ACOUSTIC STREAMING MEASUREMENTS BY PIV

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Other keywords: image processing, acoustic streaming

ABSTRACT:

The acoustic streaming is a second-order steady flow, which is superimposed on the dominant acoustic velocity. It is induced by the nonlinearities of the acoustic propagation. These non linear phenomena are present in oscillating flows and generally result in a efficiency degradation of thermoacoustic devices. In this paper an exploration of the acoustic velocity field by PIV enabled to highlight and quantify these secondary flows. The measurements performed in phase synchronisation and by scanning the temporal period give us information on streaming profiles and allow plotting the acoustic velocity over time.

INTRODUCTION.

The study of acoustic resonators can lead to a variety of subjects, from music [1] to photoacoustic spectrometry [2], [3] through thermoacoustics [4], [5], [6]. The present study is motivated by this last discipline. Thermoacoustics is actually a relatively new research field in physics which started in 1980s at the Los Alamos National Laboratory (LANL) in the USA. It is based on the reverse conversion between acoustic and thermal energy. The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts which give them a high reliability as well as a long life span. It is a clear, reliable energy and further development of these systems will lead to attractive renewable energy options. The most basic systems consist of an acoustic resonator within which is located a stack equipped with two heat exchangers at its ends. In the case of an engine, if the temperature difference maintained by the exchangers between the stack sides is sufficient, it can create an acoustic wave. In the case of a receiver, it is the fluid oscillations created by an acoustic generator that will allow pumping heat along the stack from the cold area to hot area. Most applications involve heating cooling or electricity production. To be more specific thermoacoustic systems can for example be applied as heat pumps for domestic applications or industrial applications like liquefaction of natural gas or solar driven cooling systems. If this new technology, clean and reliable is a clear interest, it still remains a challenge. Indeed in thermoacoustic engines and heat pumps significant thermal losses are present due to non-linear effects. An important class of these non-linear effects is streaming flows, which are second-order steady flows, superimposed on the first-order acoustic oscillations. Several types of streaming exist: Gedeon streaming, Rayleigh streaming or jet streaming. One type of the acoustic streaming which is always associated with a standing-wave resonator is called Rayleigh streaming. It refers to the streaming motion that is induced by acoustic standing waves in thermoviscous fluids between plane walls. It actually originates from the action of Reynolds stresses developing in the Stokes boundary layer (boundary layer near a solid wall in a viscous and oscillating fluid) [7]. These flows create steady mass-fluxes that transport heat away from the hot heat exchanger to the cold heat exchanger of a thermoacoustic engine, without contributing to energy conversion, or in case of a refrigerator in the opposite direction of the heat pumping, leading in both cases to a degradation of performance. The understanding of these non-linear effects will therefore be important in improving system performances. It is thus necessary to develop a methodology to provide insight into these phenomena.
Although acoustic streaming has been widely investigated, few works on experimental measurements were performed. Studies generally confine to local pressure and acoustic velocity measurements. Evaluating experimentally a non-linear

effect of the acoustic wave such as acoustic streaming is a real challenge in metrology and signal processing. In the field of thermoacoustics Poignand [8] used LDA to measure the particle velocity inside a thermoacoustic refrigerator composed of one cubic cavity with two or four loudspeakers attached to the walls. Laser Doppler Anemometry has a very good time resolution and therefore gives very good results when one wishes to have access to the local temporal evolution of the velocity. In the previous study PIV was used jointly with LDA. Unlike LDA, the Particle Image Velocimetry enables instantaneous measurements of the spatial field. For that matter PIV was also used by Debesse and al. [9] to measure acoustic streaming in thermoacoustic systems. The singular value decomposition (SVD) allows them to reconstruct the acoustic signal despite the sub sampling without requiring a phase reference. The mean-field study, conducted on an almost 7m-long resonator, shows streaming flows with velocity amplitudes between 1 and 8 cm/s. Yet the authors remain reticent as for the repeatability of these second-order flows. Studies were also carried out on simple acoustic resonators. Thompson and Atchley [10] used LDA to study the acoustic velocity as well as the streaming velocity inside a cylindrical standing-wave resonator filled with air. They showed that the magnitude of the streaming is influenced by the dependence of fluid viscosity with temperature. This mean of measurement was also used by Sourice and al. [11]. In fact they developed an algorithm for signal processing allowing real-time estimation of the acoustic velocity. Eventually this algorithm was implemented on a LDA system. Their method was validated on a simple case, in a Plexiglas tube excited by an electrodynamic loudspeaker. Gazengel and Poggi [12] evaluated two LDA measurement systems. Reference velocities were defined from pressure measurements combined with a model of sound propagation. The equipment was then put in place to minimize errors on the velocity reference. These velocities are used subsequently to validate the results of the LDA.

