Flow field characterisation within a rectangular cavity

by
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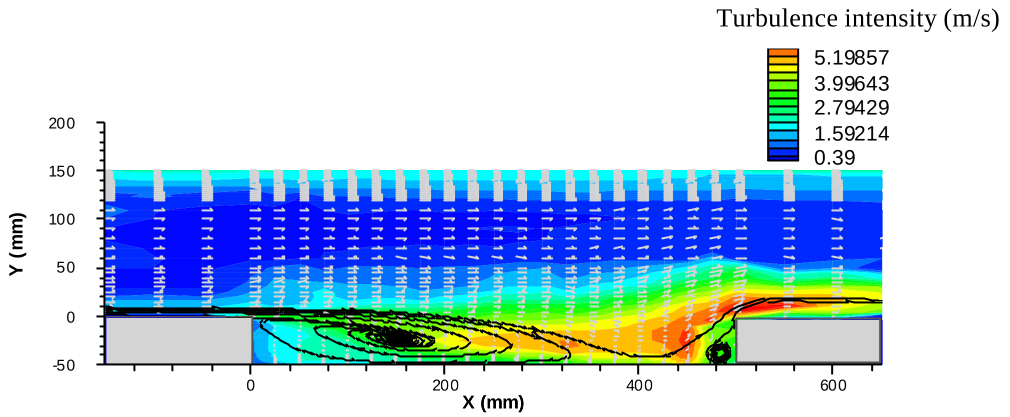
ABSTRACT

In addition to engineering applications, the present experiment provides a useful database to validate numerical simulation codes at low Reynolds number and an interesting separated flow behaviour to provide insight on the flow physics.

The flow field within a rectangular cavity at low Reynolds number and for a length-to-depth ratio of 10 is described with a representation of velocity vectors and turbulence intensity. The “stagnation zone” in the flow is specially focused on and a detailed description of the flow evolution downstream and upstream from the cavity is given. These measurements show that no reattachment point exists at the bottom of the cavity but a sub-layer with negative axial mean velocity appears.

Reynolds stress profiles inside the cavity are presented with a spectral analysis of the LDV signals at the axial location of the stagnation point for a description of the behaviour of the sub-layer. For a complete description of the flow field, a comparison with backward facing flow data is conducted. The results show that the area including separated shear layer upstream from the stagnation zone is unaffected by the rearward facing step and, in the same time by the second recirculation zone.

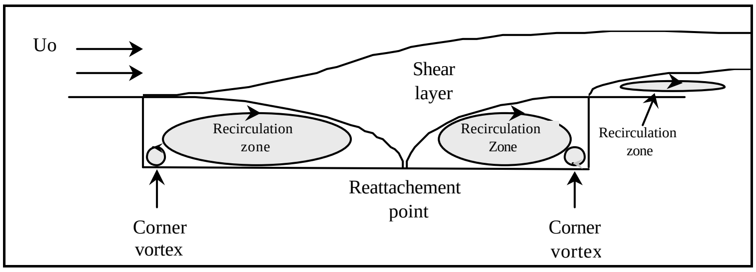


Turbulence intensity and streamlines within the cavity (Uo=20 m/s)

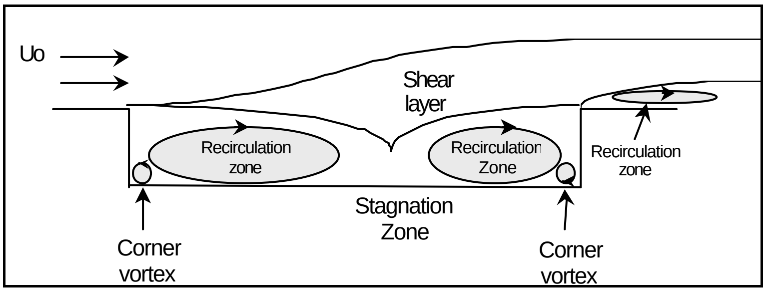
1. INTRODUCTION

The flow within a large cavity has received significant attention in view of engineering applications (TGV boogies, bomb bay..). Computational studies concerning cavity flows are interested usually in flow in shallows cavities behaviour with a length-to-depth ratio of 5 or less. In that way, numerical results frequently concerns square cavity. Yet, few experiments have been performed to analyse the details of the flow field inside a rectangular cavity at low Reynolds number and for a length-to-depth ratio of 10. Moreover, experimental data with optical techniques such as LDV in this configuration are very rare.
The behaviour of structures formed in a cavity strongly depends on the Reynolds number and the cavity length-to-depth ratio. In that way, the shear layer pattern seems to respond to these different parameters. Yet, few experiments have been performed to analyse the details of the flow field inside a rectangular cavity at low Reynolds number. In particular the flow characterisation for a rectangular cavity with a length-to-depth ratio of 10 (or more) is rare.
The purpose of the present study is to provide insight on the flow behaviour in a rectangular cavity for two inlet velocities conditions corresponding to Reynolds numbers, based on the cavity depth, of 3.8×10^4 and 6.4×10^4. This cavity is tested for a length-to-depth ratio $L/D = 10$ and for a width-to-depth ratio $W/D = 1$.

