Phenomenological study of the pressure swirl atomizer internal flow

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The context of the present work is an investigation on the unsteadiness of the internal flow structure of a pressure swirl atomizer. The oscillations observed on the aircore/liquid interface are the main evidence of the unsteady character of the flow. Vizualisations and measurement techniques based on LDA, high-speed camera pictures and laser beam diffusion are used on a large-scale pressure swirl prototype. The measurements show the important part of the inlet jet interaction and also reveal the fundamental influence of the geometry of the nozzle. A study of the conical film behaviour at the outlet of the atomizer shows that internal unsteadiness may play a role during the external liquid sheet disintegration. Finally, we present first results of a 3D and unsteady numerical simulation of the internal flow.

1. Introduction

Pressure-swirl atomizers are found in a wide range of engine and industrial turbines, due to their good atomisation characteristics and their relative geometrical simplicity. They produce hollow cone fuel sprays with gaseous core extending all along the axis of the swirl cavity. The design of effective atomizers depends on the control of the spray characteristics as the spray angle or the exit film thickness. Currently, it is well known that these ones are affected by the nozzle internal geometry [1]. However, the inner flow pattern is rather complex and is still misunderstood. Recent studies were carried out to give an insight into the internal structure in the swirl chamber. Wang and al. [10] describe a sophisticated flow pattern within the atomizer as confirmed by our own research [7]. But, several questions remain concerning the regime characterisation of the internal flow and the unsteady effects which are revealed by the aircore behaviour : all the authors have observed oscillations on the aircore [2],[10],[6],[7] and claim that these waves induce large variations of the liquid film thickness at the outlet of the atomizer which may play a role in the atomisation process, or at least in the liquid droplet diameter distribution (Figure 1).

Figure 1 – Spray produced by the pressure swirl atomizer

The present paper provides a detailed examination of the aircore oscillations and links them with the unsteadiness behaviour of the internal flow. In the same way, the first results of a detailed 3D simulation of an atomizer flow performed with the CFD software Fluent is presented.

2. Experimental setup

The large–scale prototype pressure swirl atomizer used in this experiment is made of optical quality Plexiglas. The injector consists of two major interchangeable parts : the swirler cup, which contains the entrance slots and the nozzle itself. These parts can be easily removable in order to simulate the effects of geometry on simplex internal flow. A schematic of the pressure swirl atomizer is shown in figure 2. The pressurized liquid enters through several tangential slots into a swirl chamber. In this way, the high swirl velocity induces a gaseous core along the axis. The liquid is then accelerated through a convergent part and exits in a hollow conical liquid sheet, which breaks up quickly into a spray (as observed in figure 1).

