets is concerned, but allow to address some aspects of compressible mixing that can be related to the steady-state entrainment that are possibly, at least partly, responsible of the acceleration of bipolar outflows that surround YSO jets (see for e.g. Micono et al., 2000). As far as the detailed analysis of the dynamics of the mid- and long-term evolution of highly compressible free-shear flows is concerned, the literature does not yet present a complete set of results. Recall that by mid-term evolution it is intended the intermediate asymptotic behaviour, valid for times and distances from boundaries, large enough for the

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influence of fine details of the initail and/or boundary conditions to disappear, but small enough that the system is far from the final equilibrium state. Few results concerning the dynamics of compressible mixing layer at Mach numbers around 5 (Brown and Roshko, 1974; Ragab and Wu, 1989; Tam, 1971; Dimotakis, 1991) are available. These studies enlightened the presence of coherent large-scale structures in the mixing, which however undergo a very limited growth rate as compared to incompressible layers. As far as this aspect is concerned, a play of density effects associated to the presence of density gradients, which are independent of the compressibility, cannot be excluded. In fact density variations imposed by the ambient conditions—that can be highly different from those of the jet—are possible in many applications and particularly in the astrophysical context. This leaves open the explanation for the thinning of the spreading angle of the mixing region with the increase of the Mach number. Besides, at the current state of the art, it is important to collect information on the long-term existence in the laboratory of the array of axial knots—a sort of coalescence of curved shocks—to which both astrophysical observations and numerical simulations give evidence (Bodo et al., 1995, 1998). The experimental facility here used is suitable to investigate the spatial evolution of a jet over a scale at least two order of magnitude larger than the formation scale, which is here defined as the orifice diameter. It must be noticed that the literature does not report of the existence of other facilities suitable for the mid-long-term observation of hypersonic free flows, apart from Lebedev et al. (2002). The hypersonic jets under study have a Mach number, upstream of the first Mach disk, of the order of 20, which corresponds to a stagnation/ambient pressure ratio of the order 10^3–10^4. In this study, the density ratio between the fluid in the jet and the fluid surrounding it is supposed to be an important control parameter for the dynamics of the jet. The aim is to understand if the density variations are really capable to affect the dynamics of the jet independently of the compressible effects. Since the density is evolving along the jet, a reference value for the density distribution in the jet has been chosen as the axial average value of the jet portion which extends downstream of the first Mach disk. We recall that, in YSO jets, the density ratio is typically close to, or slightly larger than unity, depending on the distance from the origin. Of course, the Reynolds number of the experiment (Re) cannot be in similitude with the Reynolds number of the stellar jets. However the experimental Re falls in the range 10^3–10^4, that is sufficient to secure a turbulent developed flow, since the jets are intrinsically unstable flows which have a first critical Reynolds number as low as 50. The similitude is thus limited to the Mach number and the density ratio between the gas flowing in the jet and the ambient gas. The present and following experiments are foreseen to produce a body of results to be used as a reference for the validation of computational procedures embodying turbulence models specifically conceived for the simulation of the astrophysical jets and highly compressible shear layers. The experiment was carried out in the fluid dynamics laboratory of the Aerospace Department of the Politecnico di Milano. A detailed description of the facility can be been found in Belan et al. (2001a,b). A synthetic description of the experiment is given in Section 2. Results concerning the jet visualizations, its axial and transversal density distributions and a confront with a numerical simulation are given in Section 3. The results discussion is presented in Section 4.

2. Experiment Description

The experimental facility consists of a vacuum chamber into which the gas is injected through a nozzle (Ashkenas and Sherman, 1966; Roth, 1990). The inner diameter is half a meter. The chamber is made up of five sections one meter long, with side windows which allow to take images with various optical systems. The jet orifice has a diameter of 2.4 mm, thus the vessel dimensions are much greater (200 times) than the initial jet diameter. To visualize the density distributions in the jets, the electron beam technique has been selected as the simplest non intrusive technique which at the state of the art can provide spatially resolved information on flow density, species concentration, velocity and temperature (Butefish and Venneman, 1973). For the detailed description of the apparatus and of the design of the various parts of experimental facility, please make reference to Belan et al. (2001a,b). In the present experiment, the test gas flows through an orifice in the chamber and then expands into a free-supersonic jet inside the vacuum vessel. The vessel is filled with the ambient gas which can be dissimilar from the gas of the jet in order to change the jet/ambient density ratio. Before of the gas injection, the chamber is brought at a very low pressure of the order of a few Pa—which is the pressure of the ambient inside which the jet develops. The pressure minimum attainable value in the vessel is 0.5 Pa.

