CHARACTERIZATION OF THE ASYMMETRIC STREAMING FLOW INDUCED BY A FOCUSED ULTRASOUND TRANSDUCER

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ABSTRACT

During high intensity focused ultrasound (HIFU) irradiation, different mechanical effects are induced such as acoustic streaming, cavitation bubbles and thermal deposition. These effects can be used for the dissolution of blood clots (thrombolysis), the destruction of kidney stones (lithotripsy) [1] or the thermal ablation of cancerous tumors [2]. Understanding the physics of these mechanisms is therefore essential in order to control them and improve the efficiency of treatment. Flows induced by focused ultrasound are generally considered as axisymmetric and then are studied by 2D Particle Image Velocimetry (PIV) techniques. However, beyond an applied acoustic pressure, the induced acoustic streaming is disturbed by cavitation bubbles whose spatial distribution is complex and may not be axisymmetric. In this study we characterize the tridimensional streaming induced by a focused ultrasound transducer in pulsed mode by using a 3D Lagrangian Particle Tracking Velocimetry (PTV) technique. Without cavitation, a steady state flow is not established, the maximum velocity is located at the focal zone and the flow is axisymmetric. In presence of cavitation, the bubble spatial distribution influences the acoustic field resulting in asymmetric streaming flow. While using pulsed sonication, the streaming becomes stationary for high cavitation activity.

Keywords: *Focused ultrasound, acoustic streaming, 3D-PTV, cavitation*

1. INTRODUCTION

High power ultrasound is widely used in the industrial and medical fields. In sonochemistry and surface cleaning applications ultrasound are emitted at low frequencies (of the order of 30 kHz) by a planar transmitter [3]. In therapeutic applications, it is necessary to spatially localize the ultrasound-induced effects. The emitters are then focused and the central frequency is higher (MHz range) [4]. The power ultrasound is the source of various induced effects such as the deposition of thermal energy on interfaces (soft tissue, solids) or nucleation, oscillation and implosion of gas microbubbles (acoustic cavitation). Another ultrasound-induced mechanical effect is the acoustic streaming, a slow mean flow set up by attenuation of the ultrasonic waves. This phenomenon makes it possible to increase, for example, the efficiency of sonothrombolysis treatment [5] by improving the mixing of the treatment area and removing blood clot fragments in the process. Acoustic streaming also improves cooling in microchannels or electronic components [6].

The acoustic streaming is generated by attenuation of acoustic waves propagating in a fluid and viscous medium. Different types of acoustic streaming can be identified depending on the ratio between the flow scale and the acoustic wavelength [7]. When the dissipation of the acoustic wave or the attenuation of ultrasound waves during propagation is dominant, the acoustic streaming is large-

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scale compared to the wavelength and is called *Eckart* streaming. The *Eckart* streaming is the prevailing streaming in ultrasound therapy or in sonochemistry for instance, and is the one we will consider in this study.

Commonly the Eckart streaming is investigated when using plane ultrasound transducers operating in a continuous sonication mode [8]. The associated flow is therefore stationary, usually described as an axisymmetric jet and experimentally assessed using a 2D Particle Image velocimetry (PIV) measurement technique [9]. Most of the experimental studies on Eckart streaming have been performed using low acoustic powers, far from the conditions of cavitation triggering. However, beyond a threshold power, the flow can be disturbed by the generation of acoustic cavitation bubbles, as the fluid must then by-pass these bubbles acting as obstacles. They are also new interfaces that can cause viscous boundary layer effects and generate their own small-scale streaming (called acoustic microstreaming [10]). When cavitation occurs in the sonicated medium, a significant increase in the streaming velocity has been observed as well as turbulent recirculation patterns that are difficultly assessed by 2D PIV measurements [11]. In this study, an Eckart streaming generated for high acoustic powers values by a focused ultrasound transducer in pulsed mode is characterized using a 3D Lagrangian Particle Tracking Velocimetry (PTV) technique. The experimental set-up is detailed in a second section, and the results are discussed in the third section.