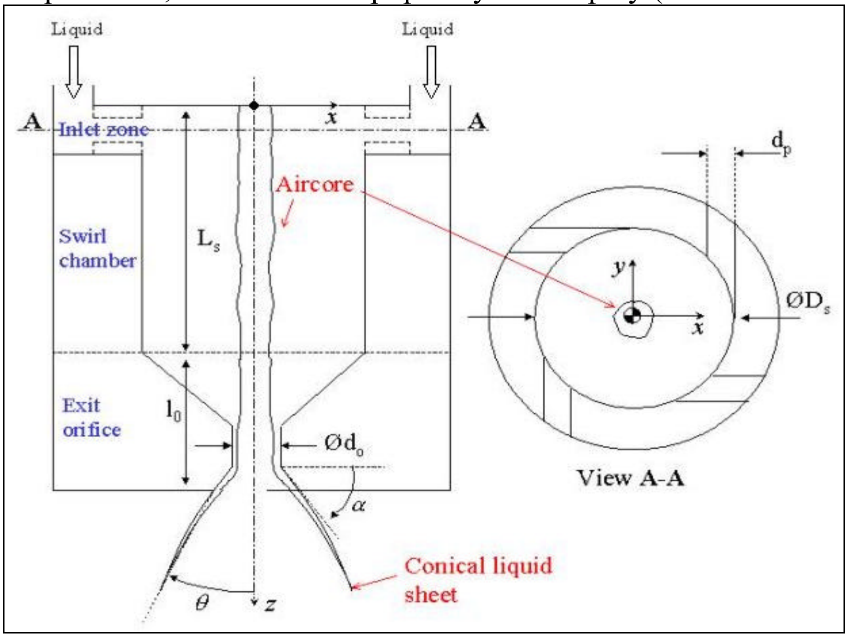

Figure 2 - A schematic of a pressure swirl atomizer

To improve the optical arrangement by reducing non-flat wall effect, the prototype is also equipped with a transparent water vessel and filtered water is the working fluid.
The inlet velocity corresponds to Reynolds numbers, $Re_w = (2\rho\Delta P)^{0.5} d_0/\mu$, ranging from 10000 to 300000 based on Walzel's definition for typical atomizer flow [3]. ρ,μ and ΔP are respectively the liquid density, the liquid dynamic viscosity and the pressure drop across the nozzle. In addition, a pressure-swirl atomizer internal flow is also characterized by several dimensionless numbers based on geometric dimensions. Among them the atomizer parameter $K=NA_p/((D_s-d_p)d_0)$, where Ap is the area of the entrance section of a slot and N the number of slots, characterizes the degree of flow swirling in the nozzle.
The investigated atomizer parameters are listed in Table 1.

Table 1 – Experimental conditions

Case	K	d_0/D_s	N
1	0.26	0.3	4
2	0.33	0.3	4
3	0.58	0.3	4
4	0.17	0.3	2
5	0.26	0.2	2
6	0.41	0.2	4
7	0.52	0.2	4

LIF visualizations were performed with a laser sheet generated from a 488 nm Argon/Krypton laser beam coupled with an I2S CCD camera with a resolution of 782*582 pixels. For high speed videos, a Phantom camera from Vision Research Inc. was used. Full frame (512*512 pixels) images were obtained at 1000 fps and stored directly on a PC. Fluorescent dye was injected into the flow in one of the swirl slots to mark out the path of an inlet jet and by this way examine the structure of the internal flow. An optical access by the top lip of the prototype allows us to acquire images and videos for different views depending on whether the laser sheet passes through the atomizer along the axis (side view) or orthogonal to it at different z-locations (top views). Temporal analysis of the different videos acquired is made up with a video post-treatment software called "Image" and developed by the ONERA. This treatment is based on the measurement of the pixel light intensity in a specific zone for each image, followed by a FFT analysis of these data.

The LDA exploration of the internal flow is realized with a Dantec Flowlite 2D two-component device. It provides radial profiles of the axial and tangential velocity components at different axial locations in the atomizer.

The characterisation of the aircore oscillations is performed with a laser beam produced by a 3mW diode, which is positioned so as to skim the aircore/liquid interface at different axial locations in the atomizer. The light deflection caused by aircore waves are measured with a photo detector linked to a Brüel and Kjaer spectrum analyser.

3. Results and discussions

3.1. *Internal flow structure*

Figure 3 shows a LIF half-side view picture of the diffusion of a fluorescent inlet jet into the swirled liquid flow. Aircore and his fluctuations appear in black at the bottom of the figure.

