

Experimental investigation of a cavitating backward-facing step flow

G Maurice^{1,2}, H Djeridi¹, S Barre¹

¹Laboratoire LEGI, Domaine Universitaire, BP53 38041 Grenoble CEDEX 9, FRANCE

²Centre National d'études spatiales

E-mail: guillaume.maurice@legi.grenoble-inp.fr

Abstract. The present study is the first part of global experimental work which is intended to produce a refined database of liquid and vapor phases and to improve CFD modeling of turbulent cavitating flows which can occur in rocket engine turbo-pump inducers. The purpose of the present experimental study is to get a better understanding of the dynamics of the liquid phase in a cavitating backward facing step flow and provide a refined database for the physical analysis of interaction between turbulence and cavitation. The backward facing step flow provides us a well-known test case to compare vortex dynamics and a realistic industrial configuration such as backflow in turbo machinery. Experiments were conducted in the hydrodynamic tunnel of CREMHyG at Grenoble, which was especially designed to study cavitating shear flows at high Reynolds numbers. To highlight the liquid phase topology and dynamics such as large vortex structures, free shear layer instability, reattachment wall interaction and reverse flow, the flow is characterized by Laser Induced Fluorescence Particles Image Velocimetry (PIV-LIF) measurements techniques and by Laser Doppler Velocimetry (LDV) techniques using spectral analysis to characterize the vortex shedding dynamics. The liquid phase was analyzed at different cavitation levels corresponding to 1% to 45% of void ratio range inside the shear layer, recirculation area and reattachment zone. The mean and fluctuating liquid velocities are clearly modified by the vapor phase and the scale of the vortical structures tends to be smaller inducing a destructure of turbulence by cavitation.

1. Introduction

The present study was conducted within the framework of research on cavitation in space turbo-pump inducers led by French space agency (CNES) and the rocket engine division of SNECMA. The main objective was to analyze cavitation effects which can occur when the local pressure of the liquid reaches values lower than the vapor pressure. This phenomenon causes erosion damage, vibrations, noise and performance deterioration. Indeed, in the case of inducers, the vapor phase appears on the suction side of the blades as attached sheet cavities (stable or pulsating cavities depending on operating conditions). The vapor phase also appears inside the gap between blades and housing where the flow is sheared, and the configuration corresponds to the separated/reattached flow such as backward facing step flow. In the context of the global effort concerning space turbo-pump development, some efforts have been devoted to study the flow on the real inducer geometry [1], [2] among others. Global behavior was characterized, performance of the inducer was estimated for different cavitation levels and the vapour distribution on the blades was observed [3]. However, the turbulence in the flow and the dynamics of the cavitating structures could not be characterized mainly due to technical



difficulties in performing measurements on a rotating device with a very complex geometry such as that encountered in a spatial turbopump inducer. It should be noted those two-dimensional laboratory geometries (such as venturi) have been tested and designed in order to reproduce the wall pressure field existing on the suction side of the inducers blade [4], [5], [6], [7]. These laboratory geometries leading to a better understanding of the vapor dynamics (occurrence of a re-entrant jet, periodical detachment of the rear part of the cavity, downstream convection of vapor clouds until collapse and periodic interface destabilization) but the unsteady behavior of the flow structures associated with turbulence instabilities is not well understood. That is why, Iyer *et al* [8] studied the influence of developed cavitation on the flow of a turbulent shear layer using Particles Image Velocimetry (PIV) techniques. Their visual observations of the shear layer suggested that the overall formation, growth and convection of the primary and secondary vortex structures are not significantly affected by the presence of the vapour phase and the largest differences between cavitating and non-cavitating cases in the centre of the shear layer consisted in the increase of turbulent fluctuations by about 15%. Bubble collapses increased the turbulence levels, as expected by Laberteaux *et al* [9].

