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Vortex Dynamics and Entrainment Mechanisms in Low Reynolds Orifice Jets

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Abstract : Classical planar 2D-PIV measurements and time-resolved visualizations enriched by low-level processing are used for the reconstruction of the Kelvin-Helmholtz vortex passing in the near field of a circular and a 6-lobed orifice jet flow. In the circular jet, the entrainment is produced in the braid region, being interrupted in the presence of the Kelvin-Helmholtz ring. The latter compresses the streamwise vortices and alters their self-induction role. Conversely, the 6-lobed orifice geometry allows the cutting of the Kelvin-Helmholtz structures into discontinuous ring segments. Consequently, into these discontinuity regions streamwise large scale structures are developing. These streamwise structures are permanent thus controlling and enhancing the jet entrainment which is not altered by the Kelvin-Helmholtz structures passing.

Keywords : Jet flow, Kelvin-Helmholtz vortex, Streamwise vortex, Image processing.

1. Introduction

The dynamics of the vortical structures developing in the initial region of jet flows has been extensively studied since the seventies, in a wide range of Reynolds numbers (Widnall and Sullivan, 1973; Brown and Roshko, 1974; Winant and Brownant, 1974; Browand and Laufer, 1975; Konrad, 1977; Yule, 1978; Zaman and Hussain, 1980; Hernan and Jimenez, 1982; Bernal and Roshko, 1986; Liepmann, 1991; Liepmann and Gharib, 1992; Loiseleux and Chomaz, 1999). The richness of this research field is of such nature that there has been not found yet an overall agreement concerning the different arisen issues.

It has been shown that the dynamics of the circular jet flow is mainly controlled by ring-like vortical structures (Liepmann, 1991; Liepmann and Gharib, 1992; Loiseleux and Chomaz, 1999). These vortices generated by a Kelvin-Helmholtz type instability (K-H) at the separation surface between the jet and its ambiance were found to play an important role in the shear layer entrainment and mixing phenomena (Zaman and Hussain, 1980; Hernan and Jimenez, 1982).

As these structures move downstream, the vortical rings merge in a vortex pairing process contributing to the growing and expansion of the mixing layer (Winant and Brownant, 1974; Ho and Gutmark, 1987). This process continues downstream until the resultant vortex rings become too large and break down into small scale vortices. The location of this structural breakdown mark-up the end of the potential core and the start of the transition region (Winant and Brownant, 1974; Liepmann, 1991; Liepmann and Gharib, 1992). It has been shown (Browand and Laufer, 1975; Yule, 1978; Liepmann and Gharib, 1992; Suprayan and Fiedler, 1994) that the turbulent structure of the circular jet becomes three-dimensional before the extinction of the potential core, with the apparition of new counter rotating vortex filaments that are connecting two K-H rings. These streamwise structures emerge between the K-H vortex rings. They are located in the braid region between two successive rings connecting the inner part of the downstream ring with the outer part of the upstream ring. In the cross-sectional planes they appear as mushroom-shaped structures and are visible on both types of images representing the ring structures and the braid regions. It is shown by Liepman and Gharib (Liepmann, 1991; Liepmann and Gharib, 1992) that their number increases with the initial Reynolds number.

It has been documented that streamwise structures and K-H vortex pairing are connected (Liepmann, 1991; Liepmann and Gharib, 1992; Romano, 2002). Indeed, the K-H vortex pairing results in successive expansions and contractions that produce an azimuthal variation of the radial velocity. Streamwise vorticity sheets are subsequently appearing at the same time in the rings and in the braid. Through a local induction mechanism, the azimuthal instabilities in the rings are attenuated and the braid is subjected to azimuthal perturbations which are out of phase with the azimuthal instabilities in the K-H rings. They are stretched and condensed, resulting in counter rotating streamwise filaments. These new structures move upstream subjected to the induced velocity of the upstream K-H ring. The latter exhibits azimuthal deformations as spatial waves that are both in-plane and out-of-plane with the ring. However, streamwise structures were also observed to exist independently of K-H rings pairing in circular jets (Suprayan and Fiedler, 1994). Suprayan and Fiedler (Suprayan and Fiedler, 1994) are explaining that their birth is a complex phenomenon that is not completely understood yet.

Liepmann and Gharib (Liepmann, 1991; Liepmann and Gharib, 1992) show that the streamwise structures may attain high energetic levels compared to the K-H vortices, having at the end of the potential core a predominant role in the global entrainment process.