2. EXPERIMENTAL SET-UP AND PROTOCOL

The experimental set-up is shown in Figure 1. It is composed of a tank filled with filtered, non-degassed water in which a focused therapeutic ultrasound transducer transducer (Imasonic) with a diameter of 10 cm is immersed. The focal point of the transducer is located 10 cm downstream of its position. The transducer is controlled by a sine wave of 500 kHz frequency generated by a function generator (Agilent, 33220 A, 20 MHz). The wave is generated with a duty cycle of 14 % over a total duration of 10 s and amplified by a power amplifier (Prana DP 300, 300 W). The signal power range of the signal in continuous mode is measured by a wattmeter and is between 5 and 60 W by varying the voltage between 102 mV and 348 mV. The flow is seeded with fluorescent particles (13 µm, emission wavelength 612 nm). These particles are excited by the second harmonic of a double pulsed Nd:YAG laser (Litron - Bernoulli - PIV 200 - 15, 15 Hz, 2*200 mJ, pulse width 8 ns). The flow is viewed by a set of 4 cameras (MiniShaker, Lavision) equipped with 25 mm lenses and 605±30 nm bandpass filters, allowing the study of a field of size 16x10x7 cm^3. To check for the presence of acoustic cavitation in the flow, a CMOS camera (Basler, acA60-750um) is added to the set-up. In order to synchronize all the experimental equipment, a pulse generator (BNC 575) is added to the set-up. The duty cycle of the sine wave sent to the transducer is synchronized with the laser illumination and the CMOS camera. The two laser cavities are triggered one pulse apart to increase the illumination rate to 30 Hz. A Shake-The-Box processing algorithm (LaVision) is used to reconstruct the particle trajectories [12]. The Eulerian volume velocity field of the liquid phase of the flow is then reconstruct.

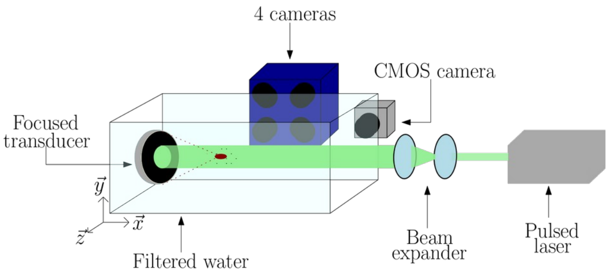

Figure 1. Experimental set-up. A laser beam is shaped with a beam expander in order to light up a volume centered on the transducer focal zone. The flow is seeded with fluorescent particles and 4 cameras follow these tracers. A CMOS camera is used to verify the presence of cavitation bubbles.

For each generated power, 20 acquisitions are carried out. In the first acquisition of the set, 100 images of the medium at rest are recorded. Then, the transducer, the laser and the CMOS camera are triggered from the 100th acquisition image. This allow to verify the absence of flow before the generation of ultrasound waves. In order to improve trajectories statistics, the 20 acquisitions are merged. Images are then post-processed and binarized, and the particle trajectories are reconstructed using the Shake-The-Box algorithm (Davis, LaVision). A reconstruction of the Eulerian velocity fields is then carried out using a binning algorithm (Davis, LaVision).

3. RESULTS

The evolution of the axial mean velocity u_x at the location of the focal point for each applied acoustic power (ranging from 5 W to 60 W) is presented in Figure 2(a). When the applied power is below 30 W, the mean velocity value fluctuates around 0.25 cm/s and imaging the sonicated medium confirms the absence of cavitation bubbles. This first regime is the low cavitation regime (I). When the applied power is between 30 W and 45 W the generation of cavitation bubbles is observed. The mean velocity value monotonously increases with the applied acoustic power. This second regime is the medium cavitation regime (II). Beyond an applied power of 50 W, the apparition of a strong cavitation field is systematically observed. This leads to an intense and reproducible flow whose velocity magnitude reaches a plateau around 2.5 cm/s. This corresponds to the high cavitation regime (III).

The evolution of the normalized axial velocity u_x for three different power values belonging to each cavitation regime is shown in Figure 2 (b) as a function of the normalized distance along the axis of acoustic propagation. The focal point is located at positions $x_f = 0$ mm on this axis. In the cavitation regime (I), the axial velocity distribution exhibits a gaussian shape around the focal point where it reaches a maximum. It is worth noting that the width of the velocity profile corresponds roughly to the profile of the acoustic intensity induced by the focused transducer along the ultrasound propagation axis (not shown here). In the cavitation regime (II), the maximum velocity is offset from the focal point and the induced acoustic streaming is broaden around the focal point. In the cavitation regime (III), the axial velocity reaches a plateau value far above the location of the focal point, meaning that the flow is established along the acoustic propagation axis. A peculiar modulation feature is observed upstream. A Fast Fourier Transform analysis of the velocity profile revealed that the characteristic frequency of these undulations is equal to the repetition frequency of the successive pulsed sonication bursts.

