Free Jets driven by a plane ultrasound transducer in liquids: experimental and theoretical investigation of acoustic streaming.

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"Not only can a jet generate sound, but also sound can generate a jet !" [1]. This sentence by Sir J. Lighthill explains in a few words what acoustic streaming is: the possibility of driving stationary and quasi-stationary flows using acoustic waves. In particular any ultrasound source emitting progressive waves in a viscous liquid produces an acoustic streaming flow. Such flows are for instance present in applications such as echography or sonotherapy and sono-chemistry. Recently, Poindexter *et al.* observed that acoustic streaming effectively occurs during ADV measurements in water depending on the settings of the ADV setup [2]. Acoustic streaming may thus incur limitations in ADV. It is therefore essential to be able to characterize flows induced by acoustic streaming, not only to exert better control on processes where it is used, but also to improve ADV measurements, where it is unwanted. We present an investigation of acoustic streaming flows induced by a plane ultrasonic source in water. This investigation combines theoretical considerations, numerical simulations and experiments in which the acoustic field and the velocity field are characterized. Dimensional and scaling analyses are also used to give first clues in the assessment of the bias due to acoustic streaming in ADV measurements.

Keywords: Acoustic Streaming, bias, liquid metals.

1 INTRODUCTION

"Not only can a jet generate sound, but also sound can generate a jet !" [1]. This sentence by Sir J. Lighthill explains in a few words what acoustic streaming is: the possibility of driving stationary and quasi-stationary flows using acoustic waves. In particular any ultrasound source emitting progressive waves in a viscous liquid produces an acoustic streaming flow. This phenomenon can be present in many applications ranging from biomedical applications (low intensity ultrasounds based diagnostics or high intensity ultrasounds based treatment) to engineering applications (sonochemisty, velocimetry, and potentially crystal growth). It can be undesired, such as in the case of prenatal echography, or used as a stirring solution in applications sensitive to heat and mass transfer. Recently, Poindexter *et al*. observed that acoustic streaming effectively occurs during ADV measurements in water depending on the settings of the ADV setup [2]. Acoustic streaming may thus incur limitations in ADV applications. It is therefore essential to be able to characterize flows induced by acoustic streaming, not only to exert better control on the process where it is used, but also to improve ADV measurements, where it is unwanted.

We present our investigation combining theoretical and experimental approaches. In both approaches, care is taken to characterize both the acoustic field and the generated acoustic streaming velocity field. The theoretical part of our work includes both CFD computations using a model developed under the *STARCCM+*™ commercial software and an analytical scaling analysis. The experimental part includes acoustic pressure measurements using a hydrophone and acoustic streaming velocity field measurements using Particle Image Velocimetry (PIV). Though we have not investigated acoustic streaming in the framework of a true ADV measurement system, we think that our work can give first clues to assess the sensitivity of ADV measurements to this phenomenon.

We present our experimental set-up and numerical model in section 2 and 3, respectively. Section 4 gives a short overview of some results from experiments, numerical simulations but also from a scaling analysis. Section 5 gives an overview of our approach to go towards the case of liquid metals, though our experimental approach is yet limited to the use of water.

2 EXPERIMENTAL SET-UP

Our set-up is sketched in figure 1. A 2MHz ultrasonic circular plane transducer, with effective diameter d_s = 28.5mm, is placed in an aquarium filled with water. Two acoustically absorbing tiles are used as walls in the aquarium; they are hatched on this drawing. The first tile is put along the wall at the end of the cavity to avoid reflected waves (on the right of the figure). The second tile is drilled with a hole which is covered with a plastic film. This plastic film is seen as a rigid wall for the hydrodynamic standpoint while it lets the acoustic waves enter the domain of investigation on the right of this tile. The hole diameter is about twice the transducer diameter. The width of the aquarium is 18cm and the depth is 16cm. The absorbing tiles position can be modified to tune the investigation domain length and location with respect to the sound source.

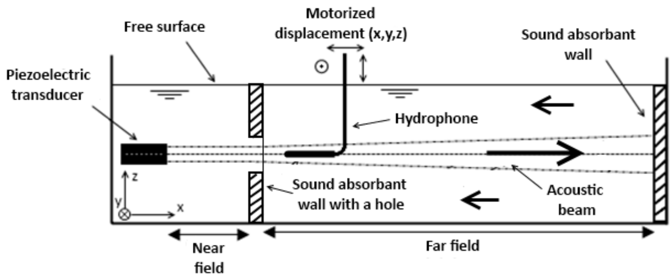

Figure 1: Sketch of the experimental configuration. The origin of the frame will be taken at the center of the acoustic source. The hydrophone is removed when PIV measurements are performed.

