A test facility for assessing simulations of jets in cross flow configurations

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Abstract

A test facility featuring jet(s) in cross flow configuration is presented. The peculiarity of the rig stems from the presence of an acoustic forcing system that introduces planar acoustic waves in the cross flow. Microphones, PIV and LDV measurements have been conducted in forced and unforced configurations. The experimental database built so far already gives the possibility of assessing in depth the predictive capability of related steady or unsteady simulations.

1 Introduction

The jet in in cross flow (JICF) configuration is of interest when developing new aeronautical combustion chambers as it features most of the phenomena present in the parietal flow of an effusion-cooled combustion chamber wall. But, in spite of the numerous studies devoted to the JICF configuration, very few of them provide an experimental database that can be used years after the data have been collected. The database built by Gustafsson (2001) is a noticeable exception to that but is limited to a JICF configuration involving only circular inclined unforced jets. As far as acoustically forced JICF are concerned though, such a comprehensive database is still not available although this type of configuration is quite important to understand how the effusion cooling parietal flow in a real chamber is interacting with acoustic waves generated for instance by some combustion instability modes. The recent large-eddy simulations (LES) carried out by Motheau *et al.* (2012) shed light on the sensitivity of the mass-flow rate through an effusion plate to the presence of an acoustic forcing in the cross flow. Such a finding is quite of importance since it indicates that the presence of acoustic waves in the combustion chamber may deeply alter the effectiveness of the wall cooling system. Since LES is bound to be the CFD workhorse in the process of developing the future combustion chambers, it is quite necessary to assess the quality of its prediction by producing experimental database for canonical but challenging flow configurations featuring most of the prominent phenomena present in a real combustion chamber such as the presence of an acoustic wave interacting with a JICF. Therefore, the purpose of the present contribution is to present the main features of the newly upgraded test facility MAVERIC aimed at reproducing such a canonical flow configuration and illustrating its relevance for assessing LES based simulations.

2 The test facility

A brief description

The objective in developing that upgraded rig was twofold: first, it will be used to investigate JICF configurations with or without an acoustic forcing of the cross-flow; second, it will provide data usable to assess the capability of simulations (RANS, LES or DNS) to predict accurately such a kind of flows. PIV and LDV measurements have been carried out on unforced and forced jets in cross-flow. This test facility represents quite a significant upgrade of the set-up originally proposed by Most (2007).

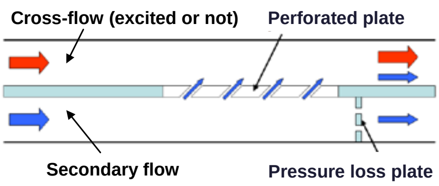

Figure 1: Generic targeted flow configuration.

The generic flow configuration investigated is depicted in Figure 2. Two parallel turbulent channel flows share a common wall which accommodates an interchangeable perforated plate. In order to generate a pressure difference between the two streams and hence a jet through the hole(s), a pressure loss plate is placed normally to the lower flow.

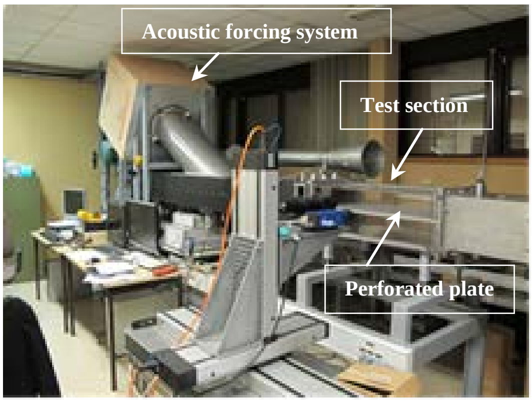

Figure 2: MAVERIC test facility overview.