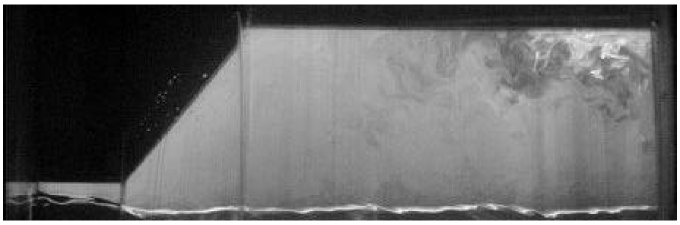

Figure 3 – Cross section of internal flow – Case 7

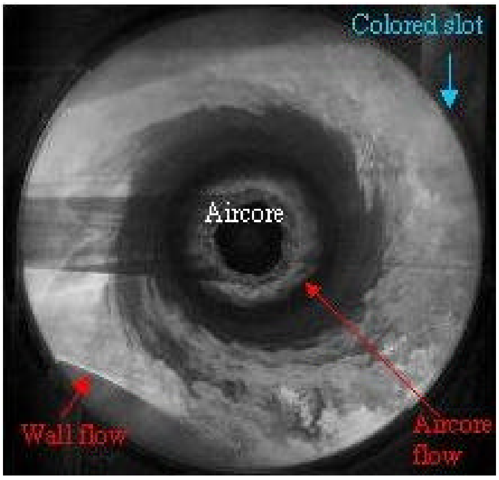

Figure 4 – Top cross section at the inlet slot level – LIF picture of case 7

At the top right, the mark of the dyed inlet jet is localized next to the wall. The zone around it looks turbulent. LDA measurements show that the internal flow in the swirl chamber is composed of two main helical streams. The first one flows next to the chamber wall and is directly fed by the inlet jets. As shown on figure 3, the supplying of the swirl chamber occurs with an intense turbulent activity. Large coherent structures are generated in the shear region, which appears between the inlet jets and the swirled main flow. These vortices lead to the diffusion of jet's momentum and their magnitude and frequency depend on the flow rate and local velocity gradients. Outside this stream, the structures look to be expulsed towards the aircore but are quickly captured by a laminar flow

core and broken up by the intense tangential velocity field. This modification of the flow regime in confined swirled flow is also observed in [4]. The second main flow is detected near the aircore and looks faster than the first. It is visible on the figure 4 which is a typical image obtained when the diffusion of the dyed inlet jet is followed step by step. This aircore stream is directly fed by an Eckman boundary layer, which is developed on the top lip of the swirl chamber. In this way a part of the liquid entering in the chamber is forced radially inward. As the flow reaches the aircore region, it is then forced axially.
All along the swirl chamber, the wall flow weakens whereas the intensity of the aircore stream increases : the flow tends to acquire the classical structure of a confined vortex as described in [5].

3.2. *Internal flow and aircore unsteadiness*

The unsteadiness aspect of the complex internal flow is revealed by the fluctuating aircore. According to the analysis of our high-speed camera frames and Coorper's observations [6], interface perturbations are the combination of several oscillations. First, the aircore has a global precession movement extended to the conical liquid film. Secondly, helical waves are observed spreading on the interface in the atomizer (see figure 10). Finally, tiny surface fluctuations associated with capillarity waves are detected.
The laser beam deflection technique allows us to obtain an accurate and proper spectrum of the aircore oscillations as shown in figure 5.