Cavity flows, as backward facing step (BFS) flows, give rise to a complex separated flow generated by a simple geometry. In that way, they are a popular choice for computational fluid studies. The boundary layer growing upstream from the cavity separates at the cavity lip. A free shear layer begins to develop and reattaches then, either downstream or on the bottom wall of the cavity. Cavity flows are said to be "closed" if the shear layer reattaches on the bottom wall of the cavity and said to be "open" if not. For a "closed" cavity, the shear layer reattaching on the bottom wall, encloses recirculation zones on each side (Figure 1). According to Plentovich et al. (1993), at supersonic regime, "open" concerns cavities with L/D greater than 13.



"closed" cavity



"open" cavity

Figure 1. Configurations of flow field cavity

The study of the flow field in a rectangular cavity has been carried out by numerous investigators in the past [Pan and Acrivos (1967), Metha and Lavan (1969), Heller and Bliss (1975), Plumbee et al. (1962)], nevertheless, very few papers investigate at low Reynolds number for a cavity with a length-to-depth ratio of 10. The majority of authors has studied deep cavities for supersonic regimes and only relates oscillation mechanisms in shallow cavities. In fact, the aeroacoustic phenomenon associated with aerodynamically induced pressure oscillations have been studied by several investigators. These studies are principally aimed to the problem of suppressing the cavity pressure oscillations.
These investigations have not attempted to explain the basic physics underlying the fluid dynamics behaviour for a large cavity at low Reynolds number. However, an analysis of the papers dealing with a higher speed allows a better understanding of the flow structure in a large cavity.

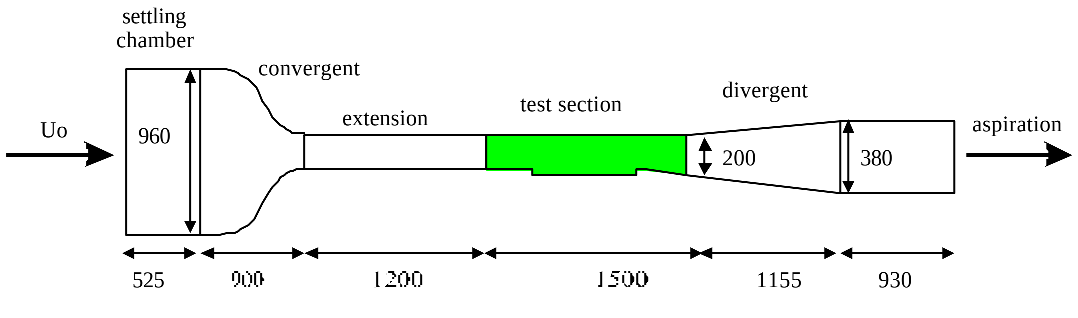
Sarohia (1977) observes the development of oscillations in shallow cavities at low subsonic speed. This important paper indicates that no acoustic resonance phenomenon appears in the axial direction. The existence of fluctuations in shallow cavities is directly due to the interaction between the shear layer, created upstream at the separation point, and the downstream corner. These oscillations induce pressure waves within the cavity. These waves are followed by a large lateral motion of the shear layer and a periodic shedding of vortices ("Feedback" mechanism). Four stages of the cavity oscillation cycle are described by Borland (1977).
Rossiter (1966) studied the case of small cavities at subsonic and supersonic regime (0.4<M<1.2). For these conditions, he shows the existence of a fundamental frequency inversely proportional to the cavity length. Yet, Rossiter also describes the interaction between the shear layer and the cavity downstream corner that give rise to the shedding of vortices.
At low Reynolds number and in a large cavity, the literature seems to be insufficient. Noger (1999) is the only one who deals with this subject. He performs experiments on a cavity with a length-to-depth ratio of 7.8 and an inlet velocity of 32 m/s ($Re_D = 1.4x10^5$), in order to characterise the flow field and the acoustic phenomena inside the cavity. His results show the lack of acoustic mode in the cavity and the existence of a shear layer reattachment on the bottom wall.
A survey of the literature regarding flows for different cavity configurations is described in Komerath et al. (1987).

The shear layer evolution and its interaction with the downstream corner or the bottom wall of the cavity seems to be identified by numerous authors. In the whole, the literature shows the importance of the shear layer evolution. Whether there is an interaction or not with the downstream corner or with the cavity bottom induces an important modification of the dynamic and acoustic characteristics of the flow within the cavity.
Cavity geometry, as BFS, fixes some of the parameters, such as the separation point, which plays an important role on the evolution of the shear layer evolution. According to the possible existence of a reattachment on the cavity bottom, the flow pattern can evolve towards a mono-cellular recirculation zone or towards multicellular recirculation zone. So, a detailed description of the shear layer is a necessary to understand the flow behaviour.
There have been many detailed studies of separated turbulent flows behind steps or similar obstacles. The mechanism of vortex interaction, pairing and merging before reattachment that occurs in two-dimensional shear layers has been investigated for decades. For cavity flows, in spite of the importance of the shear layer evolution, not any investigation has been conducted in the past. The comparison between the evolution of the shear layer in a BFS flow and a cavity flow may help to understand the influence of the rearward facing step on the flow pattern.