An overview of the test facility MAVERIC corresponding to that generic flow configuration is presented in Figure 2. It consists basically of two 2.5m-long superimposed channels of identical rectangular 400mm (Width W) x 120mm (Height H) cross-section followed by the Plexiglas-made test section which accommodates the removable perforated plate. The test section is followed by the exhaust section which evacuates the air flows outside through the lateral wall of the room. The two air-streams are generated by two centrifugal fans powered by two 1-KW electrical motors controlled by two Siemens Micro-Master MC420 inverters. In order to generate a pressure difference between the two streams and so to generate the JICF configuration, a pressure loss plate housing 90 evenly spaced holes of 13 mm of diameter is inserted in the test section at the level of the exit section of the lower channel. The maximum porosity of this plate, defined as the ratio between the holes surface and the plate surface is equal to 25%. This porosity can be adjusted by simply occluding a given number of holes. For generating the present experimental database, 5 evenly spaced rectangular 10-hole clusters have been occluded which corresponds to an effective porosity of 13.9%. In such a configuration, varying the rotation speed of the lower centrifugal ventilator permits the adjustment of the pressure drop ΔP_{jet} between the lower and the upper channels from 10 Pa to 140 Pa. The perforated plates housed by the test section (see Figure 3) are featuring either one-hole, one-row or twelve-row patterns. The holes have been individually realized by electro-erosion in order to reproduce at scale 12.5 the real shape of aeronautical combustion chamber holes obtained by laser drilling. A photo of the three perforated plates used is presented in Figure 4. The plates are sharing the same shape of the hole(s), namely a converging section in the jet flow direction yielding elliptic sections at the suction (largest section) and blowing side (smallest section).

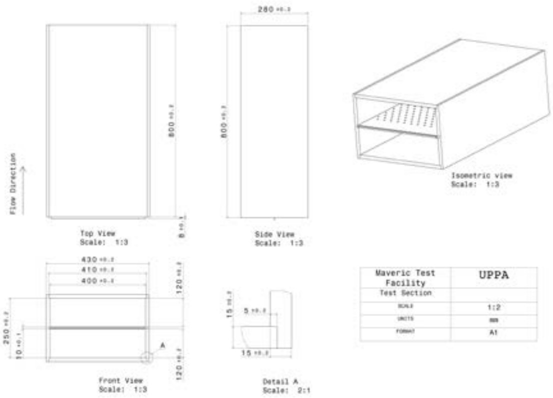

Figure 3: Detailed drawings of the MAVERIC test section.

This shape was chosen as it mimics to some extent, the shape of holes drilled by laser in a real combustion chamber wall. The choice of the layout of the holes was chosen in order to ensure a hierarchical nesting of the different hole patterns i.e. the location of the hole of the 1-hole plate corresponds exactly to that of the sixth hole (i.e. the central hole) of the 1-row plate, and the location of the row of the 1-row plate corresponds exactly to that of row 9 of the 12-row plate. The acoustic forcing of the cross flow is produced by a high fidelity loud speaker (Raptor 15 MK2) with operational frequency ranges from 30 to 350 Hz. The maximum sound pressure level (SPL) in the membrane section of the speaker reaches 130dB for its nominal input power. A tube of 380mm of diameter with an inclination angle of 30° with respect to the upper channel axis permits the insertion of an acoustic wave in the cross flow.

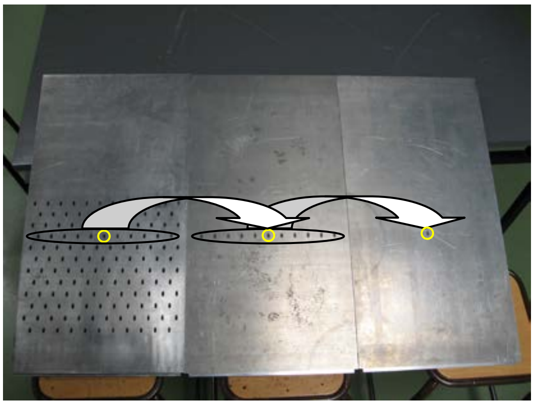

Figure 4: Overview of the perforated plates used on MAVERIC. 12-row plate (left), 1-row plate (middle) and 1-hole plate (right).