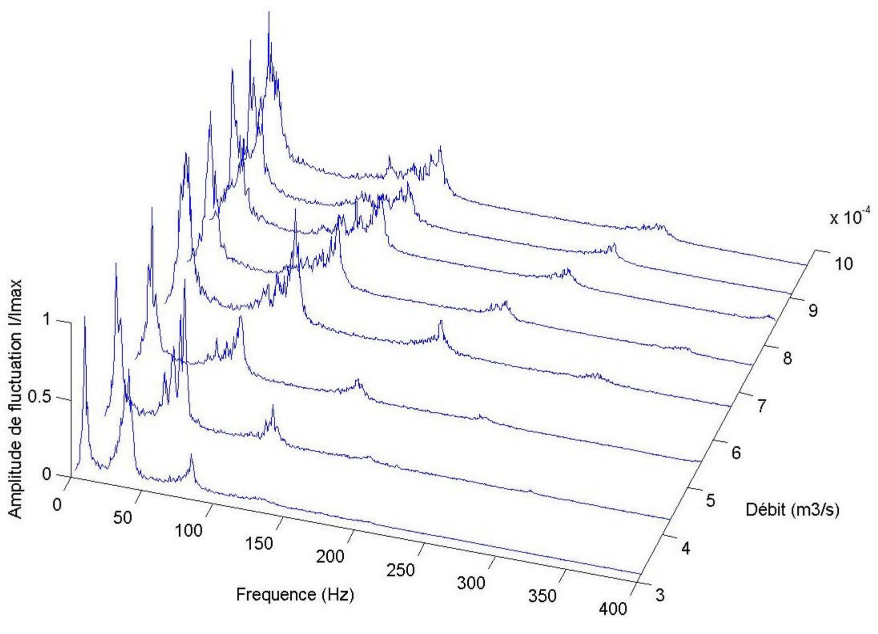

Figure 5 – Interfacial wave frequencies for different flow rates – Case 1

Spectra reveal two fundamental frequencies called f1 and f2 ranging around 10 and 300 Hz depending on the atomizer geometry and operating conditions. A third frequency is also detected but is taken as a harmonic one. As observed on the figure 5, these frequencies increase linearly with the flow rate and this growth depends on the geometry of the atomizer.
To translate these results as a dimensionless form, we introduce a Strouhal number St as :

$$St = \frac{f\left(D_s - d_p\right)}{W_i}$$

which is compared to the Reynolds number Re_w for each peak. W_i is the mean flow rate velocity and is equal to $Q/(NA_p)$.

As shown on figures 6 and 7, in each case the Strouhal number is self-similar relative to the Reynolds number but depends on the atomizer parameters K and d_0/D_s.

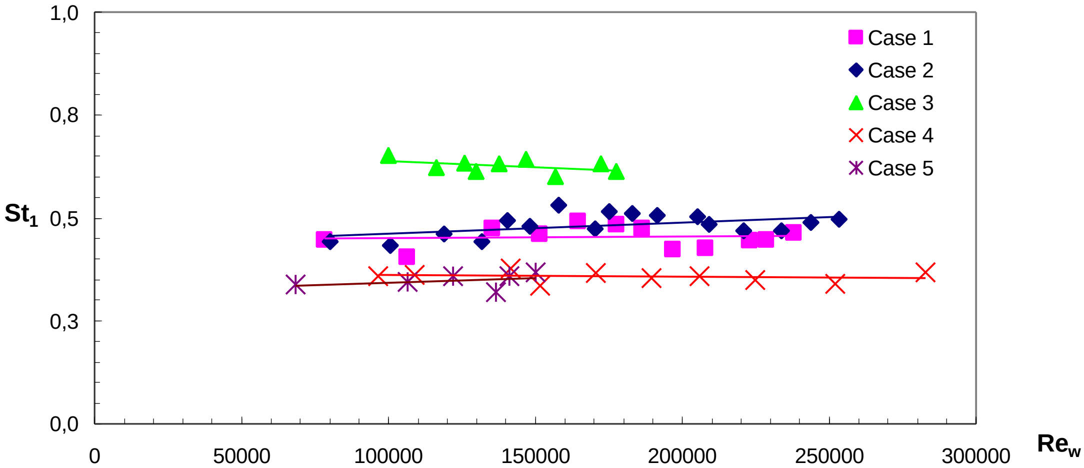

Figure 6 – Frequency f1 versus the flow rate in dimensionless coordinates (see table 1)

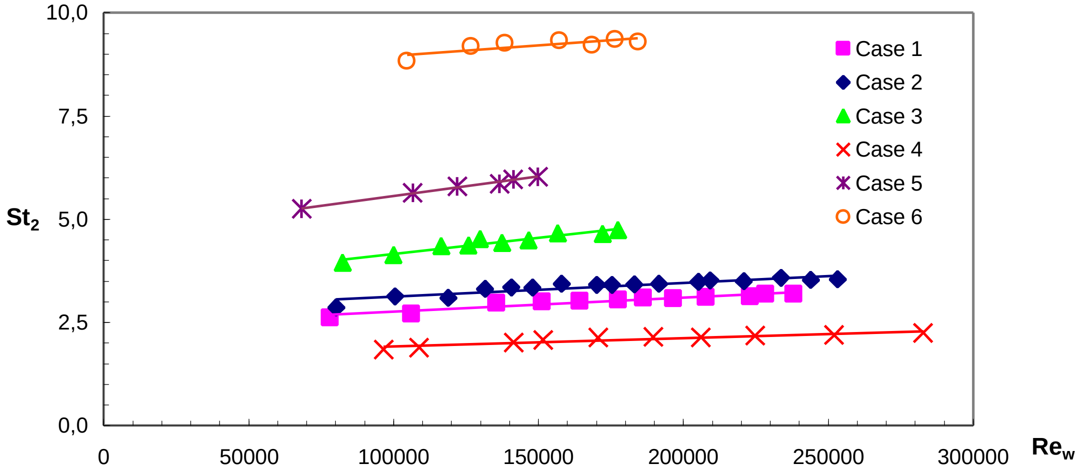

Figure 7 - Frequency f2 versus the flow rate in dimensionless coordinates (see table 1)