The acoustic field is characterized via pressure measurements. A three dimensional motorized system is used to move a 1mm diameter needle hydrophone from *Precision acoustics*™ in order to map the acoustic pressure field in the horizontal middle plane (see figure 2). We use the *Labview*™ software through a PXI unit from *National Instruments*™ to supply the transducer via a power-amplifier and a wattmeter, to acquire voltage on hydrophone terminals and to control the motorized system motion. The wattmeter allows us to read the incident electrical power sent to the transducer; this power is regulated to stay constant all along the experiment. The acoustic streaming flow is characterized by Particle Image Velocimetry measurements (PIV) thanks to another independent system. The two characterizations cannot be made simultaneously since the hydrophone and its holder are intrusive; they are removed before carrying out PIV sessions.

3 NUMERICAL MODEL

We have implemented a numerical model of this experiment using a commercial software, namely *StarCCM+*™. This model is based on the incompressible Navier-Stokes equations, featuring an acoustic streaming force term given by the following expression:

$$\vec{f}_{ac} = \frac{2\alpha I_{ac}}{c}\vec{x}, \qquad (1)$$

for a wave propagating along the x direction with the acoustic intensity I_{ac}; here α and c are respectively the attenuation coefficient and the celerity of sound in the medium. We propose a derivation of this expression in a recent publication [3]. The acoustic intensity is computed from the acoustic pressure which is itself calculated under *Matlab*™ using a linear propagation model. Under the plane wave approximation, the relation between acoustic pressure, p_{ac}, and intensity is the following:

$$I_{ac} = \frac{p_{ac}^2}{2\rho c}. \qquad (2)$$

A typical acoustic pressure field is plotted on figure 2. This is a typical acoustic field radiated by a plane monochromatic source. As expected from the diffraction theory, it features a near-field/far-field structure. Note that the near field length is nearly ten times the source diameter.

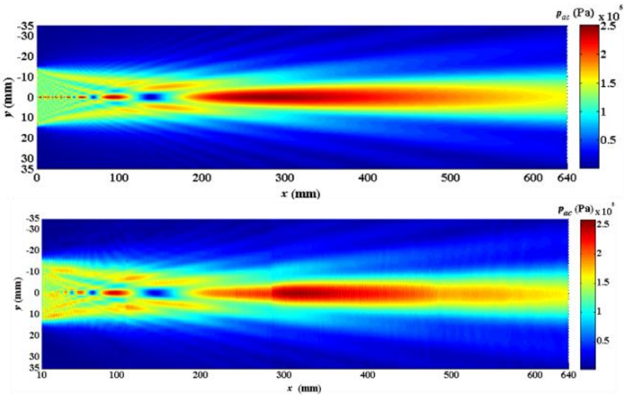

Figure 2: Iso-values of the acoustic pressure amplitude emitted by a circular plane transducer, issued from our linear propagation model (top) and experimental measurements (bottom).

The mesh grid is made of regular cubic cells and is refined in the central region where the acoustic beam is located. The bigger cell has a side of 2mm and a typical mesh has around four million grid cells. The coupled finite volume solver uses a second order upwind scheme. Some computations have been performed using an unsteady solver, with an implicit, second order, scheme. We have verified that the obtained velocity fields were not mesh dependent. For more details on the experimental and numerical methods, please see reference [4].

4 RESULTS

Figure 3 shows typical velocity fields issued with the same parameters from the experiments (top view) and from the numerical model (bottom view). As can be seen on these measurements, a good agreement is obtained between the numerical and experimental results.

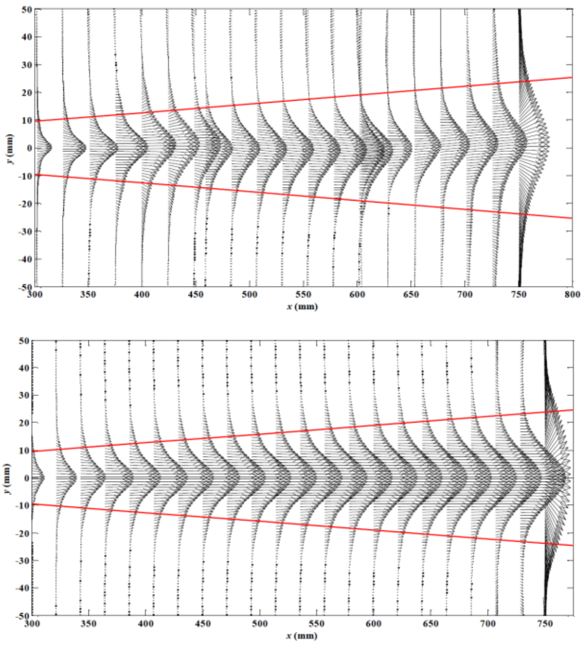

Figure 3: Typical velocity field, in the far field, issued from PIV measurements in the experiment (top) and from a numerical simulation (bottom). The red lines give the shape of the acoustic beam.

The edges of the acoustic beam are sketched by red lines: the beam has the shape of a cone, the half-angle θ of which is such that $\sin\theta = 1.22\ \lambda/d_s$. One can see that the enlargement of the jet follows the enlargement of the beam due to acoustic diffraction.