2. EXPERIMENTAL SET-UP AND TEST CONDITIONS

2.1 Wind tunnel

This experiment is conducted in an open wind tunnel (figure 2). The settling chamber and the convergent upstream from the test section conduct to a uniform velocity profile in the free-stream region upstream from the cavity.
The reference velocity conditions are measured above and upstream from the inlet step plane ($X = -50$ mm and $Y = 50$ mm), they are $U_0 = 12$ m/s and $U_0 = 20$ m/s with a free-stream turbulence intensity below 1%. The Reynolds number based on the length of the backward-facing step for these two conditions are respectively 1.2×10^6 and 2.1×10^6, providing a turbulent boundary layer at the inlet of the test section. The thickness of the boundary layer at the separation is approximately 23 mm for the two inlet velocities.



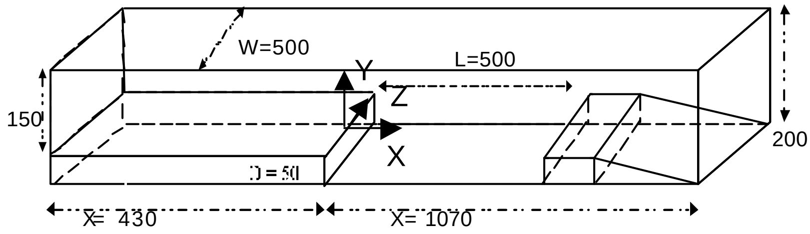


Figure 2. Wind tunnel and test section with the rectangular cavity (lengths in mm)

2.2 Velocity measurement

Velocity measurements are made by means of a two-component TSI Laser Doppler Velocimetry (LDV) system. Green (514.5 nm) and blue (488 nm) laser beams from a 2 W Argon ion laser are used to make direct measurements of the axial (U) and transverse (V) velocities. A double rotation of the laser head, in the X and Y directions, is necessary in order to move the focal volume (measuring station: 0.1x 0.1 mm in the (X,Y) plane) near the walls inside the cavity. These measurements consist of 50000 velocity samples at each location inside the cavity, with a mean sampling frequency of approximately 1000 Hz.
All the measurements are conducted in the middle plane of the test section (Z=0).

2.3 Wall static pressure

Static-pressure measurements are made on the wall at the bottom of the cavity. The wall is instrumented with 41 static-pressure orifices. The static-pressure is measured with a pressure transducer referenced to the inlet static pressure (X=-355 mm, Y=80 mm). The 223B Pressure Transducer (MKS Instrument) measures the differential pressure according to its full scale range (10 mmHg).

3. RESULTS AND DISCUSSION

The results presented in this paragraph are obtained for an inlet velocity of 20 m/s. Some are compared with the measurements at 12 m/s but all acquisitions are available for both velocities.

3.1 Analysis of the flow field

On figure 3 are presented the vector plot of the average velocity field. The acquisition grid consists in 27 transverse profiles with 83 measurement points. The use of stream-traces helps in the interpretation of the main velocity pattern.

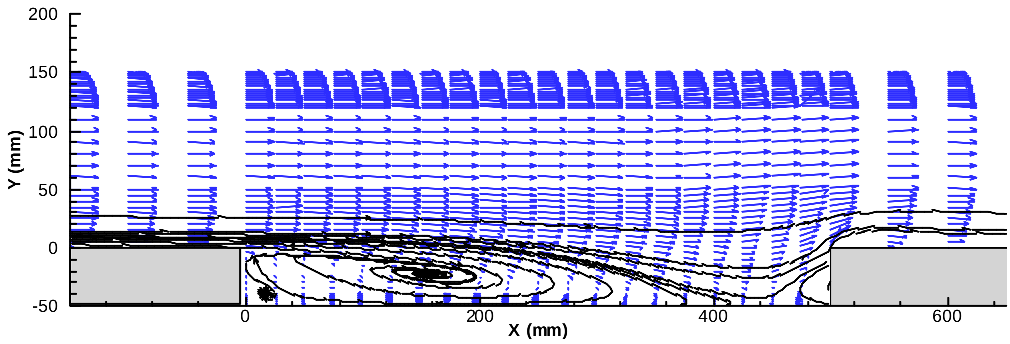


Figure 3. Vectors plot and stream-traces pattern within the cavity (Uo=20 m/s)

The behaviour of the flow field evolves as if it was a closed cavity with shear layer reattachment at the bottom of the cavity : recirculation zones take place within the cavity on each side of a "stagnation zone" with two small corner eddies close to the step faces. Nevertheless, a focus on the region near the wall shows a thin layer of fluid which stops the development of the shear layer (figure 4). The flow, downstream from the first recirculation zone, is submitted to the effects of the second recirculation zone and gives rise to this sub-layer on the whole length of the cavity with a negative axial velocity. In this way, the shear layer is stopped by this sub-layer within the flow field and that gives rise to a stagnation point (zero velocity) approximately 2 mm above the bottom wall (X=400 mm for 20m/s case). There is no reattachment of the shear layer on the bottom wall of the cavity. So, in this configuration, the cavity can be termed "open".