It is to be noted that, since the sixties, much before the findings of Liepmann and Gharib (Liepmann, 1991; Liepmann and Gharib, 1992) on the important part played by the streamwise structures in mixing, artificial streamwise vorticity generation methods are used in aeronautics and combustion in order to improve mixing (Kuchar and Chamberlin, 1980; Paterson, 1984; Presz et al., 1986, 1994 and 2002; Zaman, et al., 1994; Zaman, 1996a, 1996b, 1999 and 2003; Ramesh et al., 2006). The currently used passive generators of streamwise vortices are small tabs or chevrons placed at the nozzle exit. Each tab generates local shear resulting in a pair of counter rotating streamwise structures which are improving mixing. The lobed nozzle is another efficient mixing device (Belovich and Samimy, 1997; Yuan, 2000; Hu et al., 2000, 2001, 2002 and 2004). Each lobe is the location of a pair of large scale streamwise structures having the size of the lobe. All these structures provide a strong entrainment in the troughs regions and strong expansion in the lobes regions allowing to multiply up to four times the amount of fluid entrained in the potential core region in comparison with a circular jet (Nastase and Meslem, 2007).

There is one obvious piece of information emerging throughout all these studies: the streamwise structures sustain the mechanisms of the entrainment process. In the circular jet the K-H rings seem to play an indirect part in this process since their passage and interaction are generating streamwise structures (Liepmann, 1991; Liepmann and Gharib, 1992; Suprayan and Fiedler, 1994).

However, there are some questions arising about the direct part of the K-H vortices in the entrainment mechanisms. In the particular case of the asymmetric jet, the question we tried to answer through the present study is: are the K-H vortices still playing a significant part in the entrainment mechanisms when passive generators of streamwise vortices are used?

In order to elucidate these issues we combined two experimental techniques allowing the spatio-temporal analysis of the two types of vortices. This analysis was conducted for two orifice jets, from one baseline axisymmetric orifice and from one asymmetric daisy-shaped lobed orifice having the same area and inlet flow rate.

We are taking advantage on the development of the high speed visualization techniques allowing high acquisition frequencies in order to capture the dynamics of the vortical structures. A comparison between images from non time-resolved PIV measurements and from time-resolved visualizations, using a low level image processing algorithm, allows a quantitative analysis of some phenomena.

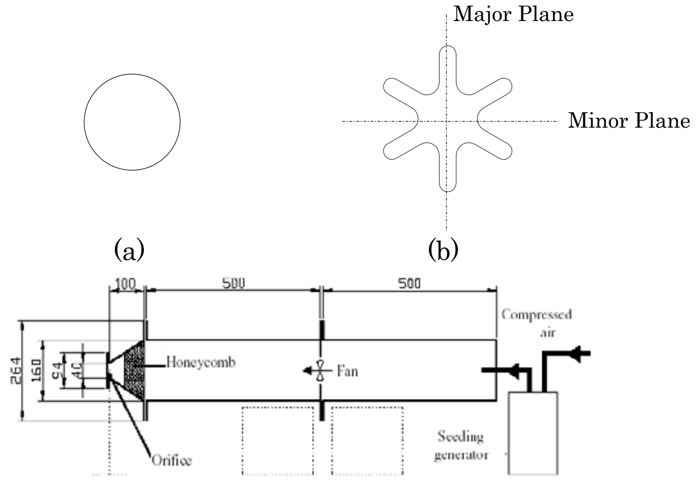
2. Exit Conditions and Experimental Technique

The two studied air jets are generated from a circular orifice (Fig. 1(a)) and a 6-lobed daisy orifice (Fig. 1(b)). The orifices have the same equivalent diameter $D_e = 10$ mm and are built-up from aluminum sheet with 1mm in thickness. The air jet experimental facility (Fig. 1(c)) consists of an axial miniature fan placed inside a metallic pipe having 1.00m in length and 0.16m in diameter. A convergent and a honeycomb were placed at the end of the pipe in order to reduce the turbulence level at the nozzle exit.

The inlet flow rate for the two jets is 7.57 $10^{-5} \pm 3$ %. The initial exit Reynolds number based on the centerline exit velocity and the equivalent diameter is on the order of 800 for both jets.

The exit profiles of the streamwise velocity are presented in Fig. 2. In the two planes of the lobed jet, the profiles display a switching over phenomenon, appearing close to the jet exit. In Fig. 2(b), in the minor plane of the jet, the streamwise velocity profile is twice as large as the one on its major plane. This switching-over phenomenon is associated to a particular dynamics which may appear in the asymmetric jet flows (Zaman et al., 1994; Zaman, 1996a, 1996b and 1999).

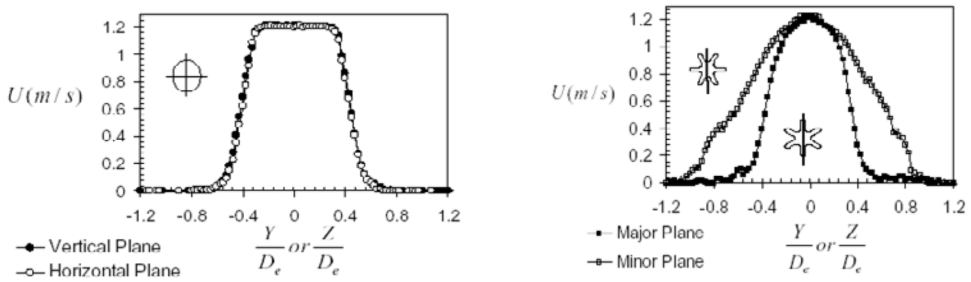
Mean velocity fields measurements employed a two-dimensional Dantec Laser Doppler Anemometer (LDA) system. The LDA system is compact and has two solid lasers: one ND:YAG of 25 mW (532 nm) and one Sapphire of 22 mW (488 nm). The sampling time during measurements was in the range of 60 to 100 s and the mean data rate ranged between 0.5 to 5 kHz depending on the flow velocity at the measurement point. The measuring volume at the lasers beam intersection is 0.04 × 0.045 × 0.378 mm large. The probe was mounted on a three-dimensional traverse system with the ranges on the *X*, *Y*, and *Z* axis, of 690 mm, 2020 mm and 690 mm respectively, and the movement resolution and reproducibility of 6.25 μm. The data were acquired on a grid in the (*YZ*) plane at each *X* location. The grid spacing varied from 0.25 mm to 2 mm with the streamwise distance *X*.