3. Morphology and Density Distribution of the Jets. Experiments Versus Numerical Simulations

A plausible schematic of the flow structure of the underexpanded jets is shown in Figure 1. Downstream of the first region, which comprehends the barrel and the first normal shock, a sequence of secondary shocks is shown. The lateral extension of the secondary shocks is supposed to reduce as the jet boundary, see Figure 1, is growing throughout the entrainment of the ambient fluid. The jet boundary is considered to be a mixing layer which is highly turbulent and intermittent. Three jet/ambient configurations have been tested: air in air (Figure 2), Helium in air (Figure 3), and Argon in air (Figure 4). The jets have been visualized by means of the electron beam and images recorded by a precision camera over exposition intervals of the order of 80 jets formation time scale. The formation time scale is of the order of 1 ms. The time scale for an increase in the ambient pressure of the 10$\sim$20% is of the order of 0.5 s. Therefore the recorded images can be considered to be visualization of nearly steady configurations. This is confirmed by the positive

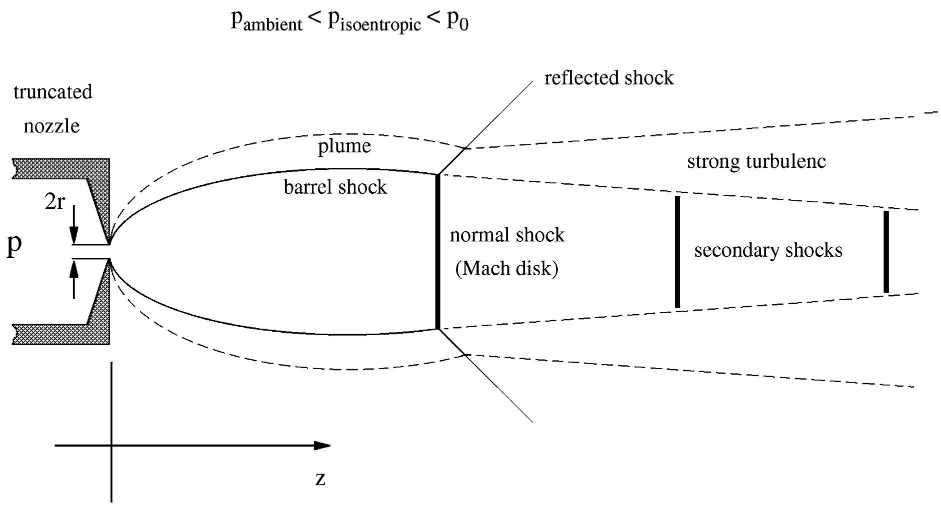

Figure 1. Sketch of the near and intermediate regions of the underexpanded jet.

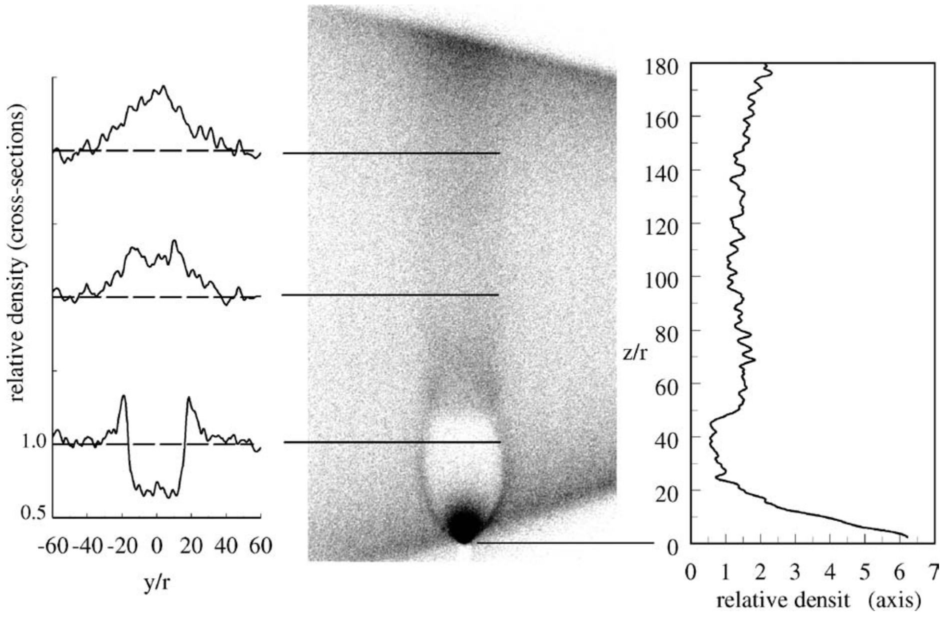

Figure 2. Underexpanded air jet in air ambient at $p_a = 7$ Pa, $T_a = 300$ K. Stagnation pressure 0.12 bar. Axial Mach number upstream of the first Mach disk $\simeq 19$.