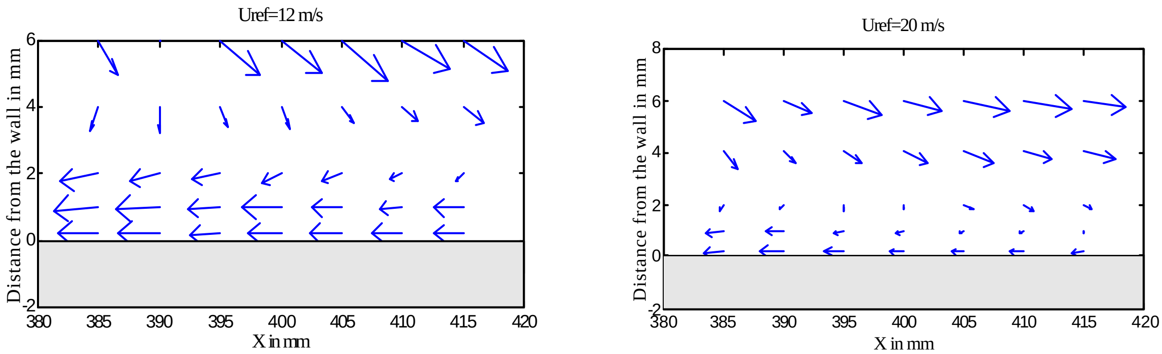


Figure 4. Stagnation zone and sub-layer at 12 and 20 m/s

The wall pressure coefficient $Cp = \frac{p - p_{ref}}{1/2\rho U^2_{ref}}$ (figure 5), acquired by the technical apparatus previously described, shows a "transitional cavity"-like evolution. This cavity flow field type is defined by Plentovich et al. (1993) as a flow field occurring in cavities whose length is between the open and closed configurations.

This characteristic evolution is described (Figure 6) :

"Pressure coefficient increases uniformly from negative values in the vicinity of the front face to large positive values ahead of the rear face".

The wall pressure coefficient behaviour confirms the existence of the sub-layer existence and the lack of reattachment on the bottom wall of the cavity.

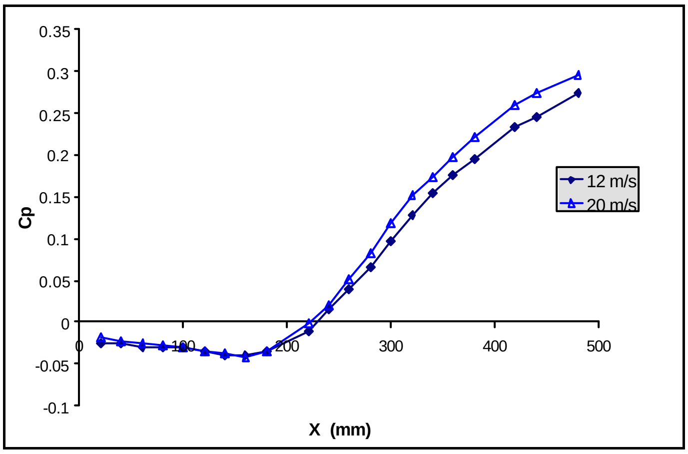


Figure 5. Cp evolution

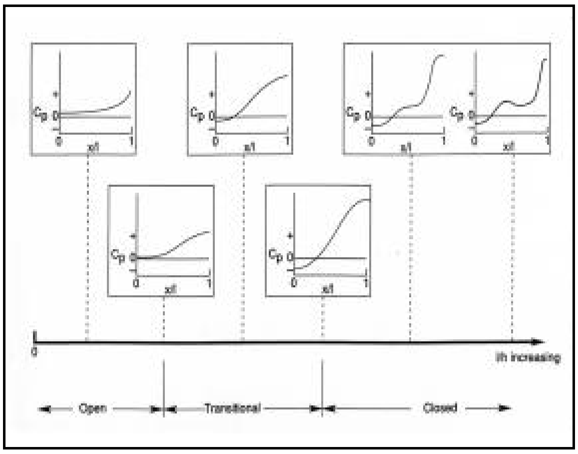


Figure 6. Cp evolution according to Plentovich et al

The separation-reattachment process is characterised by a complex interaction between the separated shear layer and the adjacent flow. The rearward facing step closeness downstream of the shear layer stagnation gives rise to significant perturbations. In order to understand the role played by the rearward facing step and the second recirculation zone, a comparison with the backward facing step flow field is possible. Upstream from the stagnation zone, cavity and BFS flow fields are similar: between the separated shear layer and the wall, a recirculation region exists with a small corner eddy close to the step face. For a backward facing step, downstream of the reattachment, the reattached shear layer gradually transforms back into a boundary layer. Full recovery of the turbulence structure at this level, is known to take some distance (Eaton and Johnson (1980) provide a comprehensive review of subsonic, turbulent flow reattachment for a backward facing step). In that way, the rearward facing step effect could be defined with BFS data comparison Data from Arnould (1998) and Reulet et al. (1999) for a backward facing step in same configuration and same Reynolds number provides a complete data base for testing.
Figure 7 shows the velocity profiles at different locations for cavity and BFS data. The area upstream from the stagnation point seems not to be by the rearward facing step and the second recirculation zone. Velocity profiles for the two configurations are more or less similar.