PIV and LDA are not the only means of measurements used to measure acoustic velocities. Huelsz and Lopez-Alquicira [13] developed a method using a hot wire probe suitable for measuring sound waves with low acoustic amplitude. Their measurements within a quarter-wave resonator nevertheless outline the presence of streaming. The process of hot-wire probe has the advantage of having relatively good spatial and temporal resolution. Also the implementation is generally simple. Besides compared with the PIV method, the measurement requires no seeding and therefore allows quick installation at low cost. However this method requires introducing a probe into the flow, which remains essentially intrusive and sensitive to changes of temperatures that can potentially twist the result. The measure is also local which requires to cover a large number of points to get a representation of the velocity field.

Few two-dimensional experimental investigations on the non-linear phenomena of acoustic streaming inside a standing wave resonator have been done. Nabavi and al. [14] applied the PIV to the standing acoustic waves developing in a 7cm² - square section resonator with air at atmospheric pressure. Measurements of the acoustic field were first performed for quasi-linear conditions in order to validate them by comparison with the results of an analytical model. The same authors [15] conducted experimental measurements inside a Plexiglas channel of 4cm² - square cross-section filled with air (the setup is similar to what was used in [14]) to analyze the formation of regular and irregular acoustic streaming patterns. When the excitation amplitude of the acoustic driver increases beyond a certain limit, regular streaming flow patterns are distorted to an irregular flow structure.

EXPERIMENTAL SETUP.

Thermoacoustic bench.

In this paper the system consists of a resonator made of stainless steel closed at one of its ends and equipped with an acoustic driver to the other. The inside diameter of the resonator is 56.3mm. The resonator is made of six segments, in which is included the PIV module prepared for flow illumination with laser light and imaging. It has three windows of visualization to let the laser beam go through and a prism to deflect the laser sheet onto the upper window into the resonator (see Fig. 1). The cell was manufactured with square section and smooth angles. At both ends it allows a smooth section change from square to circle to fit the resonator, without modifying the cross section area. The optical elements for visualization have been treated against-reflection for the wave length 532nm (see the pink color on Fig. 1), which is the laser wavelength.

The shaker, acting as acoustic source, (LDS -Ling Dynamic Systems- V450/1 - PA 500L) was chosen for reliability reasons considering its working conditions and thus matching those resources to provide as much as possible for monochromatic waves without getting measurements altered by parasitical thermal effects. It provides a mechanical

vibration which amplitude can be selected by modifying the piston stroke. Consequently the piston displacement and the operating frequency can be adjusted.
The piston diameter matches the resonators inside diameter of 56.3mm. Its stroke varies from 5 to 18mm.