(a) (b)

(c)

Fig. 1. Orifice geometries: (a) Circular, (b) Daisy-lobed, (c) Air jet facility sketch.



(a) (b)

Fig. 2. Streamwise velocity exit profiles: (a) Circular jet, (b) Daisy-lobed jet.

On the other hand, Particle Image Velocimetry (PIV) was employed to acquire instantaneous spatial distribution of the in-plane velocity in the transverse planes at the jets exit. The PIV Dantec system was composed of a high resolution Flow Sense M2/E CCD camera of 10^6 pixels and a NewWave Gemini of 120 mJ laser. The acquisition frequency of the PIV system was 15 Hz. The images calibration gave a spatial resolution of 26.8 µm per pixel which corresponds to a 42.8×31.7 mm^2 field of view. In each plane, a number of 805 image couples were acquired and processed through an adaptive multi-grid correlation algorithm handling the window distortion and the sub-pixel window displacement. In this multi-grid approach, the prediction-correction method was validated for each grid size if the signal to noise ratio of the correlation was above a threshold of 1.1. In average, less than 2 % of the vectors are detected as non valid and are corrected by using a bilinear interpolation scheme. The final grid is composed of 32×32 pixels^2 size interrogation windows and overlapped by 50 % leading to a vector spacing of 37.39 pixels which represents a spatial resolution of 1 mm. A systematical inspection of the particle displacement histograms showed a bimodal distribution (no peak locking) due to sufficient pixels number associated to a tracer particle (between 3 and 5 pixels). In both cases of the LDA and PIV measurements, the air jet flows were seeded with small paraffin oil droplets, of 1 to 3 µm in diameter, provided by a liquid seeding generator.

In order to approach the global dynamics of the studied flows, high speed visualizations in the streamwise and transverse planes were performed. The visualizations were performed using a CMOS Nanosense MKII camera and a 4W Nanopower laser providing a 795 nm laser sheet. The acquisition frequency of the visualization system could attain up to 5 kHz for a 512×512 pixels^2 window. The dynamic range of the gray scale levels is encoded in 8 bits corresponding to 256 levels. Contour detection and temporal analysis of characteristic quantities extracted from contours allow a better understanding of the vortical phenomena. This approach was validated by a spectral analysis of the streamwise velocity signal recorded from a hot wire placed in the shear layer of the flow.

3. Results and Discussion

In Fig. 3, a high speed visualization images of the cross plane at three axial distances $X = 1D_e$, $X = 2D_e$ and respectively $X = 3D_e$ are presented. In the circular jet a continuous K-H ring is clearly visible at $X = 3D_e$. As it has been suggested in the literature (Liepmann, 1991; Liepmann and Gharib, 1992) this ring seem to “crush” the three streamwise structures which are visible as early as $X = 1D_e$. The marks of these structures on the top of the ring correspond, as shown by Liepmann and Gharib (Liepmann, 1991; Liepmann and Gharib, 1992), to the streamwise structures located downstream the ring, in the braid, and which are rolling on this ring.

The images of the daisy-shaped jet (Fig. 3(a)) confirm the axis switching phenomenon previously noted on the exit streamwise velocity profiles of this jet flow (Fig. 2(b)). At $X = 1D_e$ one could observe on the flow periphery, on the minor axes of the orifice, the presence of streamwise structures as small lobes oriented towards the exterior of the flow. These structures grow up in the detriment of the initial lobes imposed by the orifice geometry.

