

Exploration of Under-Expanded Free and Impinging Supersonic Jet Flows



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Abstract The impact of jets on a wall remains one of the most effective means allowing a significant increase in local exchanges of heat. These configurations are therefore particularly used in aerothermal systems. The literature reports several studies on the impact of moderately to strongly under-relaxed jets, both from an aeroacoustics and thermal point of view. Nevertheless, the aerothermal behavior and consequently the effects of exchange with the wall remain little known. Moreover, these flows appear to be difficult to simulate from a numerical point of view. We propose here to describe the first part of an experimental study focused on the description of the topology and dynamics of both free and impinged under-expanded jets with the aim to define an accurate database dedicated to the improvement of numerical flow models.

1 Introduction

The physics of supersonic circular jets has been under investigation since a long time due to the many aerospace and industrial applications. When gas exits a circular nozzle with a pressure higher than the surrounding one, an under-expanded jet forms. In this case, the pressure of the jet reaches the ambient pressure through a series of shock and expansion waves. This configuration becomes more complicated when the enthalpy of the jet is important or when it interacts with an impingement surface. This jet is widely described in the literature (see the synthesis established by Franquet [1]). Particularly, numerous studies focused on the comprehension of under-expanded jet flow structures [2] and on the specific mechanism being the source of instabilities such as the production of screech noise [3].

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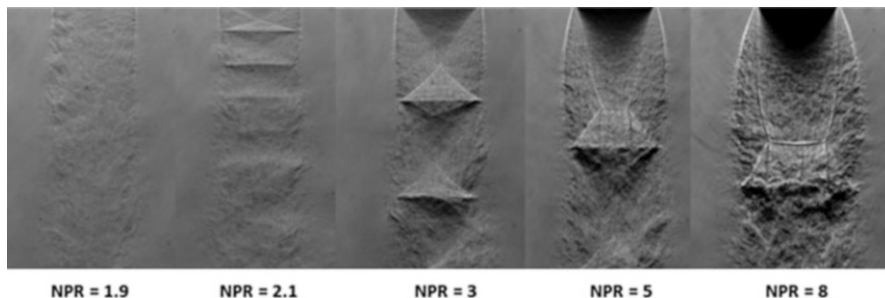


Fig. 1 Evolution of shock wave structures for different NPRs (instantaneous schlieren images)

Under-expanded jets are characterized by the nozzle pressure ratio (NPR), which is equal to the ratio between the total pressure of the jet (P_t) and the ambient pressure (P_a). Figure 1 gives a qualitative evolution of the NPR jet topology from schlieren visualizations realized in the present study. A detailed description of the flow can be found in Cumber [4]. The classical main geometric criteria that allow the characterization of the evolution of the shock structure in the near-field zone for NPRs greater than 2 are the position and diameter of the first Mach disk. A set of data as well as a set of correlations exist (e.g., Antsupov [5], Ashkenas [6], Alvi [7], gathered in Franquet [1]); nevertheless, their comparison shows a non-negligible deviation of results, probably due to the difficulty of the measurement and the generation of the jets. Indeed, performing measurements in supersonic jets is quite a challenge. Recent studies demonstrate the ability of achieving measurement with nonintrusive laser techniques such as LDV or tomo-PIV. Schlieren optical techniques are also a classical way to observe the complex structure of this kind of flow. Among them, the background-oriented schlieren (called BOS) allows the assessment of the density field and its fluctuations. Combined with additional measurements, BOS technique will improve the understanding of such a complex flow as proposed by [9].

In impingement condition, the structure of the flow is conventionally divided into three distinct zones called, respectively, “free jet zone,” “impinged zone,” and “parietal flow zone.” In the supersonic case, this structure depends strongly on the distance h between the nozzle section and the wall which conditions the development or not of a recirculation zone at impact. For a very small distance h , the deflection of the current lines at supersonic velocity near the wall induces the formation of a so-called “plateau” shock that extends over the width of the supersonic jet core. In the case where this distance h remains low, the first Mach disk can interact directly with the plateau shock to form a double central shock structure. As the gap increases, the annular shock is positioned downstream of the Mach disk and the first shock structure remains insensitive to the impingement. Depending on the NPR and the distance h , this sliding line can interact with the boundary layer developing at the wall, and a recirculation bubble can appear in front of the impinging zone. This evolution of the flow structure is well characterized by Henderson [8].

In the present article, we describe an experimental campaign on the case of an under-expanded jet ($NPR = 5$) in free conditions and perpendicularly impinging a flat wall considering a small spacing ($h/D = 3$). The main aims of this work are first to acquire a complete and robust experimental database by performing advanced measurement methods as 3DBOS. Second, we want to improve the knowledge of the flow behavior during impingement for such a configuration with the final objective of defining a validation case for a high-fidelity numerical simulation approach.