Since the cut-off frequency of the upper and lower channel is 412.5 Hz, the acoustic waves propagating through the test section are planar. Particle image velocimetry (PIV) as well as one-component laser Doppler velocimetry (LDV) are used to characterize the velocity field. An overview of the PIV system is presented in Figure 5. A computer controlled 3-axis translation stage is displacing the cameras and a 1-axis stage is used to displace the laser sheet in a synchronized way in order to keep constant the distance between the laser sheet and the cameras once the calibration procedure is achieved. The initial adjustment of the translation stages was carried out by using and displacing a telemeter pointing on some specific part of the test facility. In order to achieve the fine adjustment and alignment along the rig axis of i) the laser sheet and ii) the displacement axis of the translation stages, specific devices were developed, manufactured and used. A grooved plate possessing the same overall dimensions as the three perforated plates presented beforehand was manufactured.

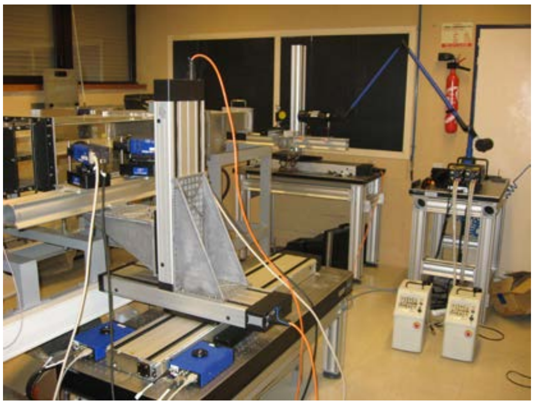

Figure 5: PIV system installation overview. Backplane: lasers, laser guiding arm, sheet generator, and mirror and 1-axis translation stage. Front plane: CCD cameras and 3-axis translation stage.

This plate can be inserted in the test section and replace a perforated plate therein. The grooves that were created on its upper face allow for the positioning of either i) the 2-plane calibration plate used for the PIV calibration process (i.e. the process which transforms the field of view of the cameras from pixels to meter) or ii) a specifically developed grooved device which supports three mobile 3-slot plates.

Since the PIV system employed is a low rate system, the question of performing the recording at a constant acquisition rate on a flow where a high frequency coherent motion is present poses the question of the conditionality of the recordings to the phase angle of the coherent motion. In other words, since the acquisition rate is much lower than that of the coherent motion, the recording performed at a constant (low) rate will be strongly correlated to a phase angle belonging to a narrow band but which is not known since it is determined by the time at which the acquisition procedure is launched.

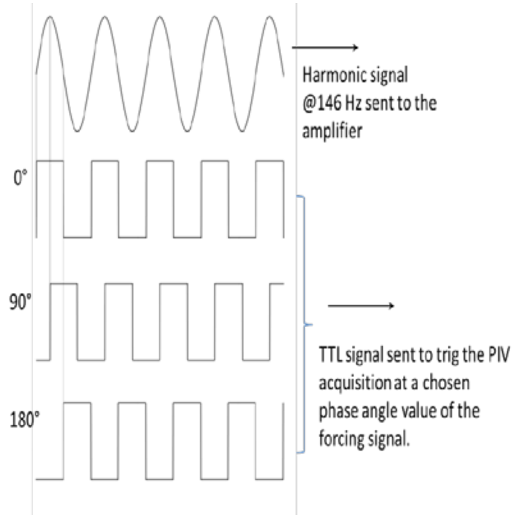

Figure 6: Phase locked PIV acquisition: trigger signal generated from the acoustic forcing signal.

A way to get rid of this is either to sample with a randomly varying acquisition rate or to phase lock the recordings and then average over several phase angles. It is the latter methodology that has been developed.

As it is illustrated in Figure 6, a trigger signal is generated from the harmonic forcing signal. The LabVIEW program used to generate the forcing signal has been designed so that the end-user can simply choose the phase angle at which the PIV recordings are wanted. All the delays have been compensated after having performed a comparison between the TTL signal sent out to the time synchronization unit and the TTL signal sent back by the camera when it is beginning to expose its first frame.