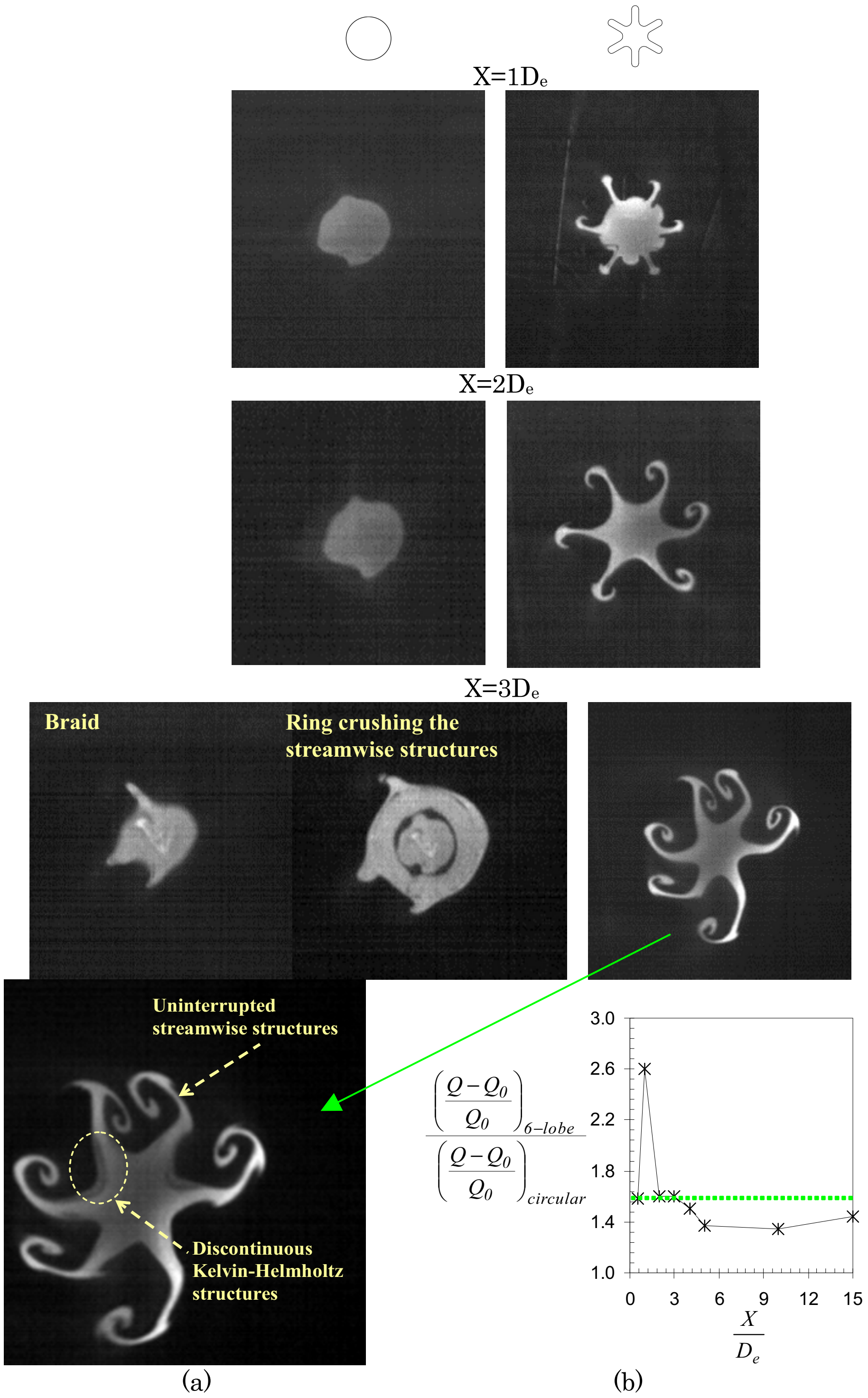
These initial lobes are completely disappearing at $X = 2D_e$ where the jet flow displays again a daisy shape twisted with 45° from the original orifice position. At $X = 3D_e$, it could be observed on the corresponding images, the coexistence of the streamwise structures with K-H “ring segments”. This discontinuity of the K-H structures in the daisy-shaped jet flow, also observed by Mao et al. (Mao et al., 2006) in the near wake of a lobed mixer, could be an essential aspect in the development of the streamwise structures and in the resulting mixing efficiency (Fig. 3(b)).

In the lack of a time-resolved PIV system, and in order to gain insight into the previous structures dynamics, we relied on time-resolved visualizations enriched with low-level image processing. This technique gives the temporal evolution of geometrical characteristics of the jet flow in the streamwise and transverse planes. It is possible afterwards, through a spectral analysis, to identify the coherent instability frequencies.

Black and white images are necessary for the contour identification image processing. The binarization of the original images is obtained through a threshold procedure. All the pixels having a grey level value superior to the chosen threshold value are colored in white while the pixels having a grey level value less or equal the threshold value are colored in black. This way, as shown in Fig. 4(b), the images are transformed such the flow region becomes white and its ambiance become black. The transition between black and white regions is then located by detecting pixels which have large variation of intensity gradient in order to draw the corresponding contour (Fig. 4(c)).

A fundamental frequency equal to 80 Hz is detected in the shear layer of the circular jet at $X = 1D_e$. This frequency appears on the hot wire streamwise velocity signal as on the circular jet transverse diameter signal D_{TR} (Fig. 2(a)). D_{TR} is obtained by low-level processing of time resolved images on a period of 2s.

In the same way, in the daisy-shaped jet, the fundamental frequency of 140 Hz on the streamwise velocity spectrum at the lobe peak, agrees with the one of the daisy transverse diameter D_{TD} (Fig 2.(b)).