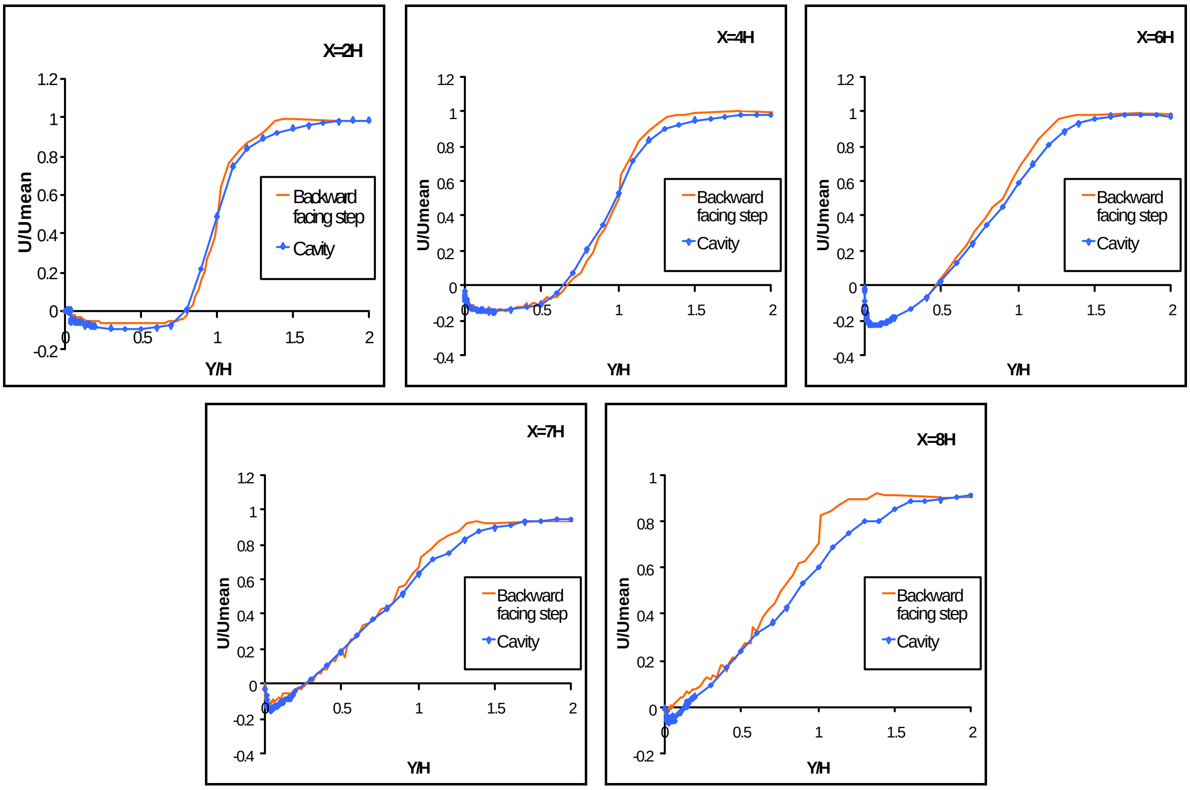


Figure 7. Velocity profiles for cavity and backward facing step

The backflow in the recirculation zone between the separated shear layer and the wall can also be described in both cases for the cavity and the backward facing step flows. Simpson (1983) proposes a description of backflow velocity profile dependent of N and U_N. U_N is the local maximum backflow velocity and N the distance from the wall at which it occurs.

$$\frac{U}{|U_N|} = A\left[\frac{Y}{N} - \log\left(\frac{Y}{N}\right) - 1\right] - 1 \quad \text{for } Y > Y_1 \qquad (1)$$

The sublayer thickness Y_1 is chosen to be 2% of the thickness of the near wall region N.

Figure 8 compares cavity and backward facing step measurements with Eq. (1). Curves for A=0.3 (as suggested by Simpson's measurements) and A=0.235 (as suggested by those of Dianat and Castro (1989)) are drawn.