CFD related issues

Ensuring that simulations and experiments are dealing with the very same flow configurations is obviously central to the relevance of any subsequent comparison between them. To that end, the test facility has been designed to provide a mean turbulent cross flow whose properties are as close as possible to those of a fully developed turbulent channel flow. As a consequence, the normal profiles (not shown here) of the axial component of the inlet mean velocity measured by LDV in the lower and upper channels exhibit a satisfactory collapse around a ($1/7^{th}$) power-law profile typical of a developed turbulent channel flow. Moreover, in order to help to finely tune the numerical procedure to be used for accurately reproducing the acoustic forcing, several ports for microphone (B&K 4197) insertion have been fitted in the inlet and outlet sections of both streams. Thus, it is possible to record the instantaneous acoustic pressure jump fluctuations that prevail between the upper and lower inlet sections as well as between the inlet and exit upper or lower test sections. Multiple resonance frequencies are observed in the 25 – 150 Hz band with an abrupt change of the sign of the phase angle between the two signals at a frequency of 149 Hz. The forcing frequency is chosen among the detected resonance frequencies and should be as low as possible to yield a value of the forcing Strouhal number close to that encountered in a real combustion chamber but not too low since otherwise the CPU requirements for the LES of such a flow would be out of reach.

3 A few flow features extracted from the database

The different configurations were investigated at atmospheric pressure and ambient temperature. The air flow temperature was 295 ± 5 K. The chosen parameters of the lower channel flow correspond to a targeted value of the mean pressure drop in absence of forcing ranging from $\Delta P_{jet} = 15 \pm 1.0$ Pa to $\Delta P_{jet} = 135 \pm 2.0$ Pa and a cross-flow Reynolds number around 8000 and 35000. A labelling strategy has been adopted to identify the different JICF configurations. For instance, the unforced configuration corresponding to the 12-row plate with converging holes, $\Delta P_{jet} = 60 Pa$ will be labelled NAF-CV-12R-60.

In presence of an harmonic acoustic forcing, the maximum forcing amplitude and the nature of the waves observed in the test section (propagative or standing) depend on the frequency.

Due to the acoustic coupling between the upper and lower channels through the air intake and exhaust tubes, the lower channel is also acoustically excited. The amplitude and phase of the forcing between the upper and the lower channel determine the effective acoustic pressure difference between the two sides of the plate and therefore the subsequent impact on the jet(s).

Last but not least, the engines entraining the centrifugal compressors are producing a quite significant peak around 22 Hz for cross-flow Reynolds number above 20000 or a pressure drop values above 60 Pa. As a trade-off between these various constraints, it has been decided to choose as forcing frequency the largest resonance frequency observed in the 25-150 Hz band, namely f=146 Hz. The corresponding wavelength is equal to 2.35 m to be compared to the overall multi-perforation length of 0.331 m and the distance separating the two microphone ports C1 and D1, namely 1.05 m. At such a frequency, the phase shift between the two signals is around -169°.

The two forced configurations investigated have been denoted by AF-CV-12R-60-146-12 and AF-CV-12R-60-146-24. In either denomination, the last two digits (12 and 24) refer to the acoustic forcing level DP'_{ac} expressed in Pa and the cross-flow Reynolds number was around 8000.