Taking into account these results, one of the aims of the current research was to characterize the turbulent-cavitation relationship through refined measurements of two-phase flow dynamics. It can be noticed that Laser Induced Fluorescence Particles Image Velocimetry (PIV-LIF) has been more and more often used in multiphase flows and especially in cavitating ones. Laberteaux *et al* [9] used this technique to analyze the flow dynamics in the wake of an attached cavitation sheet where the Strouhal number and the Reynolds stress tensor were estimated. An interesting use of PIV-LIF was to couple it with a standard visualization camera [10], [11], [12]. By synchronizing the two techniques, it became possible to simultaneously perform instantaneous velocity field measurements and cavitation structure visualization. Another original PIV technique adaptation for velocity measurement in a cavitating two-phase flow has been used by Vabre *et al* [13], where ultra-fast X-ray imaging was performed using absorbent particles. However, the spatial modification of the vortices due to cavitation was not thoroughly investigated. Aeschlimann *et al* [14] using X-ray attenuation detection investigates the specific length scale of cavitating structures in the turbulent mixing layer for higher void ratio compared to the Iyer *et al* [8] study in order to highlight the physical mechanism of the turbulent agitation due to the vapour phase. Consequently, in the current research, the choice of studying a fundamental case has been made in order to limit the flow complexity in reproducing the specific dynamics of the backflow inducers. Advanced instrumentation is used to characterize the liquid and vapor phase and quantify accurately the turbulent properties of cavitating turbulent flows and a spatio-temporal evolution of vortex structures under several conditions of cavitation. The chosen case was backward facing step flow, with the step height of 51.8 mm for a mean inlet velocity of 11.15 m/s which leads to a fully developed turbulent flow at Reynolds number $Re_h = 570000$.

The main objective of this study is the characterization of the turbulent properties of the liquid phase in presence of vapor phase. The present paper is organized as follows: Section 2 is devoted to the presentation of experimental device, flow configuration and instrumentation. In Section 3, results of liquid phase topology are discussed. The last section presents the conclusions and perspectives.

2. Experimental apparatus

2.1. Water tunnel

Experiments were conducted in the CREMHyG hydraulic research center of Grenoble in a hydraulic tunnel especially adapted to study backward facing step flow. Upstream the section, the flow cross a setting chamber containing honeycomb frames and grids in order to homogenize the flow and dissipate the large scale turbulent structures. Then flow is accelerated through a converging section to attain the proper velocity and pressure at the test section. This converging

section was optimized to avoid detachment and pressure drop overshoot. The test section was 400 mm long and had a rectangular cross section of 80 mm wide (w) and 88.8 mm high (H) and the step height (h) was 51.8 mm which leads to a confined geometry. ($ER = \frac{H}{H-h} = 1.4$, $AR = \frac{w}{h} = 0.64$). The water temperature and the dissolved gas are measured. A degasification protocol was systematically performed before each measurements in order to ensure a minimum value of 3.5 ppm of dissolve O_2 to reproduce the same cavitating conditions. Pressure and flowrate are controlled also using regulation devices.

2.2. Operating conditions

The chosen flowrate, to perform experiments, was $Q = 33$ l/s resulting in a mean inlet velocity above the step of $U_0 = 11.15$ m/s which leads to a fully developed turbulent flow ($Re_h = \frac{U_0 h}{\nu} \approx 5.10^5$). For measurements commodities, the cavitation parameter σ is based on the total pressure at the inlet of the converging section and defined as:

$$\sigma = \frac{P_{ref} - P_v}{\frac{1}{2}\rho U_0^2} \quad (1)$$

Six operating conditions were studied corresponding to the single phase flow (called noncav) and two-phase flow (called inception, streaks and cav1, cav2 and cav3 respectively). Inception was characterized visually and acoustically. The corresponding value and flow situation of this cavitating parameter are presented in Table 1. The operating conditions correspond to different

Table 1. Operating conditions

CASE	$P_{ref}(Pa)$	σ_{ref}
noncav	139720	2.2 ± 0.019
inception	107338	1.736 ± 0.015
Streaks	92612	1.489 ± 0.013
cav1	82622	1.325 ± 0.012
cav2	76819	1.232 ± 0.011
cav3	64227	1.107 ± 0.009

levels of cavitation in the vortical structures of the shear layer. The inception occurs in the small but very energetic streamwise vortical structures, the streaks case corresponds to a full saturation of vapor inside these streamwise structures. The cav1 and cav2 cases correspond to different levels of cavitation inside the bidimensional spanwise structures, until the cav3 where these bidimensional spanwise structures are saturated with vapor. A snapshot of developed cavitation in the shear layer is shown in Figure 1 for the cav2 case. To ensure reproducibility of the flow condition, the inlet velocity profile which is plotted in Figure 2 has been determined using Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry(PIV) measurements for each operating conditions.