For a fixed orifice diameter, the Strouhal number St_1 (for f1) increases with the increase of K and reaches a constant value. The analysis of several configurations shows the important influence of the inlet slot dimensions and of their position in relation to the swirl chamber. It leads to the following correlation :

$$St_1 = A.K^B \left(\frac{d_0}{D_s - d_p} \right)^C \left(\frac{D_s}{D_s - d_p} \right)^D$$

where the values of A, B, C and D are respectively 2.1, 0.48, 0.5 and –2.63.

In previous work [7] frequencies f1 are associated with a global precession movement. With these new observations the aircore behaviour seems to be the result of the interaction between all the inlet jets and the main swirled flow in the first part of the swirl chamber. A temporal investigation of the intense coherent structures which emerge from inlet jet shear zones developed in the turbulent layer is then conducted (see figure 8). Spectrum extraction of LDA measurements is also realized. With the both methods, the peak f1 is detected. The figure 9 shows the consistency between the frequency of turbulent structure production for different flow rate and the frequencies f1 measured. Although these structures are quickly destroyed by the intense swirled flow, part of them can reach the aircore by the Eckman boundary layer at the top lip of the chamber.

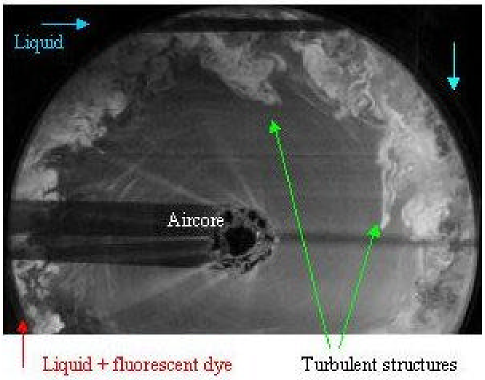

Figure 8 – Top view of turbulent structure production all along the chamber wall - Case 7

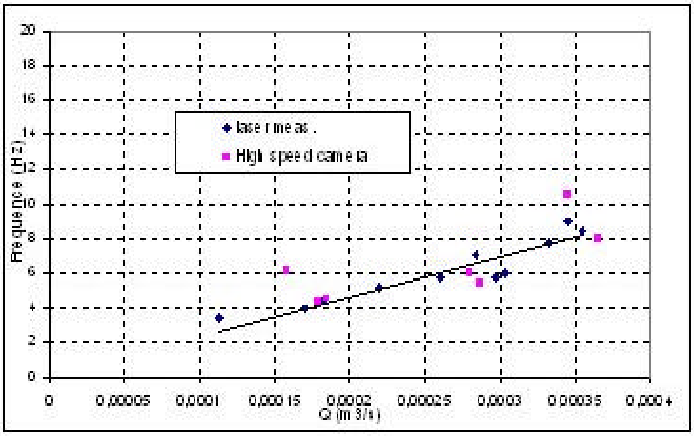

Figure 9 – Turbulent structure frequency versus f1 measured by laser beam deflection technique – Case 7

Frequencies f2 are associated with the helical wave in double helix, which is detected on the interface (see figure 10). As shown on figure 7, Strouhal number St_2 is still dependent of K and especially of exit orifice dimensions, since d_0/D_s leads the swirl velocity of the internal flow.