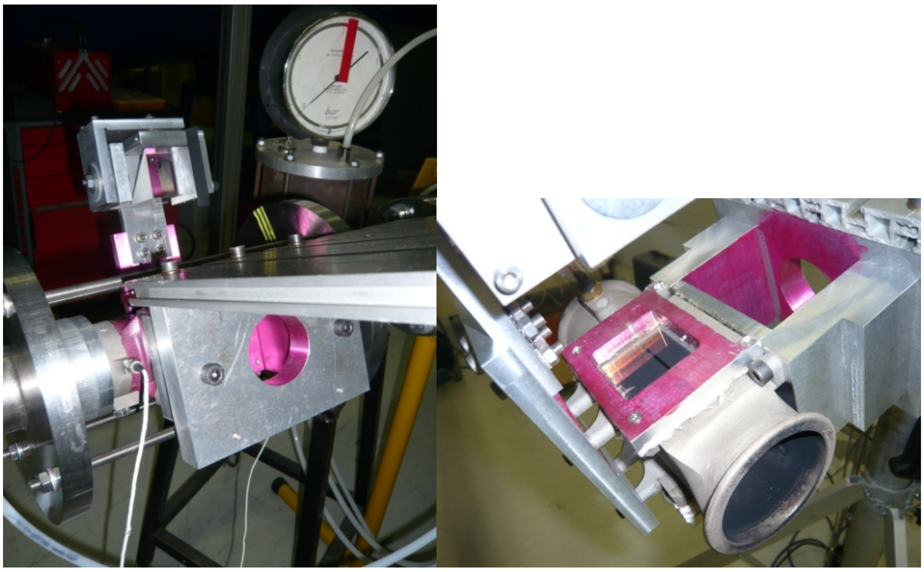

Fig. 1 Views of the PIV cell, treated against reflections

Equipment

PIV Equipment. Flow field measurements were performed using a PIV system. The laser sheet is generated by a laser 200mJ Nd :Yag multipulse (PIV 190 PS1/TwinsBSL Quantel) with a wavelength of 532nm combined with spherical and cylindrical optical components. The laser sheet is sent to the prism and then deflected perpendicularly onto the upper window of the PIV cell. The light sheet inside the resonator is parallel to its axis (on the focal plane of the camera).

The image acquisition is then achieved with a CCD camera (TSI PIvCam 13-8) of 1024x1248 pixels. The images from the camera are recorded at a frequency of 3.63 Hz.
The camera is connected to a synchronizer (LASERPULSE Synchronizer – TSI Model 610034) allowing triggering the image acquisition with the control signal of the shaker. Consequently the PIV measurements are synchronized with the acoustic wave.
An aerosol generator (TOPAS ATM 210) is used to generate the seeding mist. The particles are made of DEHS (Di-2-Ethylhexyl-Sebacat). The size of the droplets produced is of the order of 0.3μ m and the droplets evaporate completely after 4 hours thus preventing clogging.
Several valves control the seeding and its injection in the resonator. The plenum chamber of the seeding system can withstand a pressure up to 10 bars and allows the homogenization of the gas-particles prior to injection into the measuring zone [16].