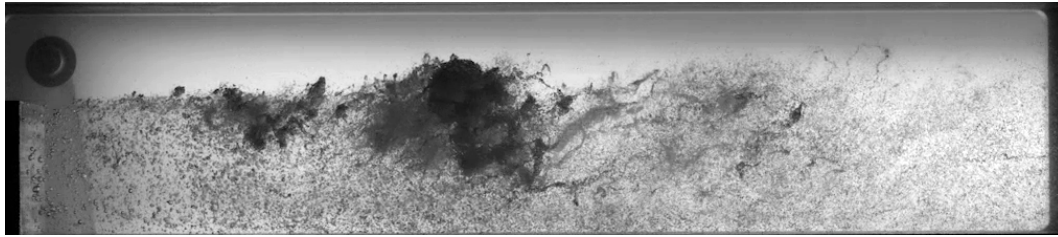


Figure 1. Snapshot of the cav2 case

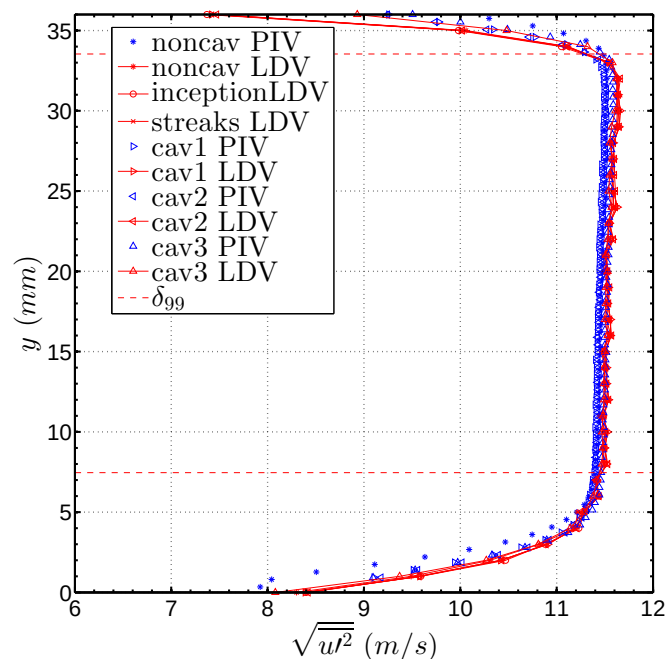


Figure 2. Inlet velocity profile

2.3. Particle Image Velocimetry (PIV) measurements

PIV Velocity measurements were performed in the (X-Y) center section ($Z=0$). To avoid bubble light perturbation the LIF principle was used. Therefore the flow was seeded with rhodamine B colored particles of $20\ \mu\text{m}$ diameter which absorb the green laser light and re-emit in the red wave length (see Figure 3 for rhodamine B absorption- emission properties). A high-pass cut-off filter was placed on the camera lens to get only the particle light. This experimental set-up, also used by Aeschlimann *et al.* [15] permits us to measure the liquid phase velocity field. The images were acquired by a Hamastu 11M HD camera. The lens was a Nikon 105 mm macro and the flow was illuminated with a $2 \times 50\ \text{mJ}$ Nd-Yag New-Wave pulsed laser. The measurement field dimensions were $400\text{mm} \times 88.8\text{mm}$ with resolution of 4000×930 pixels. Dantec software was used for the adaptive multi-pass cross-correlation image treatment algorithm to calculate velocity field. First pass was done with a 64×64 pixels interrogation window and last pass was done with a 16×16 pixels interrogation window with 50% overlapping. The final resolution of the velocity field is 483×106 two components vectors with a grid size of $0.89\ \text{mm}$. The inter-frame delay was $150\ \mu\text{s}$ to ensure a maximum particle displacement of $1/4$ of the initial

interrogation window. 5000 image pairs were recorded at a frame rate of 2.2 Hz, and the statistical convergence has been verified. The whole velocity field converged in 500 samples within a precision of 0.1 m/s for the average and 0.3 m/s for the standard deviation.