(a) (b)

Fig. 3. (a) Time-resolved visualizations in the transverse planes, (b) Axial evolution of the normalized entrained flow rates.

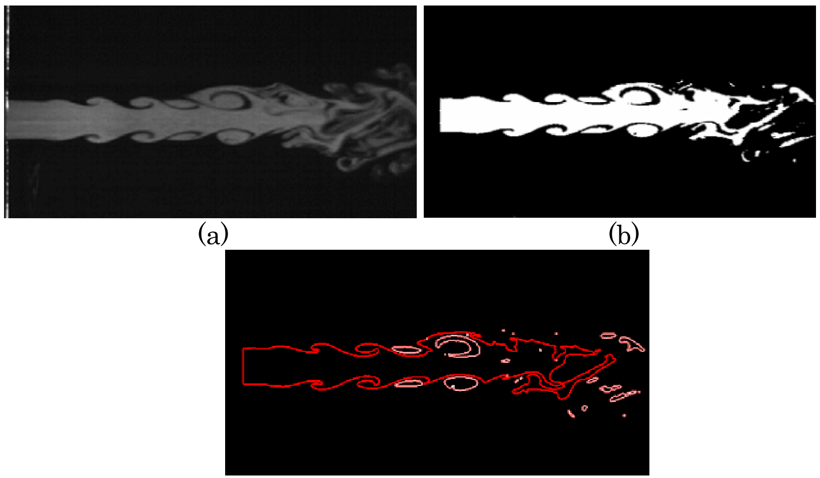
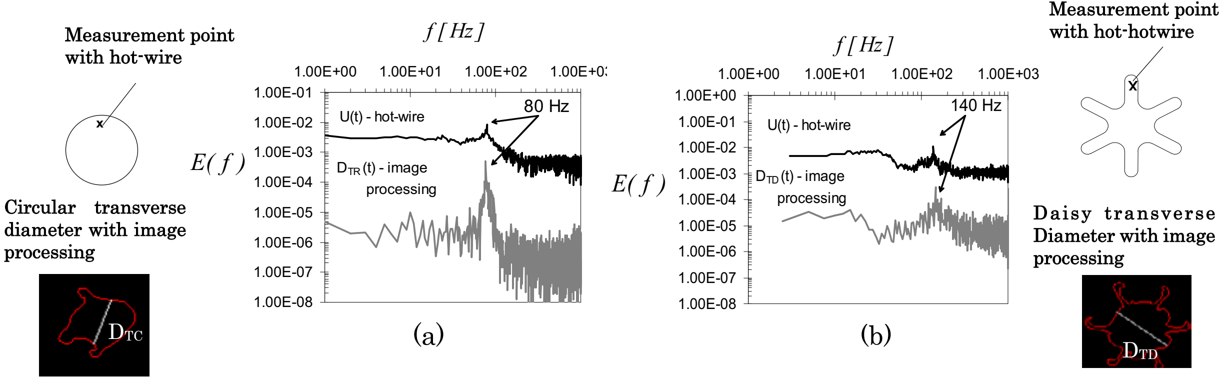

(a) (b) (c)

Fig. 4. Example of image processing in the streamwise plane of the circular jet: (a) Original image, (b) Thresholded image, (c) Identified contour.



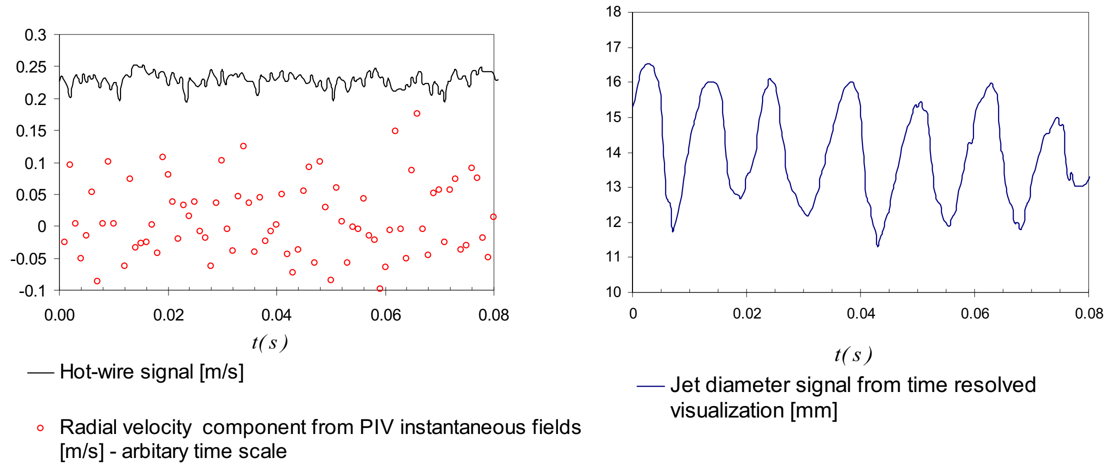
(a) (b)

Fig. 5. Comparison of the streamwise velocity spectrum and of the temporal variation of the jet dimension : (a) Circular jet, (b) Daisy.