comparison between the barrel shock structure shown by the present jets and that shown by the underexpanded jet experimented by Welsh and Cain (Welsh and Cain, 1995) in a very different kind of facility designed to provide steady flows (the continuous low density nitrogen tunnel, DRA Farnborough). For the three jets the initial ambient pressure was kept constant at 7 Pa, while the stagnation pressure

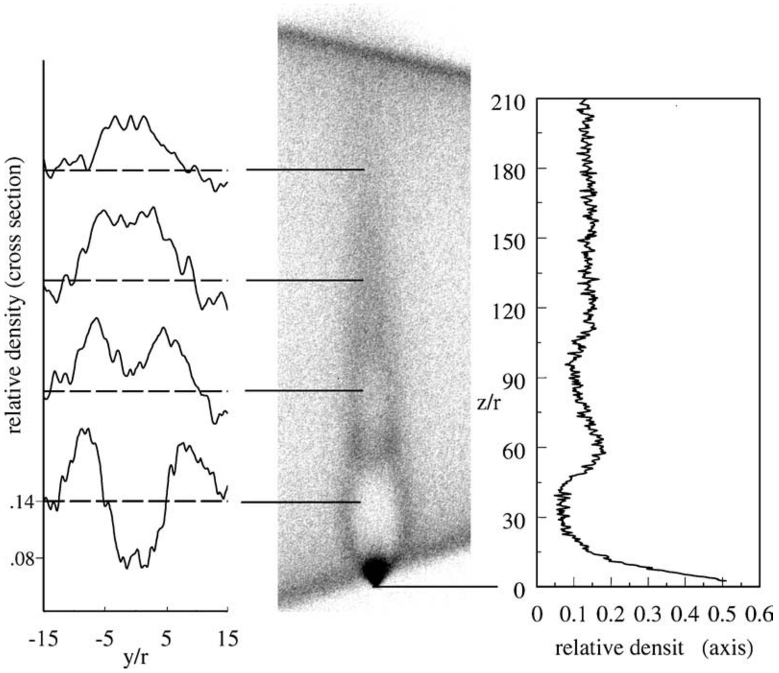

Figure 3. Underexpanded helium jet in air ambient at $p_a = 7$ Pa, $T_a = 300$ K. Stagnation pressure 0.12 bar. Axial Mach number upstream of the first Mach disk $\simeq 29$.

was was kept equal to 0.1 atm. All the jets are sonic at the exit section of the nozzle, which is a simple orifice in this experiment.

The light intensity (gray scale) in the present images is proportional to the density of the gas in the jet. The density in the figures is always normalized with respect to the density of the ambient gas in the vessel. To get the concentration distributions it is necessary to take into account also the color of the pixels, thing that will be carried out in future works. The density distributions are laterally cut in order to show the central part only of the jets, where the concentration of the gas flowing in the jet is higher than about 0.9. The comparison of the jet visualizations shows an interesting result: when the longitudinal density distribution after the first Mach disk is of the order of the density in the ambient, as it happens in the air-air jet and in the Ar-air jet, the spreading of the boundary mixing which surrounds the core of the jet is nearly zero (slip lines normal to the Mach disks), when the longitudinal density distribution is lower than the density in the ambient the spreading is positive (convergence of the inner slip lines, reduction of the disks transversal extension). This different dynamics cannot be explained in term of compressibility effects only. In fact, the Ar and He jets are similar in this concern, since, for instance, their Mach numbers upstream of the first normal shocks are both equal to 29. More, the air-air jet—which behaves similarly to the Ar-air jet—