Unforced JICF

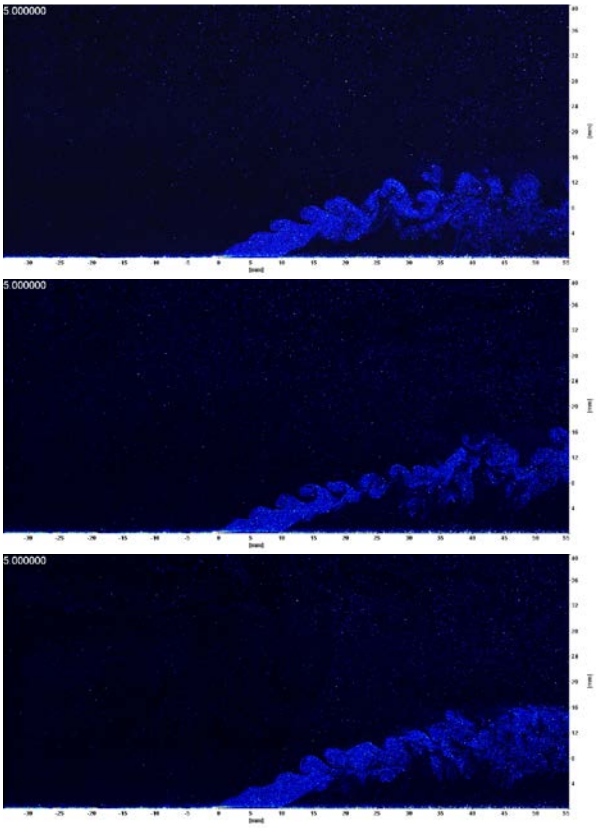

Figure 7: Examples of instantaneous jet patterns in the mid-span plane of the jet issued from the central hole of the 1-row plate with acoustic forcing switched off (mean pressure drop of 45 Pa and a cross-flow Reynolds number of 35000).

Figure 7 presents snapshots of the JICF extracted from the database built for cases without acoustic forcing. It corresponds to a one row plate with a dynamic pressure difference of 45 Pa. The expected roll-up structures associated with the Kelvin-Helmholtz instability are clearly visible on the leading side of the jet while they are quasi absent at the lee side.

For the 12-row plate, the PIV measurements are very useful to grasp the overall flow topology and its spatial evolution along the perforated plate. A visual inspection of the mean velocity field plotted in Figure 8 indicates that the jets are increasingly deflected when one is moving from row 1 to row 11. This is confirmed by the corresponding trajectories plotted in Figure 9 where the dashed vertical line corresponds to the location of the LDV measurements (not shown here but available in the database) which accompany the PIV ones.

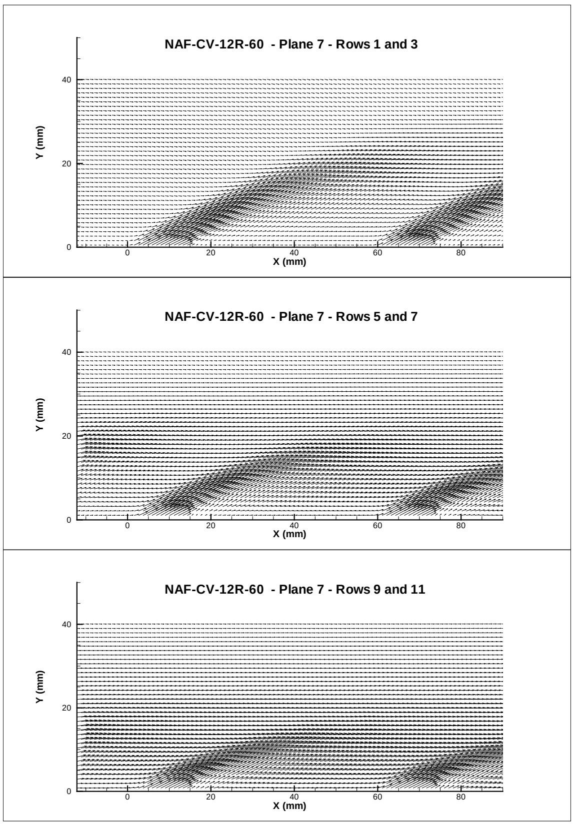

Figure 8: NAF-CV-12R-60 - Mean velocity field for the six different rows considered (The cross-flow Reynolds number was around 8000, each field corresponds to an average over 1200 instantaneous vector data sets).