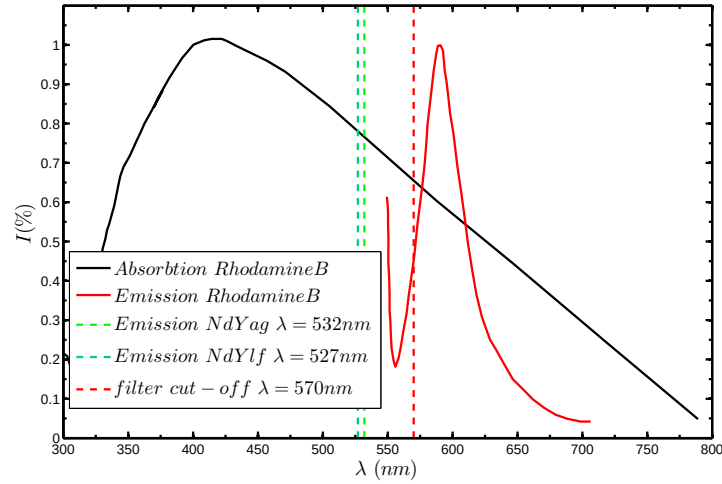


Figure 3. Rhodamine B properties

2.4. Laser Doppler Velocimetry (LDV) measurements

In order to investigate shear layer dynamic and the vortex shedding process, spectral analysis at the edge of shear layer have been performed. Velocity measurements were performed using a two component flow-explorer LDV system distributed by Dantec dynamics. The laser beams wavelength was red $\lambda_r = 660$ nm and infra-red $\lambda_i = 785$ nm. The focal length lens for beam converging device was 500 mm which leads to measurement volume of $0.2 \times 0.2 \times 1$ mm. This measurements volume was moved in the flow by a 3 degrees of freedom automated displacement device with a precision of 0.1mm in all 3 directions. Silver coated glass particles of $10 \mu m$ were used as flow seeding. Ten records of 200000 samples were acquired at the edge of the twophase flow which was determined by a visual criteria on the standard deviation of visualization for the most cavitating case. The mean data rate for these configurations was 10kHz, to perform spectral analysis, the signals have been re-sampled using a linear interpolation method. Measurement positions are $x^* = 0.5 < x^* < x^* = 5$, ($x^* = \frac{x}{h}$)

3. Results

3.1. Flow topology

The global recirculating topology has been investigated and is highlighted by computing the transversal vorticity, defined as:

$$\Omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad (2)$$

Figures 4 and 5 show for the noncav case the entire mean velocity field and a zoom view near the step wall superimposed on the transversal vorticity fields.

As documented by Armaly [16] we found a main recirculating area and a secondary corner vortex.