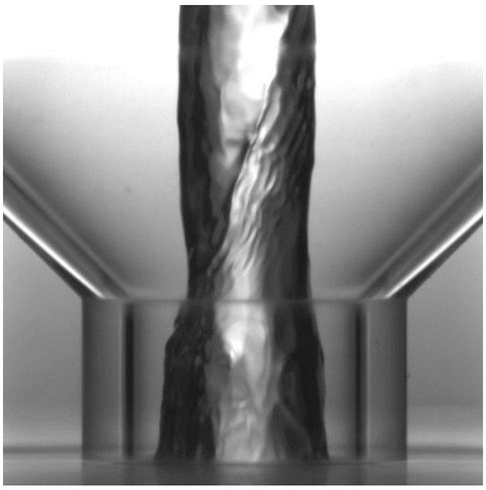

Figure 10 - Helical wave on the aircore interface

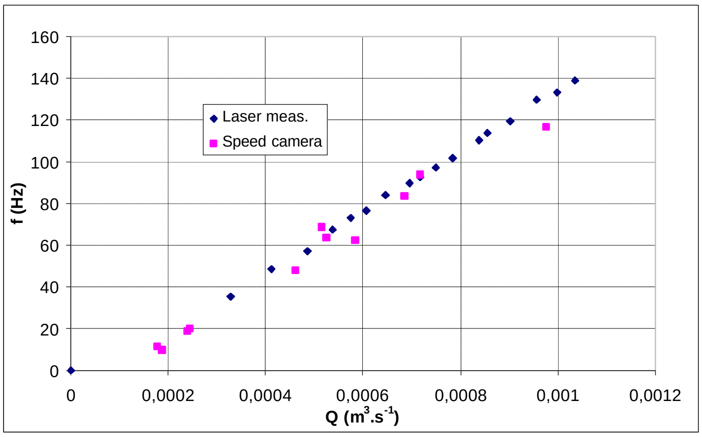

Figure 11 - Comparison between f2 frequencies measured with laser beam deflection technique and FFT analysis of helical wave propagation on the aircore – Case 2

St_2 has been measured for several geometric variations at the same position in swirl chamber. In this way, a correlation is proposed with the following expression :

$$St_2 = A.K^B \left(\frac{d_0}{D_s - d_p} \right)^C$$

where the values of A, B and C are respectively 1.14, 0.72 and -1.85.

For a same flow rate, the measured spectrum is still uniform all along the swirl chamber (figure 12). However a weak increase is detected in the convergent and outlet orifice parts of the nozzle. It is associated with the liquid film acceleration. Besides, the outside conical liquid film shows oscillations with similar frequencies. For a low flow rate, these liquid sheet fluctuations can be detected just before atomisation, but as flow rate increases they seem to disappear as the aerodynamic influences grow.

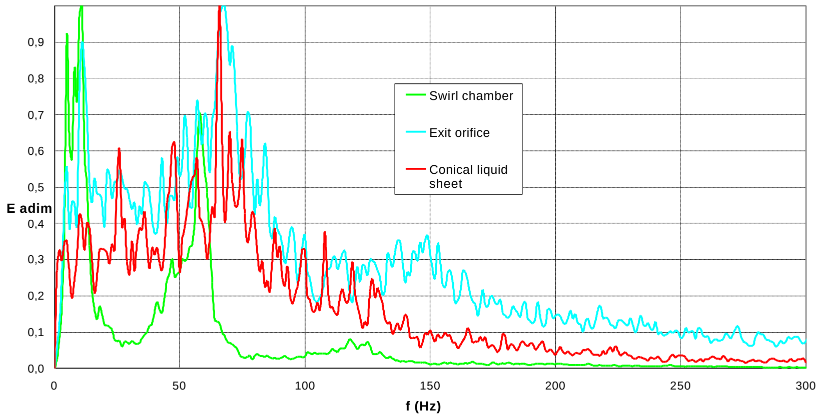

Figure 12 – Spectrum measured all along the aircore and conical liquid sheet for the same flow rate

4. Numerical approach

In previous work, a 2D numerical simulation of the internal flow performed with the CFD software Fluent 5 was realized. Results presented in [7] shown good agreement with experimental ones. However, the three-dimensional and unsteady behaviour of the pressure swirl internal flow imposes a new approach of the numerical problem. Thus, a 3D simulation was initiated, based on the geometry of case 3 (see table 1). The flow field is computed on a structured mesh of about 150000 cells. An adequate resolution is taken in the central region to simulate properly the rotating gaseous core. The free surface between the aircore and the working fluid is modelled using a VOF interface-tracking algorithm [8]. The Walzel reynolds number for our flow simulation is about 150000 and regime is considered to be laminar. The simulation is processed on a Silicon Graphics Origin 3400 calculator. Figure 14 is an illustration of simulation results. The flow has a highly 3D character and the wavy shape of the aircore is obvious. The interface is colored by the aircore velocity magnitude.