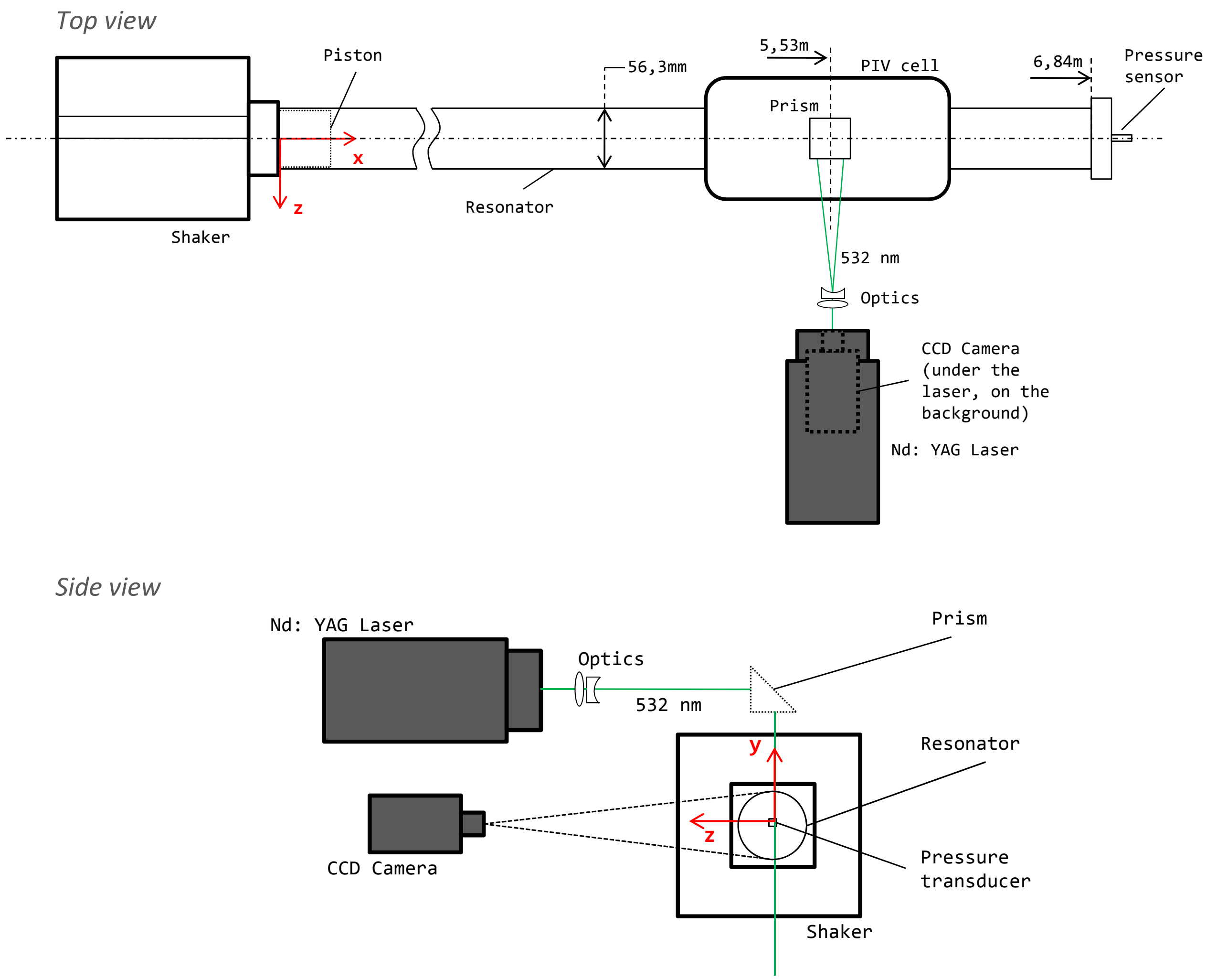

Fig. 2 Schematic of experimental apparatus and instrumentation

Pressure and temperature acquisition. In addition to the PIV system, the resonator is equipped with pressure and temperature sensors (see Fig. 3). The pressure transducers are Kulite transducers (WCT-312 and XTEL-190) connected to an acquisition board National Instrument (Ni SCX1-1000). A K type thermocouple provides the average temperature within the PIV cell. The thermocouple allows knowing the temperature inside the resonator, temperature from which can be calculated the acoustic wave velocity thereby deducing the resonance frequency.

The set of signals is captured at a sample rate of 15 KHz. The "drive ratio"-defined as the ratio of the maximum amplitude of acoustic pressure over the mean pressure- is calculated from pressure measurements taken at the resonator’s plug (closed end).

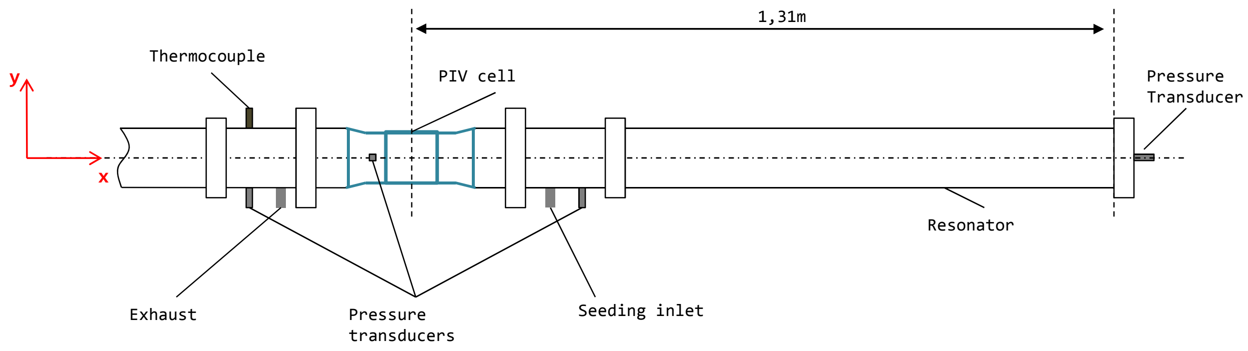

Fig. 3 Acquisition process pressure and temperature signals

Post processing

Image acquisition is done using Insight 3G software that controls various parameters:
- LPD (ie, its Laser Pulse Delay): time between the acquisition trigger order and the first laser flash = 220μs
- The Δt= time between two laser flashes = 25μs
- PIV-Cam frequency: acquisition frequency of each pair of images (here 3.63 Hz, which is the maximum allowed by the camera).

50 pairs of images are recorded for each phase knowing that twenty-one phases are studied on the acoustic cycle. The trigger of PIV occurs on the rising edge of the signal generated by the synchronizer from the acoustic signal. The image quality has an influence on the correlation performed by the PIV software (Insight 3G). Appropriate treatment/processing is then operated on different images: the noise is first subtracted from each snapshot, and then several operations are performed on the instantaneous velocity vectors fields.