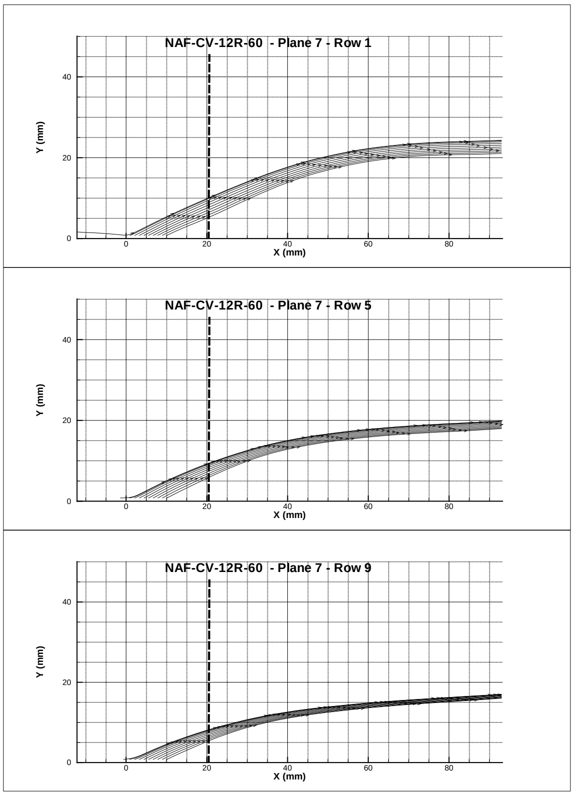

Figure 9: NAF-CV-12R-60 - Mean trajectory of the central jets issued from rows 1, 5 and 9.

Forced IJCF

The effect of the acoustic forcing on the flow topology is quite spectacular. This is illustrated by the contour plot of the mean normal velocity component for the jets issued from rows 1 and 3 and presented in Figure 10. If the initial jet development zone seems to be quite marginally affected, this is clearly no longer the case as soon as the jet is moving sufficiently far away from the home exit. The stronger the acoustic forcing, the earlier the jet trajectory is affected. A qualitatively similar alteration of the jets is observed for the other rows.

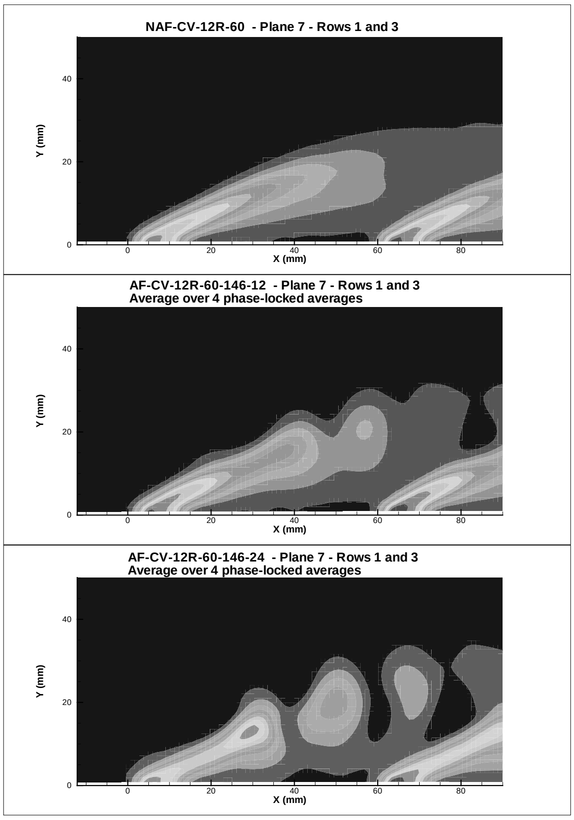

Figure 10: Unforced vs.forced JICF configurations for the 12-row plate. Central jets issued from rows 1 and 3. Field of the mean normal velocity component (average over 1200 instantaneous vector data sets).

3 Conclusions

A quite unique test facility featuring JICF configurations with or without acoustic forcing of the cross-flow has been presented along with a few results extracted from the available experimental database. The strong sensitivity of the flow topology to the presence of an acoustic standing wave in the cross-flow has been clearly evidenced. The presently available measurements give already the possibility of extracting numerous velocity profiles for a future fruitful LES assessment.

Acknowledgements

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