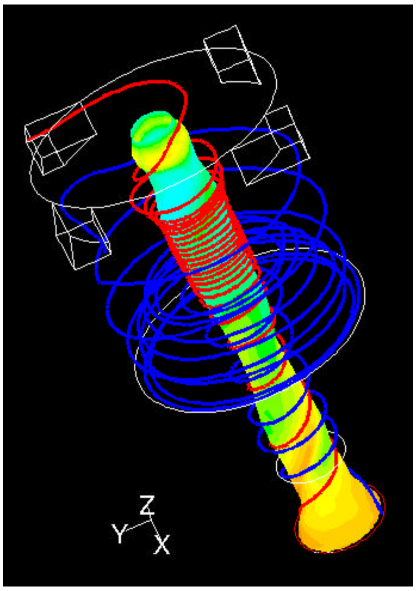

Figure 13 – Particle paths and aircore shape in the 3D simulation

The aircore rotates and a helical disturbance is observed on its surface.

Particle paths illustrate perfectly the mean streams which compose the internal flow. In particular, the red one is for the aircore stream and shows a spiral trajectory next to the top lip due to the presence of the viscous Eckman boundary layer. At this level, the aircore looks pinched and is under the boundary radial flow. The origin of part of the fluctuations is then localized at the stagnation point at the wall lip. Similar numerical observations were obtained by [9]. To validate our simulation, velocity profiles are compared to LDA measurements. As shown on figure 14, the Rankine structure of the flow is well captured and comparison is fairly consistant.

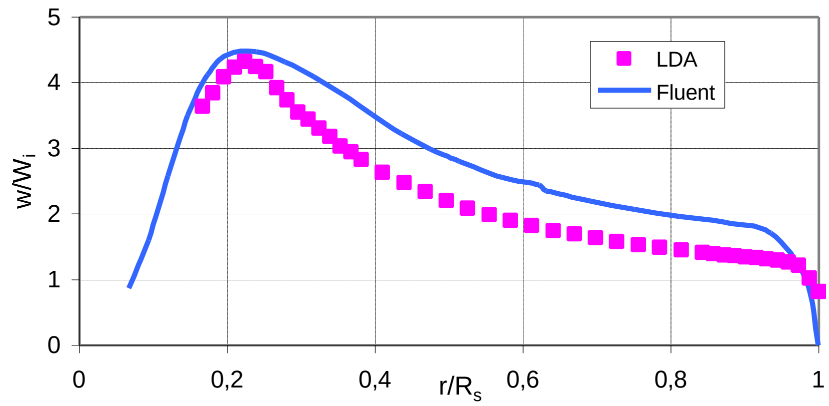

Figure 14 – Comparison between experiments and 3D simulation for the tangential profile of the velocity in the swirl chamber (z/Ls=0.7) – Case 3

5. Conclusion

From both experimental and numerical means, the internal flow unsteadiness of a pressure swirl atomizer is described. In particular the study focuses on the aircore fluctuations, which are generated at the nozzle top lip and propagate towards the exit orifice. Spectrum obtained shows two main frequencies. The lowest is associated with a precession movement of the aircore due to the inlet jet diffusion. The second is the result of a rotating double helix wave. These two frequencies are measured all along the internal gaseous core and also on the conical liquid sheet outside. In the author's opinion, this interfacial unsteadiness may be involved in the sheet atomisation process, but complementary works are needed.

The influence of atomizer geometry on the aircore fluctuations is then demonstrated from a parametric analysis and dimensionless coordinates correlations are produced. The role of the swirler dimensions appears as fundamental. A 3D numerical simulation confirms the experimental observations.

6. References

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