The two signals – from hot-wire measurements and image processing – are qualifying the same periodical phenomena of the K-H structures detaching but the variation of the spectra obtained from the image processing is larger than those obtained by hot-wire. As reported by the literature (Jorgensen, 1971) the hot-wire measurement of the normal velocity component in three-dimensional flows is contaminated by the tangential and binormal velocity components. In our case (Fig. 6(a)) the jet's radial component of the velocity measured by PIV attains more than 50 % of the signal from the hot-wire. This way, the radial velocity component may be considered as an important pollution source for the normal velocity component detection by the hot-wire sensor.

Moreover, it is well-known that at very low velocities the heated wire can cause a relatively significant vertical movement of fluid due to buoyancy effects on the lower density fluid adjacent to the wire. This results in a change in the effective velocity around the wire (Collis and Williams, 1959; Christman and Podzimek, 1980).

These two contamination sources should be considered together with the intrusive nature of the hot-wire itself. In our case, probe's length (3 mm) is on the same order as the detected K-H structures thickness (about 4 mm for the circular jet and about 1 mm for the daisy jet). All these contamination sources explain the noisy nature of the hot-wire signal. Consequently the K-H passing frequency peaks on the spectra are relatively reduced. Contrary, the signal from image processing is not noisy. In the same time the temporal variation of the jet's diameter is almost harmonic (Fig. 6(b)) and the proposed method is rendered very robust for this type of detection.

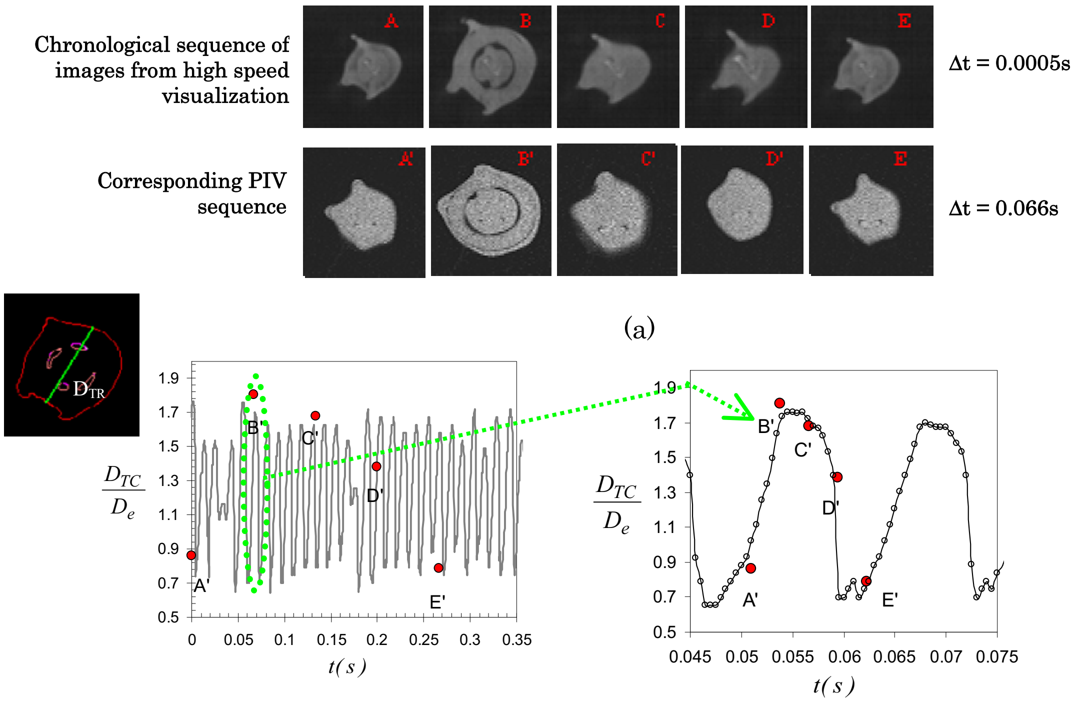


(a) (b)

Fig. 6. (a) Velocity signals from hot-wire and PIV measurements, (b) Jet Diameter signal from image processing, Round jet X = 1D$_e$.

The acquisition frequency of the PIV system being 15Hz, the detected periodical phenomena are not covered. However, through a comparison between PIV images and chronologic time-resolved visualization images (Fig. 7(a) and Fig. 8(a)), it is possible to reconstruct a pseudo time-resolved PIV sequence as indicated in Figs. 7(b) and (c) for the circular jet, and in Figs. 8(b) and (c) for the daisy jet.