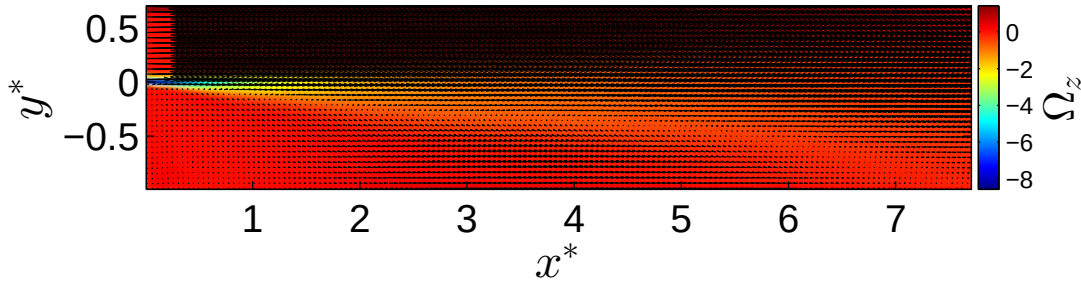


Figure 4. Global velocity field

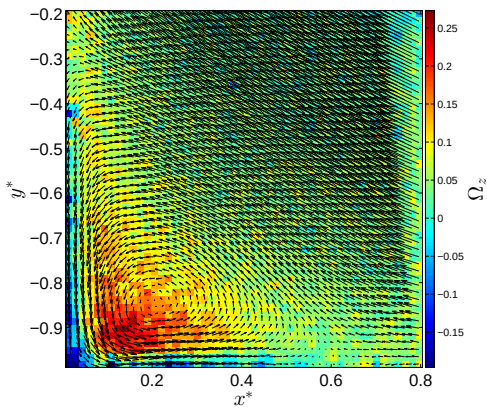


Figure 5. Near step velocity field

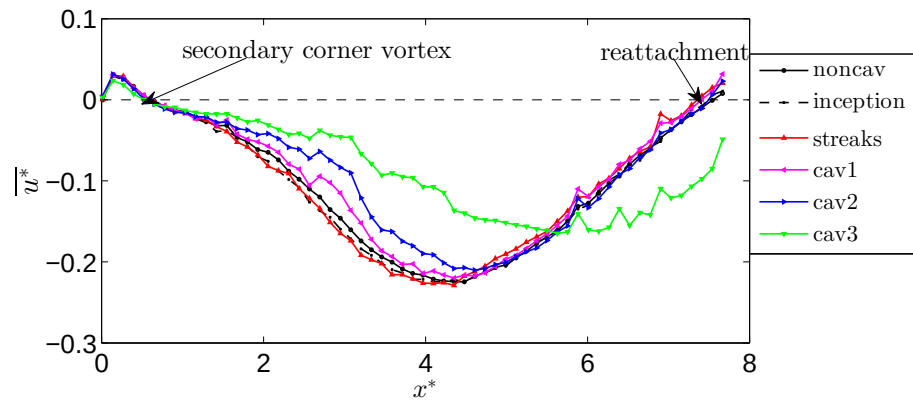


Figure 6. Longitudinal wall velocity

The reattachment length X_r is 7.36 times the step height which is in the range of previous experimental and numerical studies [17],[18],[19],[20],[21],[22],[23],[24]. Figure 6 shows the evolution of the longitudinal velocity at $x^* = -1$ for the different cavitating cases. From noncav case to cav2 case the global recirculating topology is not widely affected by cavitation. The corner vortex and the reattachment point, highlighted by the sign-change of the wall longitudinal velocity, are still at the same location. However for the cav3 case, the reattachment is longer than the measurement field length and exhibits a major change in global flow topology. This is due to a further re-compression of the flow. Moreover the backflow velocity is weaker as cavitation level increases. In fact the motive strength of the backflow is due to the shear layer. When the layer density decreases this motor strength will decrease as well. This result can be shown by the resurgence velocity (vertical velocity component) near the step wall which is also decreasing with cavitation level (see Figure 7). The shear layer topology is also not really affected by cavitation level except for the cav3 case. Figure 8 shows the evolution of the vorticity thickness defined as :

$$\delta_\omega = \frac{U_0}{\frac{\partial U}{\partial y}|_{max}} \quad (3)$$

in the streamwise direction with the cavitation level.