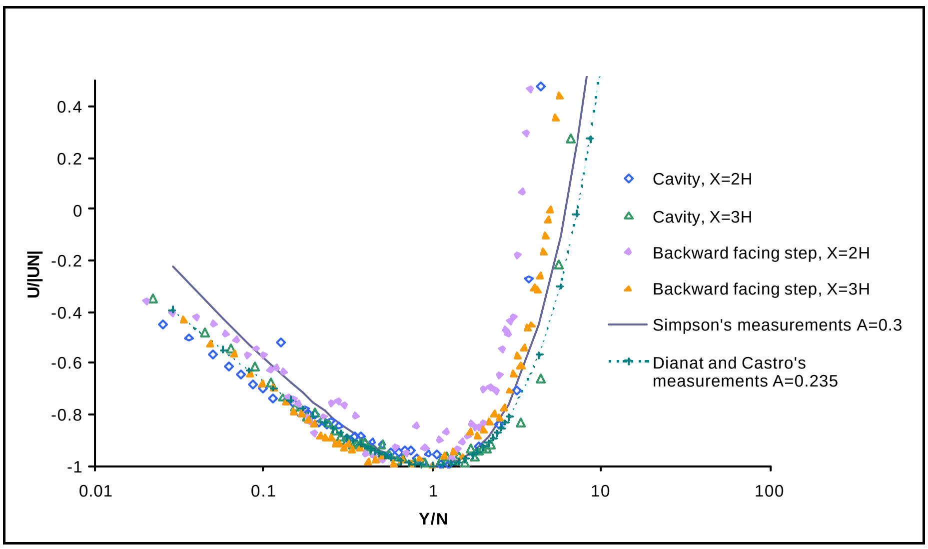


Figure 8. Normalised backflow mean velocity profiles compared with Eq. (1)

In both cases, for Y<N, the results agree very well in particular with Dianat and Castro measurements. The recirculation zone pattern is roughly similar for the cavity flow field and the backward facing step flow field in the vicinity of the wall. For Y>N, there are discrepancies between the two experiment measurements and the theoretical profiles.

3.2 Velocity fluctuations

The detailed fields of the turbulence intensity $I = \sqrt{u'^2 + v'^2}$ are presented on Figure 9. The importance of the turbulence level upstream from the stagnation point (X=400mm) is connected with the influence of the oscillations of the recirculation zone interacting with the shear layer near the separation point. A rapid decrease of the turbulence level in the vicinity of the stagnation zone suggests a significant change of turbulent structures.

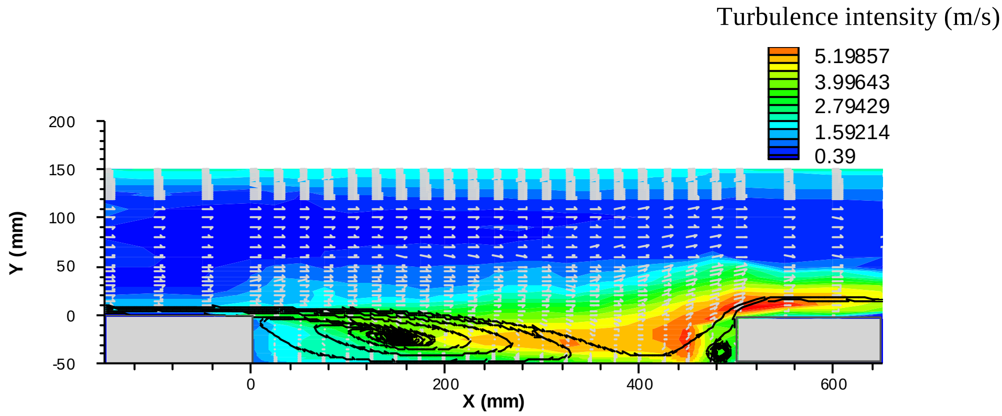


Figure 9. Turbulence intensity and streamlines within the cavity (Uo=20 m/s)

The literature concerning backward-facing steps also describes, in the vicinity of the reattachment point, an important decrease of the Reynolds stress [Chandrsuda and Bradshaw (1981), Troutt et al. (1984)]. Numerous authors have connected this phenomenon to the change of the vortices structure near the wall. Pronchick & Kline (1983) determine that the evolution of the turbulence level near the reattachment zone, for a backward-facing step, is connected to the convection of coherent structures along three paths. Some eddies seem to move immediately downstream while others go first upstream in the recirculation zone direction before progressing downstream. A third path consists, for impinging eddies, in following the step bottom wall upstream into the recirculation zone.
In the present configuration, structures approaching the stagnation zone are submitted to the sub-layer influence towards the first recirculation zone. It is thought also that some eddies move downstream in the direction of the second recirculation zone. In that way, the decrease of turbulence level near the stagnation zone seems linked to a dissociation and a separation of eddies around the stagnation point.

A comparison of Reynolds stress ($-\overline{u'v'}$)between cavity results and Arnould's data for the backward facing step is presented figure 10.
The behaviour of $\overline{u'v'}$ for both configurations is similar and the turbulence intensity is of the same order. In both cases, an important decrease of Reynolds stress is observed close to the stagnation point. In the case of cavity flow, an increase of these fluctuations appears downstream from this point, due to the rearward facing step.