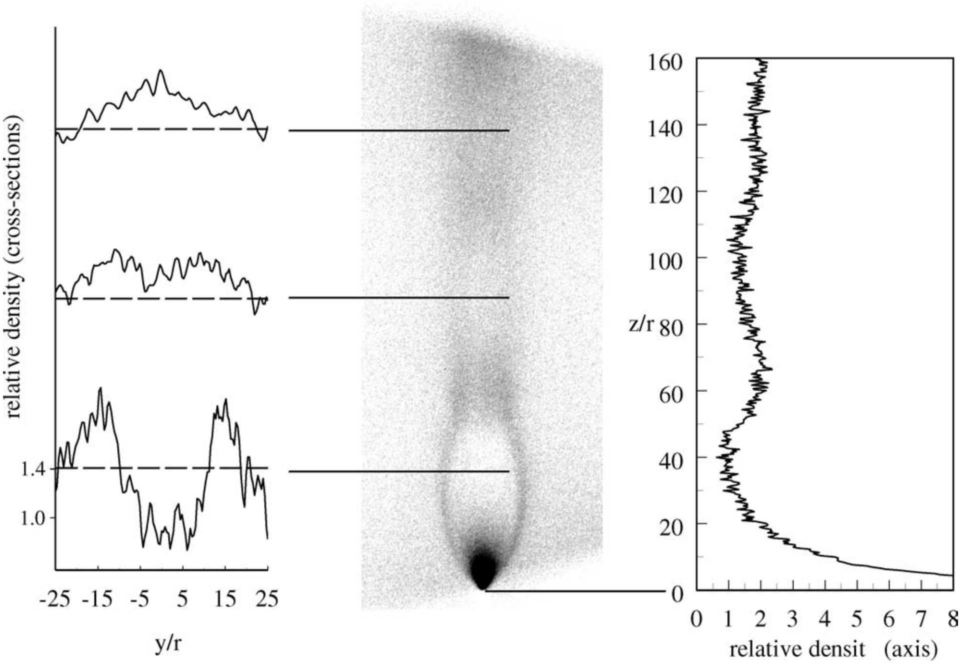

Figure 4. Underexpanded argon jet in air ambient at $p_a = 7$ Pa, $T_a = 300$ K. Stagnation pressure 0.12 bar. Axial Mach number upstream of the first Mach disk $\simeq$29.

reaches upstream of the first disk a Mach number of 19. The feasibility of using these experiments for the validation of numerical simulations is shown in Figure 5, where a laboratory air-in-air jet at $\rho_0/\rho_a = 2 \cdot 10^{-4}$ is contrasted with a numerical simulation carried out with an Eulerian PPM code. This comparison is carried over the first part of the jets because the experimental images, which are averaged over a time interval of 80 ms (nearly 500 temporal generation scales), cannot be contrasted in the region downstream of the first normal shock with the very detailed, but instantaneous, numerical images. Leaving aside the very near jet region, the first 25 radii, where the high density saturation typical of the electron beam technique (see Gadamer's curve; Muntz, 1968) does not allow for reliable measurements, a very good laboratory-numerical computation agreement is experienced as far as the axial density distribution upstream of the first Mach disk is concerned.

4. Discussion

This experiment evidences two main points. First, the fact that laboratory observations of the density distributions in the middle and far region of hypersonic jets are feasible. Second, that the ambient density conditions are playing an important role

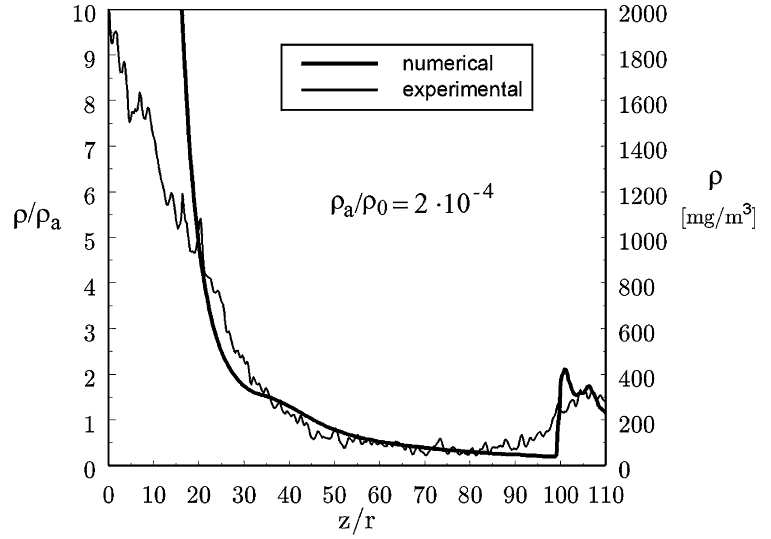

Figure 5. Axial distribution of the density up to the first Mach disk for an underexpanded air-in-air jet. $p_a/p_0 = \rho_a/\rho_0 = 2 \cdot 10^{-4}$. Upstream of the first disk the Mach number is equal to about 20. The numerical simulation is a representation of the near jet at $t = 207$ units. The time scale is defined as R_{or}/c_{or}, where R_{or} is the orifice radius and c_{or} is the speed of sound of the flow at the orifice section.

in the jet dynamics since they can change the morphology of the shock sequence in the intermediate region downstream of the initial barrel shock region. See, in Section 3, the reduced lateral extension of the normal shock sequence, which must be associated to a growing mixing layer surrounding the core of the jet, that the He-air jet shows in comparison with the air-air and Ar-air jets. The changes in the morphology are very important, because of the associated changes in the entrainment process, which are very important to comprehend the stability properties and the transport properties (mass, momentum, energy) of the hypersonic jets and relevant astrophysical applications. If the ambient conditions are capable to highly influence the intermediate evolution, as it has been observed in the present experiment, it can be concluded that density variations that are independent of the compressibility will also concur to the inertial effects to determine the long-term dynamics of the jets: a fact which up to now was not fully considered. The good agreement shown by the experimental morphology of the near region of the underexpanded air-air jet with that shown by the relevant Eulerian numerical simulation is also an important result, which leave open the possibility to use such a kind of experimentation for the numerical simulation validation sake.

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