1. The instantaneous velocity fields are statistically averaged. A mean velocity field is then created for each phase.
2. To overcome the side effects, only a portion of the image is kept.
3. For streaming velocity fields, the fields are averaged over the acoustic signal.
4. Velocity profiles and a temporal representation of the acoustic velocity variation over a time period can be then deduced from the velocity fields.

RESULTS

Drive ratios (Dr) from 3% to 6% were obtained with the following experiment conditions:

- Resonance frequency: 25Hz
- Atmospheric pressure
- Fluid: air

The detailed experiment conditions are summarized in the following table.

	Test1	**Test2**	**Test3**	**Test4**
P_m abs. (bar)	1,0146	1,0108	1,0165	1,0140
P_1 (mbar)	34	42	49	56
Drive ratio P_1/P_m (%)	**3,3**	**4,2**	**4,8**	**5,5**
T_m (°C)	21,7	21,9	21,5	21,8
Piston stroke (mm)	7,07	8,48	9,90	11,3
T (period in s)	0,040	0,040	0,040	0,040
f (Hz)	**25**	**25**	**25**	**25**
L (m)	6,85	6,85	6,85	6,85
Acoustic driver	Shaker	Shaker	Shaker	Shaker

Tab. 1 Experiment conditions of the tests conducted in air

With P_m : mean pressure in the resonator
P_1: acoustic pressure
L: resonator length

The next figure (Fig. 4) presents the temporal variation of the axial velocity inside the resonator for four different drive ratios. The velocity, averaged spatially, is shown over time in ms, for one period. The shape of the curves is far from being sinusoidal and is actually much distorted. In addition the higher velocities, presented in the second half of the period, are revealing a strong dissymmetry of the axial velocity, which drives away the particles from the shaker. This pattern is most likely explained by the demonstration of a non linear phenomenon and probably the presence of superior harmonics, distorting the sinus. Comparatively the piston amplitude, presented on Figure 5, follows a perfect sine curve, which indicates that the presence of superior harmonics in the flow isn't related to the acoustic driver.

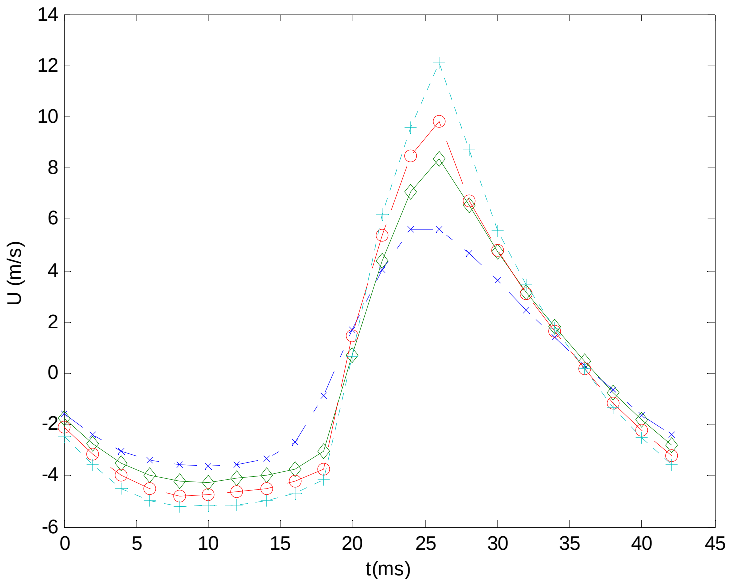

Fig. 4 Time variation of the axial velocity over a period for different drive ratios,
×: Dr=3.3%, ◊: Dr=4.2%, o: Dr=4.8% +: Dr=5.5%