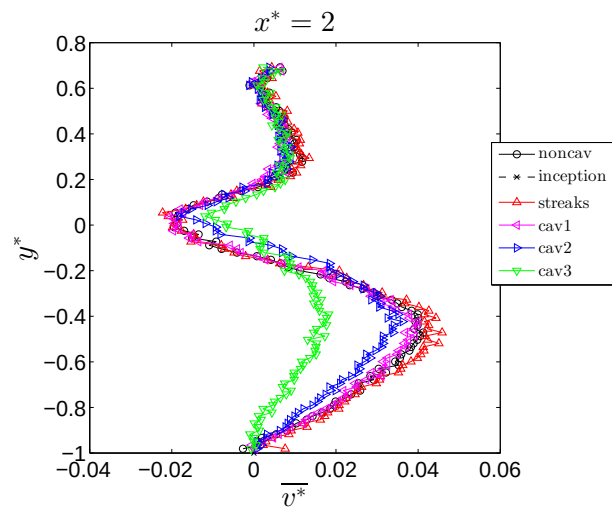


Figure 7. Near step resurgence velocity $\bar{v}$

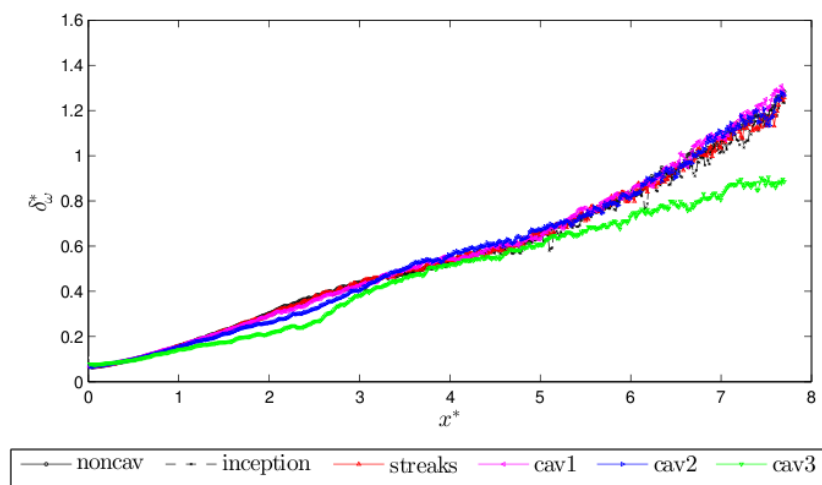


Figure 8. Vorticity thickness in the longitudinal direction

Again the cav3 case shows a different evolution. Where all the cases from noncav to cav2 expand together from $x^* = 5$, the shear layer for cav3 case seems to expand slower. This is why we found a further re-compression and a longer reattachment length. At the beginning of the flow, the effect of the vapor appearance inside the shear layer is to decrease the growth rate. This result is not in agreement with Aeschliman *et al* [15] who worked on a free 2D cavitating shear layer. This may be due to the stronger backflow ratio which can cause vortex breakdown.

3.2. Shear layer scale and dynamics

In the shear layer, vortices travel and expand. To characterize the size of these vortices, the integral scale of velocity fluctuations L_{yu} is calculated as defined below.

$$L_{yu} = \int_{-h/2}^{h/2} R_{uy}(\delta_y) d\delta_y \quad (4)$$

Where $R_{uy}(\delta_y)$ is spatial cross-correlation velocity fluctuations defined as:

$$R_{uy}(\delta_y) = \frac{\overline{u(y_0)'u(y_0 + \delta_y)'}}{\sqrt{\overline{u(y_0)'^2}} \cdot \sqrt{\overline{u(y_0 + \delta_y)'^2}}} \quad (5)$$

To compare the vortex sizes to the shear the layer scale, the integral L_{yu} is normalized by the local vorticity thickness. The results plotted on Figure 9 show a systematic decrease of integral scale with the cavitation level. The velocity fluctuations seem to be less coherent in presence of cavitation. This behavior explains the continuous decrease of integral scales. The cav3 case still exhibits a different behavior which is not yet clearly understood but may be due to a change in vortex shedding process. This process has been identified in a previous study on pressure fluctuation dynamic [25] and also observed in a venturi flow by Saito *et al* [26]. The power