2 The Experiment: Test Section and Measurements

The BAT facility of ONERA consists of a 22 mm diameter convergent nozzle, supplied by 80 bar pressurized air tank (as shown on Fig. 2). A 570 kW electric heater allows output temperature regulation up to 400 °C at a maximum pressure of 10 bar. For a flow rate of less than $0.45 \text{ kg}\cdot\text{s}^{-1}$, the bench can operate continuously. The pipe is insulated downstream of the heater to minimize thermal losses. The nozzle is covered by a flat flange in order to be under confined conditions. The shape of the nozzle ensures a straight sonic condition on the jet exit. Experiments with nozzle pressure ratios ranging between 2 and 8 are performed with two total temperature T_i conditions (i.e., 293 K and 423 K). For impingement conditions, the jet produced by the nozzle impinged a titanium plate placed perpendicularly to its axis at a distance h such that $h/D = 3$.

In order to characterize the flow of both free and impinging cases, a visualization campaign is carried out with a Z-shape schlieren bench. Two approaches are

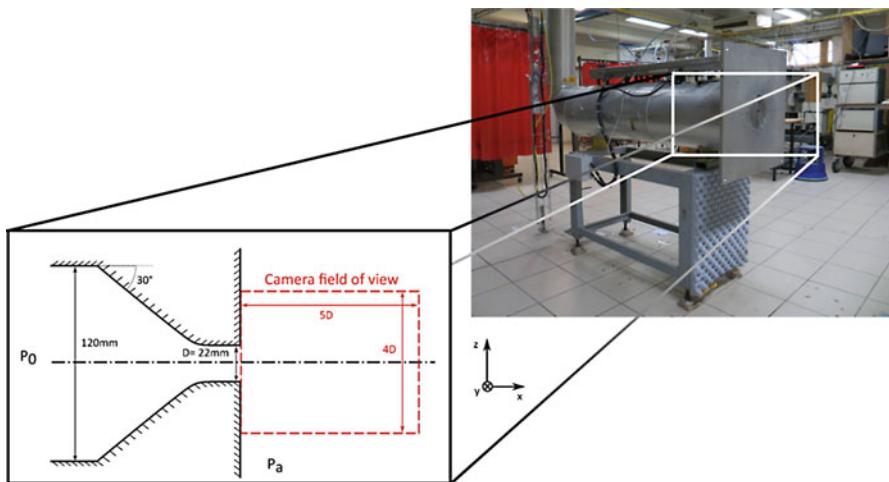


Fig. 2 The aerothermal jet facility BAT used for under-expanded jet studies. General view (top right) and sketch of the nozzle and camera field of view for BOS application (bottom left)

considered. First, averaged schlieren images are produced for exposure times of several milliseconds captured on CCD camera. The images obtained give an approximation of the structure of the flow and allow an estimation of the averaged position of compressible structures. In a second step, images of the instantaneous flow are produced by using a “Nanolite” type light source coupled to a condenser allowing exposure times of the order of 200 ns as illustrated in Fig. 1. In order to have some information on aeroacoustics behavior of the jet with impingement, a microphone is positioned in the vicinity of the flow to record the noise spectra of the jet. The database is completed with both velocity and density measurements.

The density measurements are performed with the 3DBOS technique proposed in Nicolas [9] which provides physically consistent 3D reconstructions of instantaneous and mean density fields. The technique is used in a first step to characterize free jet configuration.

The characterization of flow dynamics for a $NPR = 5$ in cold condition ($T_i = 293$ K) is performed with LDV technique. Indeed, velocity measurements for this type of flow remain difficult due to the wide range of velocities and the important gradients encountered (shock passage, mixing layer, and impinging zone). In this study, LDV technique has been preferred and the configuration of the system optimized according to the choice of the frequency ranges (imposed by the limits of the apparatus). The two-component measurements are carried out following a forward scattering configuration with a seeding of silica particles whose mean diameter is around $0.4 \mu\text{m}$. According to a numerical pre-study performed in order to estimate the drag of the particles during the shock crossing, source of bias, this kind of particles does not affect the measurement of velocity upstream of the shock structures.

The acquisition system used for this study is a TSI FSA 4000 signal analyzer allowing a rapid scan over a very wide band of frequencies. The 3D mesh is composed of 3000 points. Depending on the explored area, between 10,000 and 20,000 particles are acquired per point.

3 Free Under-Expanded Jet: Results and Discussions

Based on schlieren visualization, the evolution of the experimental mean diameter and position of the Mach disk for each free jet configuration is gathered in Fig. 3. By comparing with classical correlations identified by [1], the results obtained for the diameter are comparable to Antsupov’s correlation for the low NPR cases (i.e., less than 6). For higher NPRs, Mach disk diameters deviate from all the selected correlations except for Addy and Alvy’s database [7, 9].