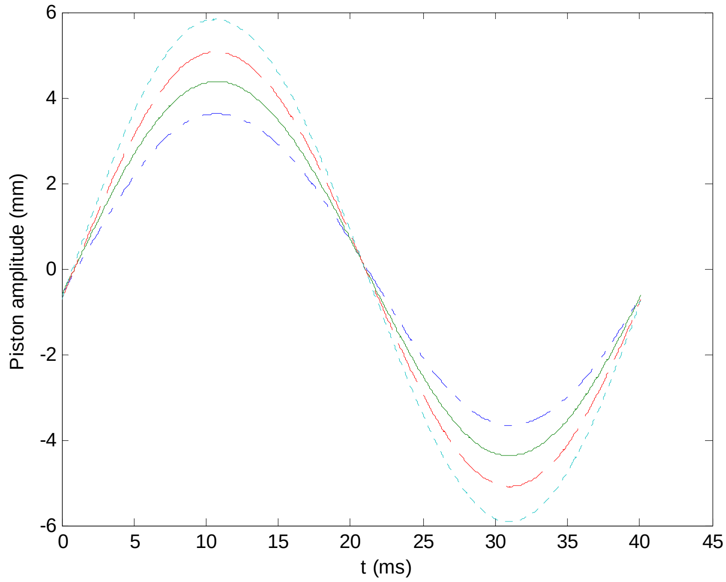

Fig. 5 Time variation of the piston amplitude for different drive ratio, '.-': Dr=3.3%, '-': Dr=4.2%, '--': Dr=4.8%, '..': Dr=5.5%.

Figure 6 presents the streaming velocity profiles inside the PIV cell, on a plane located at the center of the resonator (xy plane). In the y-axis is the height of the resonator in mm and in the x-axis is the axial velocity in m/s.

The shape, well defined at high drive ratio (see Dr = 5.5%), gives a vortex-like streaming velocity or what is called the Rayleigh streaming (Rayleigh cell) with opposite velocities at the center and on the wall of the resonator, which was expected [16]. Yet the resolution of camera doesn't allow to have the complete shape of the cell velocity profile since detailed data close to the walls are not available. The amplitudes are similar to what was found in the work of P. Debesse [17]. However the 3-D characteristic of the streaming flow was not studied here and has to be taken into account if we want the fully characterize the streaming.

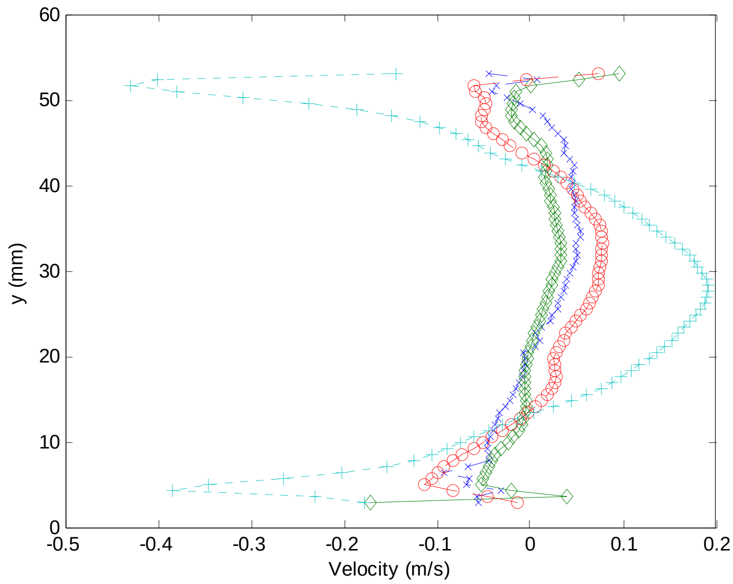

Fig. 6 Streaming velocity profiles for different drive ratios, ×: Dr=3.3%, ◊: Dr=4.2%, o: Dr=4.8% +: Dr=5.5%

CONCLUSION

The work presented is part of an experimental exploration phase of acoustic streaming in thermoacoustic systems. This first phase has allowed to adapt the technique of PIV to the specific character of Rayleigh streaming considering the low intensity of this order-two phenomenon that under certain conditions is comparable to the accuracy of current equipment.

Measurements were also performed under specific conditions dictated by the imperatives of geometry: low pressure (air at atmospheric pressure) and isothermal flow. In addition, the three-dimensionality of the flow streaming is not studied here and should nevertheless be taken into account if one wishes to fully characterize the fluidic phenomena. However the results allowed revealing the nonlinear character of the acoustic wave in conditions close to the thermoacoustic (drive ratio around 5%). Thus, in addition to the higher harmonics that distort the sound signal, streaming profiles measured in the xy plane appear to correspond to representations of Rayleigh streaming observed in pipes of length suitable to the establishment of a standing wave.

Currently it is planned to perform further experimental measurements on a Plexiglas channel of a square section allowing optical visualisation along the whole resonator.

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