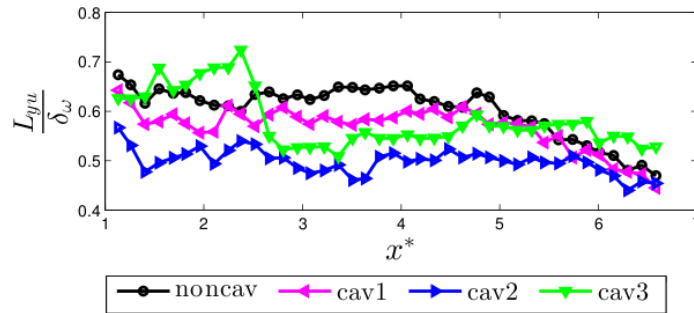


Figure 9. Local integral scale of velocity fluctuation

spectral densities obtained from LDV measurements are plotted for two positions $x^* = 1.5$ and $x^* = 4.5$ on Figure 12. They show a dominant frequency for each evaluated operating case. This dominant frequency is associated with the vortex shedding process which occurs in the shear layer and can be attributed to Kelvin-Helmholtz vortical structures. The Strouhal number corresponding to the dominant frequency defined as:

$$St_h = \frac{fh}{U_0} \quad (6)$$

is significantly decreased with cavitation level ($St_h = 0.76$ for noncav, $St_h = 0.64$ for cav1, $St_h = 0.54$ for cav2, $St_h = 0.27$ for cav3). This observation helped us better understand the effect of the cavitation on the structures of the shear layer. If the vortical structures and their shedding frequency are smaller, this means that the spatial interval between vortices is bigger. The probability to create a vortex from the shear flow is proportional to the shear layer strength which is widely affected by the shear layer density. Since the cavitation bubbles appear, migrate and collapse in the shear layer, the shear layer density will decrease with cavitation level affecting the vortex shedding frequency.

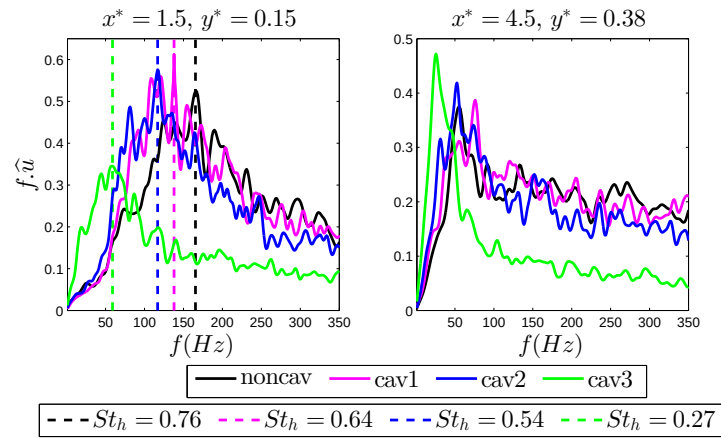


Figure 10. Power spectral density of velocity fluctuation for two positions $x^* = 1.5$ and $x^* = 4.5$

3.3. Fluctuations and turbulence characterization

Two dimensional turbulent kinetic energy k_{2D} is calculated using the expression below, considering that the third components variance $\overline{w'^2}$ is approximately equal to the second $\overline{v'^2}$ as shown by Piirto *et al* [27] for a monophasic case.

$$k_{2D} = \frac{1}{2}(\overline{u'^2} + 2\overline{v'^2}) \quad (7)$$

The maximum 2D turbulent kinetic energy per section is plotted on Figure 11. For the noncav case the turbulent kinetic energy increases until $x^* = 4$ then it starts to decrease corresponding to the faster expansion of the shear layer (see Figure 8). As cavitation level increases the 2D turbulent kinetic energy start to decrease.