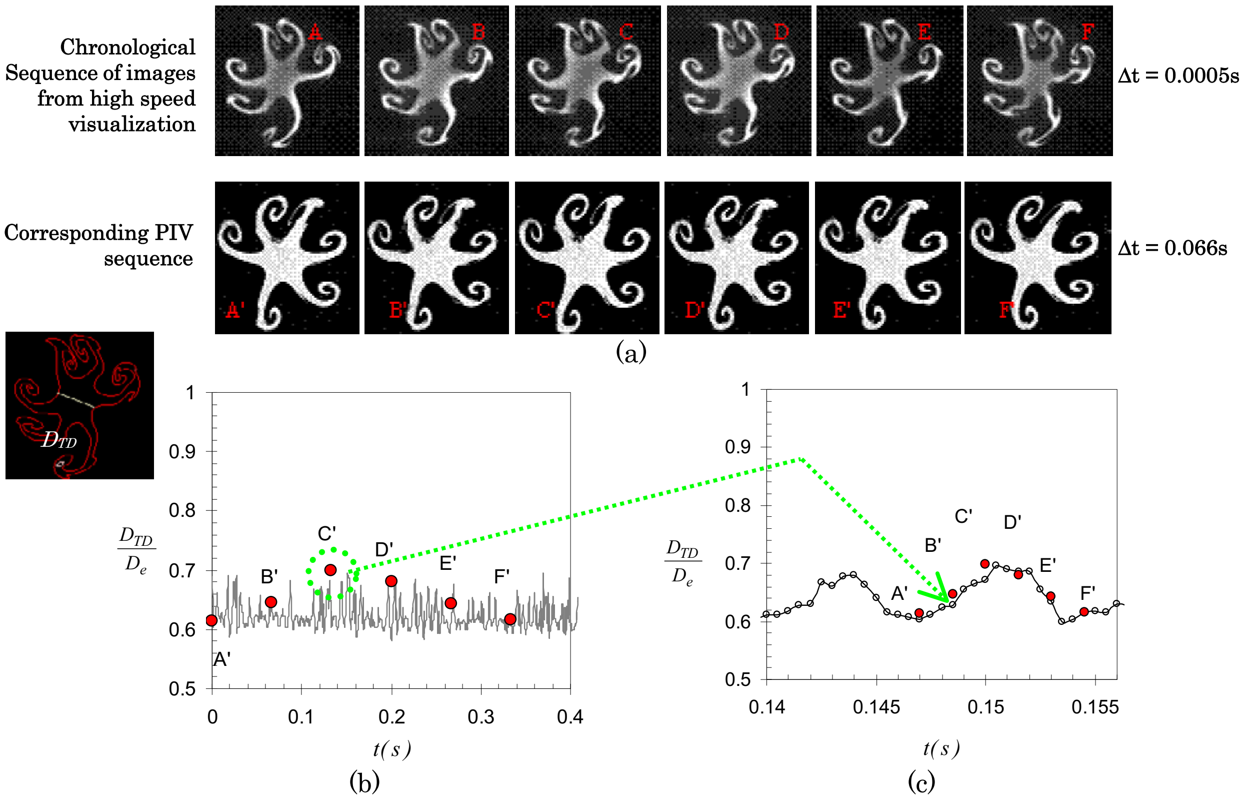
The instantaneous velocity fields corresponding to a period of the K-H structure passing was obtained by the previous reconstruction. These fields allow the characterization of the jet flow dynamics throughout this period. We represented in Fig. 8. for each jet and for each image sequence, the angular variation of the radial component of the velocity at two radial distances: $r = 0.6D_e$ and $r = 1.2D_e$. If in the circular jet (Fig. 9(1a)) the K-H ring controls the sign of the radial velocity, it is not the same for the daisy-shaped jet (Fig. 9(1b)) in which entrainment and expansion coexist permanently, in the presence or the absence of a K-H structure.



(a)

(b) (c)