Figure 4 gives a reconstruction of the mean density field of the jet for $NPR = 5$. The 3D reconstruction is performed from displacement fields averaged over 900 images with 12 points of view (i.e., cameras) distributed around the flow (see [9]). The flow topology is well recovered, with two shock cells visible. Behind the normal shock of the first Mach disk, the subsonic zone is present. The 3DBOS

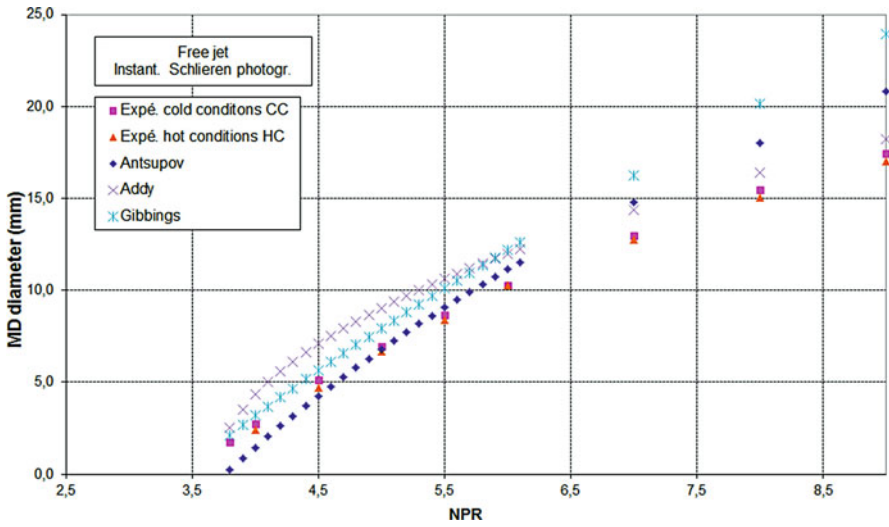


Fig. 3 Diameter of Mach disk compared with correlations gathered in [9]

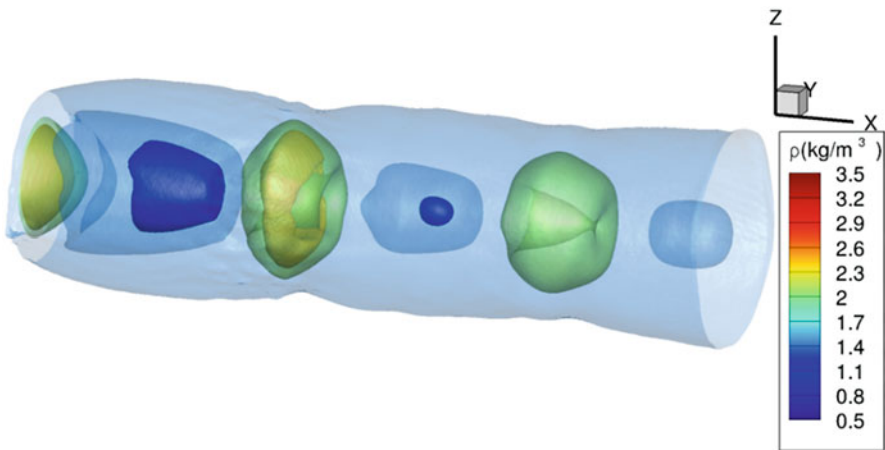


Fig. 4 3D mean density field reconstruction (iso-surfaces) NPR = 5

reconstruction shows very good result, and density levels as well as flow topology are well recovered, with a consistent location of the shock cells compared to schlieren data.

4 Impinged Under-Expanded Jet: Results and Discussions

A set of images obtained with averaged schlieren approach was performed and helped to determine the evolution of the flow topology (structure of the compressible flow, shocks, and impinging flow behavior) and to confirm the highly unsteady nature of the flow. They tend to show that, for the spacing considered here, the impinging wall slightly affects the structure of the jet upstream of the impact. This is confirmed by the measurements of the position (on the axis) and the diameter of the Mach disk which indicate that in both cases the free jet zone is comparable with free conditions' case.

The structure of the flow is given in Fig. 5. The impingement zone is well marked by the presence of an annular shock. One can note also the presence of acoustic waves propagating from this zone of impact through the confined space. The instantaneous schlieren images show that these waves are able to interact strongly with the upstream jet flow (oscillations or deformation of the shock structure around the triple point).