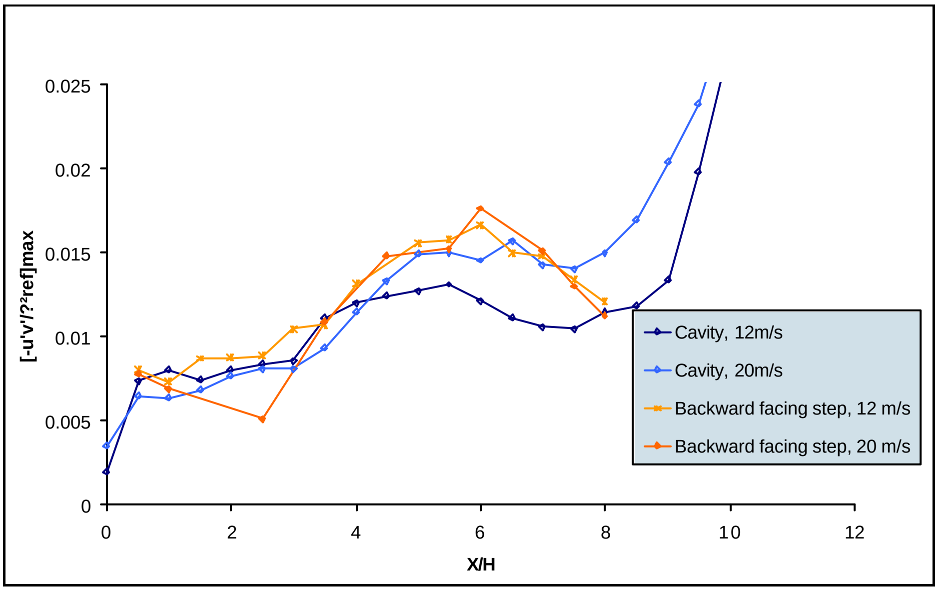


Figure 10. Maximum Reynolds stress for cavity and backward facing step flows

This similar evolution of Reynolds stress quantities upstream from the stagnation zone confirms that the separated shear layer in this area is unaffected by the second recirculation which only influences the second part of the flow, downstream from the stagnation zone.

In spite of a similar pattern upstream from the stagnation, the cavity flow shows a sub-layer of fluid near the wall which seems generated by the rearward facing step perturbation, and, at the same time by the second recirculation zone. Even if the separated shear layer seems shown a similar comportment before reattachment for both flow field, turbulence structures could not follow an identical pattern considering the fluid obstruction on the sub-layer level.

Downstream from the stagnation zone, the flow oscillates : an important increase of the turbulence level is visible on figures 9 or 10. This behaviour, specific to cavity flows, can be connected with the presence of a small third recirculation zone above the rearward facing step (figure 11). The flow, with a negative axial mean velocity at this position, induces a perturbation in the flow field issued from the cavity and shows an influence on the flow exit. While the flow is blocked up, velocity fluctuations increase.

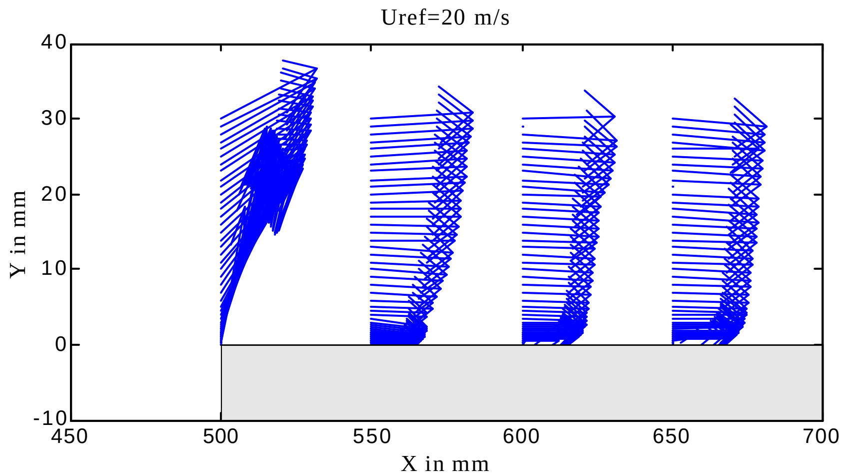


Figure 11. Velocity vectors above the rearward facing step at 20 m/s

Moreover, the flow oscillations near the rearward-facing step seems generated a flow which feeds the sub-layer, all along the wall.

3.3 Spectral analysis

In order to acquire a better understanding of the flow behaviour, energy spectra of axial and transverse velocity components are calculated near the separation point and at the stagnation location.

100000 samples are obtained with a mean sampling frequency of about 3 kHz. An equal-time-spaced signal (Fe=1000 Hz) is reconstructed with a linear interpolation [Ramond and Millan (1999)] and transformed by a classical Fourier transform to obtain the spectra.

Figure 12 shows the spectra calculated on the vertical velocity component downstream from the separation point at a constant height. The main detachment frequency is clearly identified. As the measurement position moves downstream, this frequency decreases because of the pairing mechanism.