The axial velocity u_x as a function of the distance along the transverse y-axis and z-axis is plotted in figure 3 for each cavitation regime. The position r = 0 mm corresponds to the common location of the focal point in transverse directions. The profile of axial velocity roughly resembles a gaussian shape centered at location of the focal point. In cavitation regime (I) and (III), symmetric velocity profiles are observed in both transverse directions, indicating an axisymmetric behavior of the flow around the ultrasound propagation axis. For intermediate cavitation regime (II), a clear asymmetry is observed which is related to the inhomogeneous distribution of the cavitation bubbles within the sonicated medium.

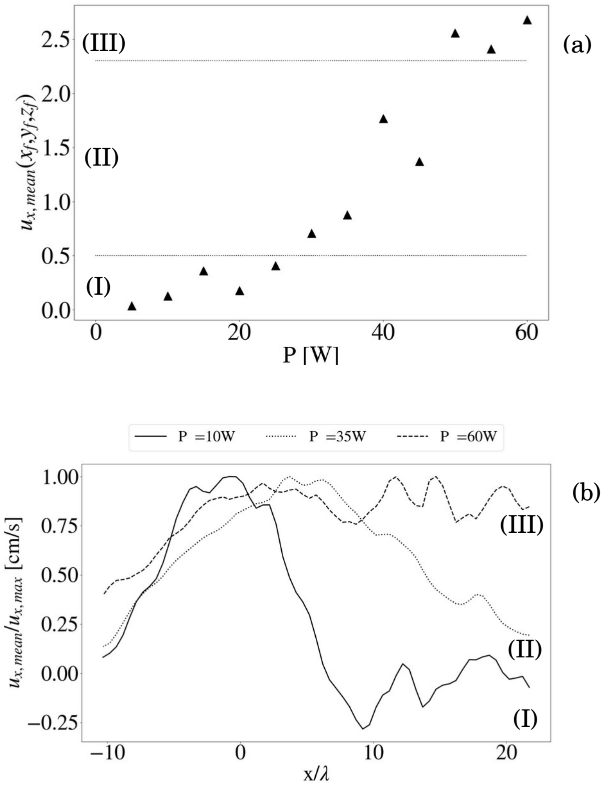

Figure 2. Distinction of the three different cavitation regimes. (a): Evolution of the maximum mean velocity at the location of the focal point (x_f, y_f, z_f) as a function of the applied power (from 5 W to 60 W). (b): Evolution of axial velocities measured for three different power values (P = 10, 35 and 60 W) as a function of the normalized distance along the axis of acoustic propagation. Velocities are normalized by the maximum value of the mean velocities. The focal point is located at the position $x_f = 0$ mm .

4. CONCLUSION

This experimental study allowed the three- dimensional characterization of the acoustic streaming induced by a

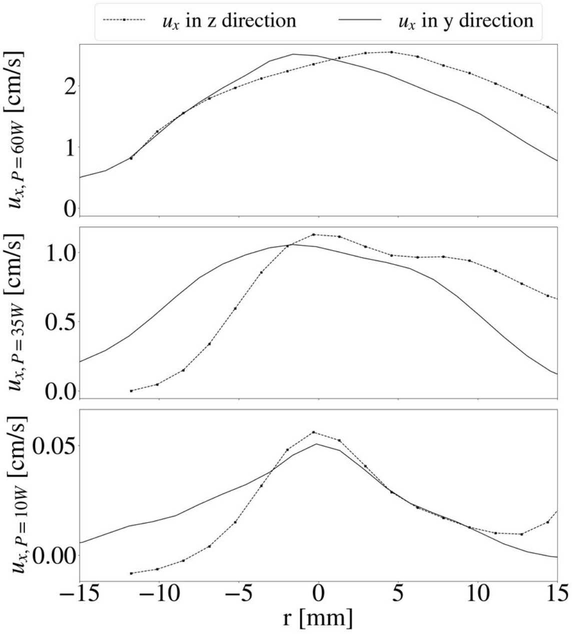

Figure 3. Evolution of axial velocities measured for three different power values (P = 10, 35 and 60 W) as a function of the distance along the transverse y-axis (solid line) and z-axis (dashed line) at the location of the focal point (x_f, y_f, z_f). The focal point is located at the position $y_f = z_f = r = 0$ mm.

focused transducer by using a 3D-PTV measurement technique. The asymmetric nature of the flow for medium cavitation regime (II) has been highlighted by the evolution of the measured velocities in the two directions transverse to the acoustic propagation. When a strong cavitation regime (III) is generated, the acoustic streaming becomes permanent in opposition to a lower cavitation regime (I) for which the flow velocity decreases sharply downward the focal point.

5. AKNOWLEDGEMENT

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