As we consider aeroacoustics of the jets, the spectra acquired reveal the presence of high-amplitude frequency peaks (up to 130 dB) accompanied by their harmonics, and the presence of the plate imposes a second peak which can be associated with the oscillations of the impact zone as pointed out by Henderson [5]. For the dynamic field, the velocity profiles obtained in the axial plane of the jet by LDV as shown in Fig. 6 reveal a recirculation zone localized in front of the stagnation

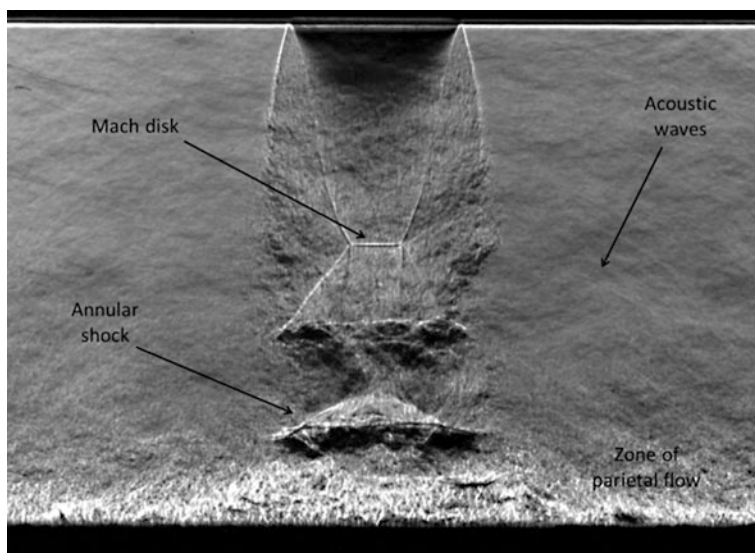


Fig. 5 Impinged under-expanded jet observed by schlieren technique (NPR = 5, $T_i = 293$ K, $h/D = 3$)

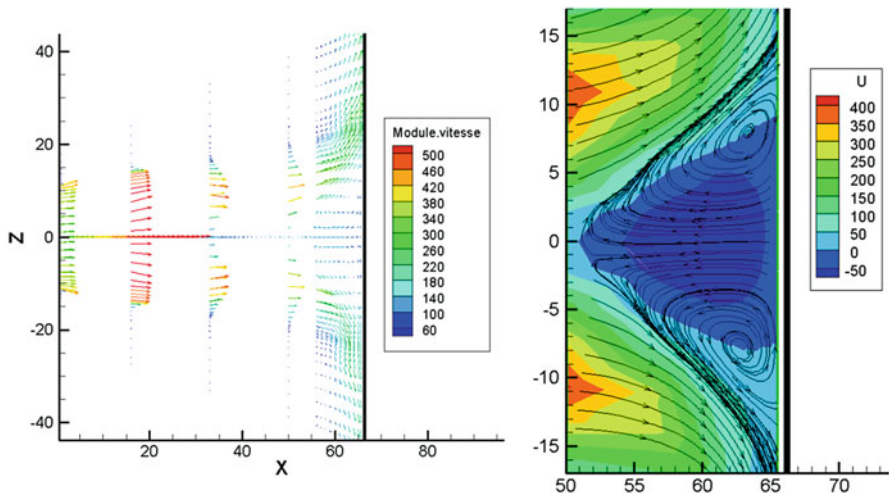


Fig. 6 Averaged velocity obtained by LDV for impinging jet ($NPR = 5$, $T_i = 293$ K); left, vector field colored by the norm of velocity (in $m.s^{-1}$); right, axial velocity field of the impinging region with streamlines (in $m.s^{-1}$)

point. A comparison between schlieren images and mean dynamic field shows the implication of the annular shock which contains this recirculation. Due to the complexity of the flow, the post-processing of the LDV data requires a fine analysis of the velocity histograms obtained for meshing points localized close to shock wave position and strong gradients characterizing mixing layer regions. By this way, we are able to track the presence of shock waves by analyzing the evolution of velocity histogram peaks.

5 Conclusions

A first exploration of an under-expanded jet is performed in order to characterize the topology and a part of the dynamics of both free and impinged flow (with $h/D = 3$) for ambient conditions ($T_i = 293$ K) for a nozzle pressure ratio of 5. For impingement case, the data highlight the highly unsteady nature of the flow due to the presence of a large recirculation in the area of impact and the circulation of intense acoustic waves which are reflected in the confined space. In a next step, these results will be completed by additional characterization of the dynamics of the flow. Thermal transfer measurement on wall will be also performed. Moreover, the 3D BOS technique could allow an analysis of the jet density structure dynamics in combination with far-field noise measurements in order to characterize the jet shear layer and shock wave interaction, which will be extended to impingement case. At the end, the completed database will be used as a validation for high-fidelity numerical simulations of the aerothermal configuration.

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