We have recently proposed [3] two scaling laws for acoustic streaming free jets, *i.e.* steady, laminar, acoustic streaming jets in a semi-infinite medium. As no confinement is considered and there is no reason for the jet to feature any significant curvature, the pressure gradient can safely be assumed not to play any significant role. The flow is thus governed by a balance between the combined effects of viscosity, inertia and the acoustic streaming force. In particular, focusing on the asymptotic case of negligible inertia effects, the following scaling law gives an estimate for the velocity level, u, reached on the beam axis:

$$u \propto \frac{\alpha P_{ac}}{\pi \mu c} \quad \text{be} \quad u \approx \kappa_2 \frac{\alpha P_{ac}}{\pi \mu c}. \qquad (3)$$

where κ_2 is a multiplicative factor of the order of 1, P_{ac} is the acoustic power and μ is the fluid dynamic viscosity.

Figure 4 gives an illustration of how this scaling law compares with experimental data both from former investigations and from the present study. A reasonable agreement is observed. One can say the order of magnitude of velocity reached by the acoustic streaming flow in water with ultrasounds at 2 MHz is seen to be of 1cm/s per watt of acoustic power.

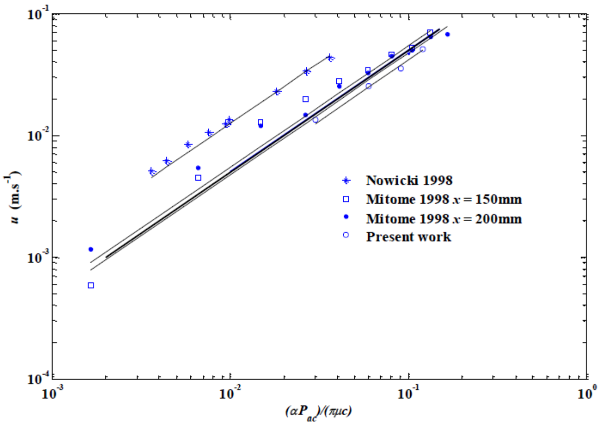

Figure 4: Comparison of present and former experimental data with the scaling law given from equation (3). The data from the literature are from Nowicki *et al.* [5] and Mitome [6].

5 TOWARDS THE CASE OF LIQUID METALS

One of the difficulties when dealing with acoustic streaming in liquid metals is that the acoustic attenuation coefficient is not a very well-known property for this type of liquids. The acoustic attenuation coefficient inside a liquid, α, is very often assumed to have three contributions. A first contribution is connected with the dynamical (or shear) viscosity μ, a second contribution is related to the bulk viscosity η, and a final contribution takes into account thermal effects. The expression proposed by Nash *et al.* [7] is:

$$N = \frac{\alpha}{f^2} = \frac{2\pi^2}{\rho c^3}\left(\frac{4}{3}\mu + \eta + \frac{c^2 \beta^2 \lambda T}{C_p^2}\right) \qquad (4)$$

where f is the frequency, ρ is the density, c is the wave velocity, β is the thermal expansion coefficient, λ is the thermal conductivity, C_p is the specific heat, and T is the absolute temperature. The dynamical viscosity μ and the properties involved in the thermal contribution can generally be obtained for standard liquids with an acceptable accuracy, so that the main difficulty will come from the estimation of the bulk viscosity η. We rely on this estimate of the attenuation coefficient, on the developed scaling laws but also on dimensional analysis and physical modelling techniques to assess the intensity of acoustic streaming expected in a liquid metal experiment. In particular, we consider the similarity of a hypothetic liquid metal set-up with our existing set-up [3]. We find that, under some assumptions, the similarity condition imposes the scale, Σ, the ratio in frequency, f, attenuation factor N and acoustic power P between the water-test and the liquid metal experiment. Under this condition the ratio in velocity observed in these apparatus is also given. Focusing on the case of liquid silicon and liquid sodium, featuring respectively a very high and a very low melting temperature, the similarity conditions is given in Table 1.

	Scale Σ	f_{test}/f_{real}	N_{test}/N_{real}	P_{test}/P_{real}	U_{test}/U_{real}
Silicon (1750 K)	8.2	0.046	0.17	8.9	0.38
Sodium (393 K)	2.5	0.23	0.28	4.9	0.59

Table 1: Similarity conditions for a model experiment in water (subscript *test*) and a liquid metal experiment (subscript *real*). The case of silicon is considered in the first line, that of sodium in the second line.

For instance, applying the ratios listed in the second row of table 1 on the values observed in our water experiment, it can be inferred that, in liquid sodium, a plane transducer of diameter 12 mm operating at 8.6 MHz would induce velocities on the order of 1.7 cm/s with an acoustic power of only 200 mW. As mentioned earlier, this numerical application makes us think that it should be taken care of acoustic streaming side-effects when measuring small velocities by in ADV in liquid metals.

6 CONCLUSION

We present an investigation of acoustic streaming driven by ultrasonic progressive waves in liquids. Our approach combines numerical simulations, experiments and scaling and dimensional analyses. Though our experiments were made only with water yet, dimensional and scaling arguments make us think that care should be taken of a possible acoustic streaming bias when measuring small velocities by UDV in liquid metals.

7 ACKNOWLEDGEMENTS

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