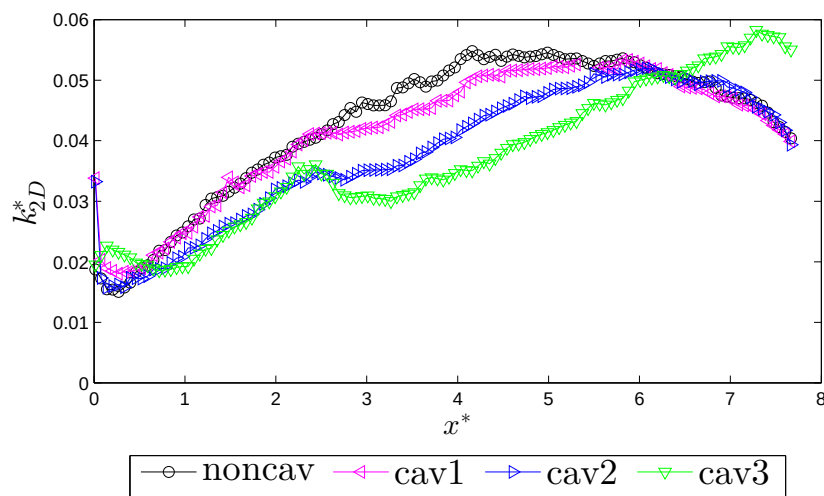


Figure 11. 2D turbulent kinetic energy

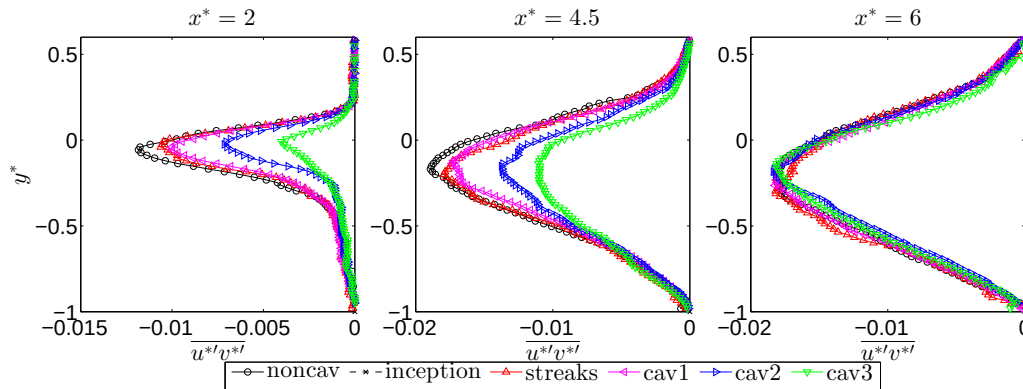


Figure 12. $\overline{u'v'}$ Reynolds stress

On Figure 12 the Reynolds stress corresponding to the main shear direction $\overline{u'v'}$ is plotted for three different sections $x^* = 2$, $x^* = 4.5$ and $x^* = 6$. This Reynolds stress is continuously decreased with cavitation level and in all the sections. It has been demonstrated in the previous part that the 2D vortical events, which are the main drivers for $\overline{u'v'}$ Reynolds stress and k_{2D} , are less frequent in the shear layer when cavitation level increases. This is why we found a deficit of 2D turbulent kinetic energy (Figure 11) and a deficit of $\overline{u'v'}$ in the multiphase area. The decrease of both $\overline{u'v'}$ and 2D turbulent kinetic energy induces that the correlation coefficients between u and v components is approximately conserved this means that the fluctuations are still due to vortical events but they are less frequent. In fact the effect of cavitation on turbulent fluctuations is to destructure vortex shedding processes. It is well known that cavitation increases velocity fluctuations due to bubble oscillations and collapses [28]. Since the effect of cavitation on this flow is to decrease 2D turbulent kinetic energy the third component should be increased with cavitation appearance.

4. Conclusion

Velocity measurements were performed in a cavitating backward facing step flow. 2D PIV- LIF was used to investigate the effect of cavitation on the mean and fluctuating velocity field. We used 2D LDV measurements to study the shear layer dynamic and identify vortex shedding frequency. The main results is that the mean velocity field was not clearly affected by cavitation level until the shear layer was fully saturated with vapor. At this point the shear layer growth rate decreases and the reattachment length increases resulting in further re-compression. This scenario tends to start with lower cavitating level but does not completely occurs. Concerning the shear layer structures and dynamics. The vortical structures scale tends to be smaller and their shedding frequency decreases. This means that spatial interval between vortices increases with cavitation. Finally the effect of cavitation is to rarefy vortex birth and diminish the coherence of existing shear layer vortices. This effect tends to decrease 2D velocity fluctuations and Reynolds stresses. Further investigation will be performed to investigate and determine the evolution of the third component and estimate its contribution to kinetic energy budget.

5. Acknowledgements

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