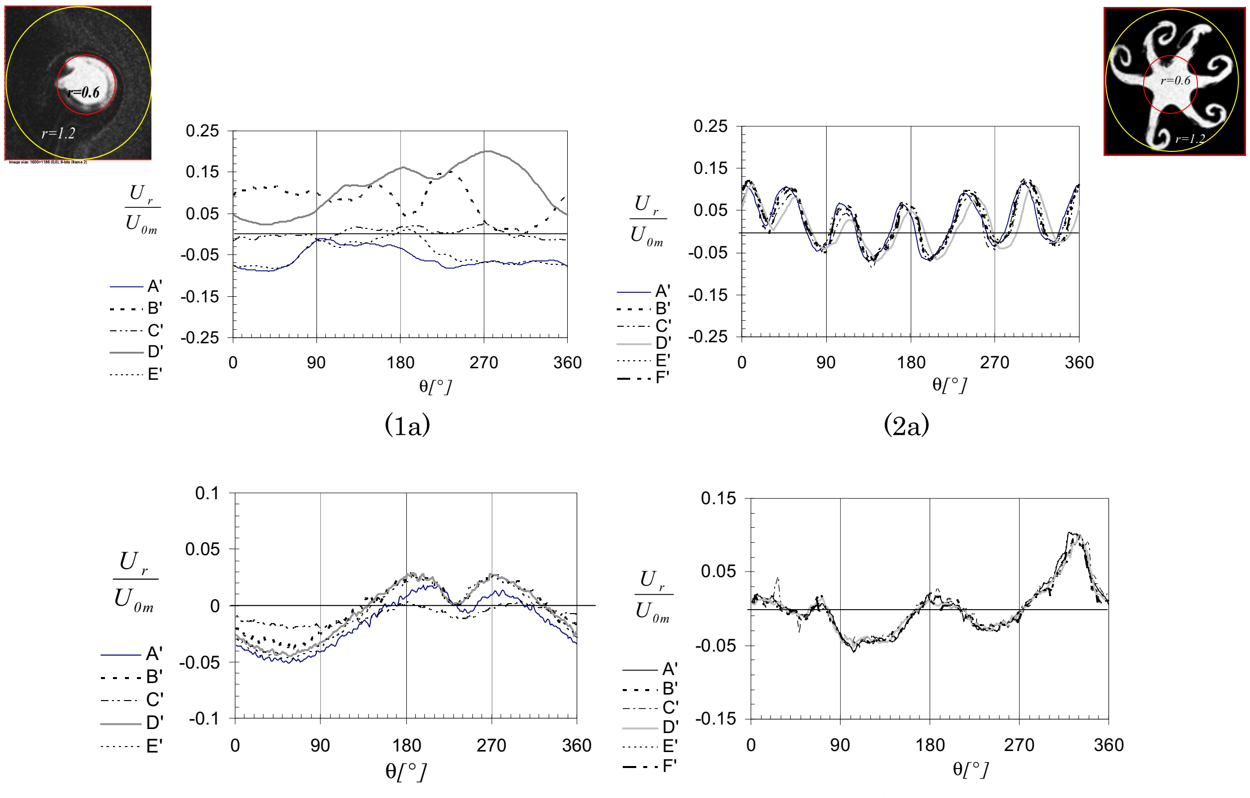
Fig. 7. Construction of a pseudo time-resolved PIV sequence for the circular jet.



(a)

(b) (c)

Fig. 8. Construction of a pseudo time-resolved PIV sequence for the 6-lobed jet.



(1a) (2a)

(1b) (2b)

Fig. 9. Instantaneous radial velocities at X = 3D$_e$: (a) r = 0.6D$_e$, (b) r = 1.2D$_e$.

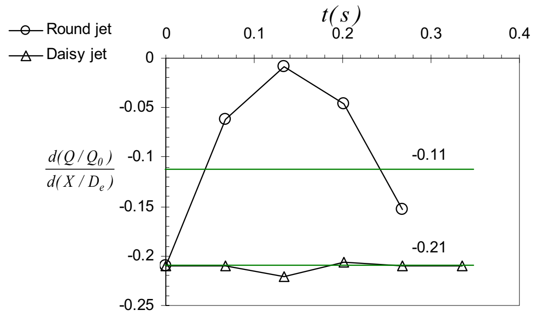


Fig. 10. Instantaneous entrainment rate variation.

The integration of the radial velocity on the periphery of the instantaneous fields at $r = 1.2D_e$ (Figs. 9(1b) and (2b)), permits to find the temporal variation of the instantaneous entrainment for each jet. These evolutions are represented in Fig. 10. For the circular jet, the instantaneous entrainment rate is variable and appears to be controlled by the presence of the K-H ring. As for the daisy-shaped jet, the instantaneous entrainment rate is constant, being almost twice as greater as the one of the circular jet, which confirms its mixing performance.

This analysis allows a better understanding of the direct part played by K-H structures in the two types of jet flows. In the circular jet, at a given axial distance, the entrainment occurs at the end of the passing period of the K-H ring, when the streamwise structures may develop. When a K-H ring is present, the streamwise structures are compressed and the self-induction is stopped throughout the passing period. In this way, the induction in the circular jet is controlled by the K-H rings. The lobed geometry of the daisy orifice permits a break of the K-H structure into ring segments, thus preventing the control of the induction process by the primary structures. Important and permanent streamwise structures develop at the discontinuities regions, and control the self-induction apart from K-H rings.

4. Conclusion

This study associates a field optical measurement technique and a high speed visualization technique, enriched by a low level image processing, in order to analyze vortex dynamics in the near field of jet flows. We show that in the circular jet, the entrainment is produced in the braid region being interrupted by the Kelvin-Helmholtz ring passing. The ring compresses the streamwise vortices and interrupts their self-induction. However, in the light of previous studies, these primary structures are indirectly responsible of the entrainment. Their passing generates azimuthal instabilities and consequently streamwise structures.

The passive methods used to enhance mixing, avoid these antagonist effects of the Kelvin-Helmholtz rings. Particularly, a daisy-shaped lobed orifice introduces local transverse shears which generate large scale streamwise vortices. These local shears fragment the Kelvin-Helmholtz structures into discontinuous ring segments. In this way, the streamwise structures are permanent and control the entrainment independently of the Kelvin-Helmholtz vortices.

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