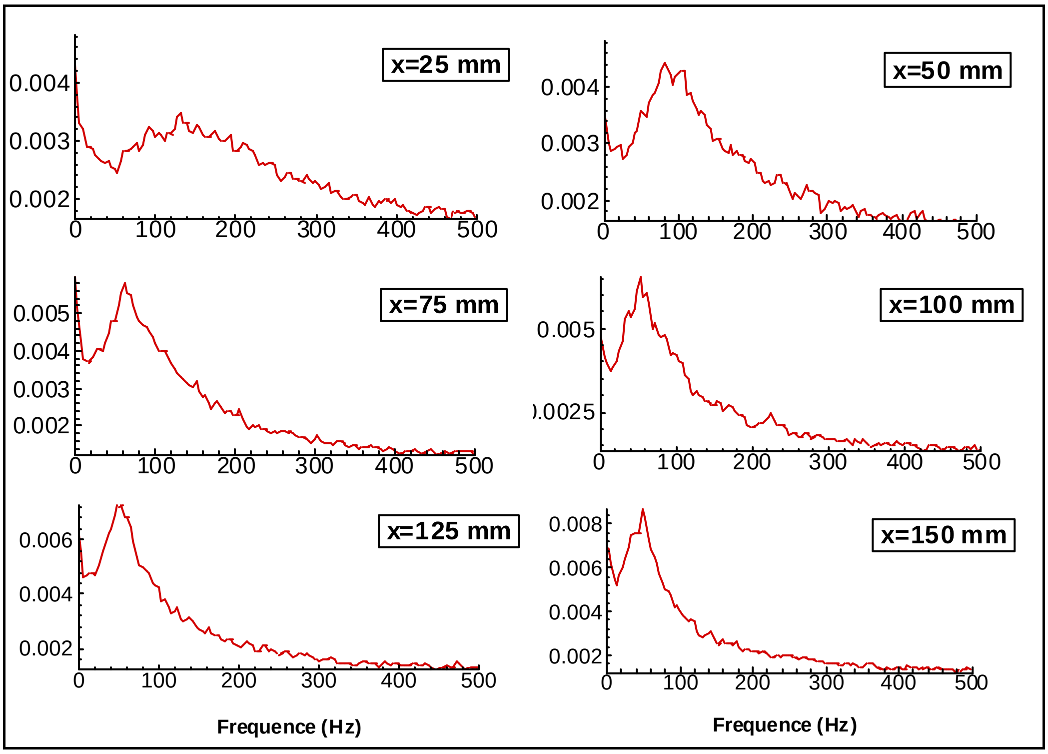


Figure 12. Spectral analysis of the coherent structures shedding

Figure 13 presents spectra of the axial velocity component at different locations near the stagnation zone. The spectra evolution shows a decrease of the velocity fluctuations when approaching the thin sub-layer of fluid moving upstream. Unsteady effects and the fluctuating character of the shear layer and the recirculation zone seem to disappear due to the presence of the sub-layer. The shedding frequency previously detected is no more visible because the turbulence intensity is too high. The coherent structures are submitted to the vortices stretching and create smaller vortices before dissipation. The spectra are characteristic of fully developed turbulence.

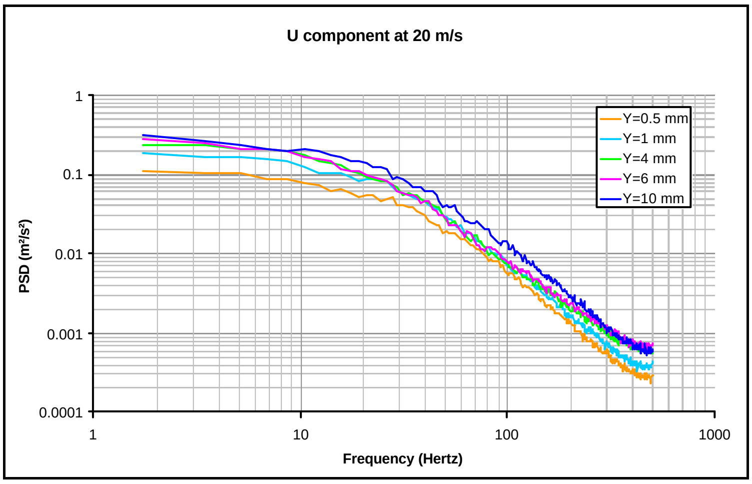


Figure 13. Spectral analysis at the stagnation point axial abscissa (X=400mm)

The shear layer oscillations and acoustic mechanisms described in the literature are missing : no fundamental frequency is amplified, so that no resonance mechanism appears. There is not a distinct peak in the spectrum measured in the cavity flow.

4. CONCLUSION

In the present paper, two-component velocity measurements for a flow over a rectangular cavity under turbulent inlet conditions are described. A detailed database with mean velocity and Reynolds stresses is available for two inlet velocities and compared with data from a backward facing step configuration at similar Reynolds numbers.

The present experiments at low Reynolds number, in a cavity with length-to-depth ratio of 10, shows, that no reattachment of the shear layer occurs on the bottom wall. However a stagnation point exists inside the cavity. The precision of Laser Doppler Velocimetry measurements near the wall shows the existence of a thin sub-layer ($y<2$ mm) which stops the shear layer and prevents the reattachment. The observation of the velocity profiles and turbulence fluctuations in comparison with backward facing step data show an insignificant influence of rearward facing step on the separated shear layer upstream from the reattachment.

A spectral analysis of LDV signals around the stagnation point presents a good agreement with the diminution of velocity fluctuations within the cavity. No resonance mechanism appears.

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