Experimental Thermal and Fluid Science 101 (2019) 37–47

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Characterization of focused-ultrasound-induced acoustic streaming

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ARTICLE INFO

Keywords:
High intensity focused ultrasound
Acoustic streaming
Particle image velocimetry
Like-jet flow

ABSTRACT

This study aims at characterizing acoustic streaming produced by High Intensity Focused Ultrasound (HIFU) propagating in a liquid medium. Particle Image Velocimetry (PIV) technique was used to determine velocity fields in an infinite medium of water subjected to a focused ultrasonic field. The tests were carried out at a transducer resonance frequency of 550 kHz for different applied acoustic pressure at the focus (ranging from 2.6 to 18.4 bar). The experimental results allowed characterizing the mean streaming flow and its evolution with the wave amplitude: In particular, it is shown that a region where viscous effects are negligible, which leads to a linear behavior of the axial velocity with respect to the excitation pressure amplitude, does exist but is limited to the region upstream of the focal area of the transducer. A scaling analysis provides an estimate of the maximum velocity, and shows that it obeys a 4/3 power law with respect to the excitation pressure amplitude, as long as the position of this maximum velocity corresponds to the focal point, which is not the case for highest pressure amplitude, for which it is shifted downstream of the focus. In addition, the streaming flow is compared to a classical free jet flow. Similarities and differences existing between both flows are reviewed and a self-similar zone for the velocity transverse profile is identified in the expansion zone of the flow.

1. Introduction

Acoustic streaming, which is the flow generated by an ultrasonic wave propagating in a fluid medium, is used in several applications. Nowadays, several studies suggest its use for optimizing crystallogenesis process and ensuring the crystalline material homogeneity by controlling temperature fluctuations. This phenomenon is also an interesting way to improve heat dissipation of micro-devices such as micromechanical components [1]. For therapeutic applications, acoustic streaming is an important contributor in the sonothrombolysis technique which could treat certain cardiovascular diseases by destroying blood clots blocking blood circulation [2]. In this technique, acoustic streaming improves mixing in the treatment zone and thus makes thrombolytic agents more effective [3]. Tachibana [4] reported that acceleration of fibrinolysis with urokinase thrombolytic drug is associated to unidirectional motion of drug driven by acoustic streaming. Ultrasound at 1.3 MHz was applied with low intensity of 0.3 $W\ cm^{-2}$ for 60 s. In other therapeutic applications, Dayton et al. [5] proved that acoustic streaming enhances particle internalization and therapeutic delivery. Measurements were conducted for four center frequencies (10, 5, 2.25, and 1 MHz) and three acoustic intensity levels (480, 240, and 120 $mW\ cm^{-2}$) with peak pressures of the order of 1 MPa. In large blood vessels and under acoustic pressures ranging from 10 to 40 bars, at 1.5 MHz, Solovchuk et al. [6] found that acoustic streaming can significantly change the temperature field and thermal lesions created by ultrasound near blood vessels. Apart from medical applications, the Acoustic Doppler Velocimeter (ADV) is widely used for the characterization of fluid flow: Secondary flows, namely generated by the ADV's acoustic pulses due to acoustic streaming, may affect the accuracy of measurements in experiments with small velocities [7,8]. For all these studies, involving focused ultrasound applications with acoustic pressures ranging from 2 to 40 bars and frequencies of few hundreds of kHz to several MHz, acoustic streaming has a significant effect. For more accuracy, acoustic streaming needs to be quantitatively estimated in such applications.

Acoustic streaming phenomenon has been known since the 1830 s and has since been the subject of several fundamental and experimental researches [9]. However, very few studies either numerical [10,11] or experimental [12,13,14] investigated acoustic streaming in the special case of focused ultrasound. And a lot has to be done to further explore and experimentally characterize this focused ultrasound hydroacoustic aspect of focused ultrasound.

From a general point of view, if the longitudinal scale of the ultrasound wave propagation medium is much larger than the

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https://doi.org/10.1016/j.expthermflusci.2018.10.001
Received 30 March 2018; Received in revised form 30 September 2018; Accepted 1 October 2018
Available online 08 October 2018

wavelength, a propagating wave is reported. Under these conditions, a steady flow appears in the liquid arising from the ultrasound absorption. This is called the Eckart streaming [15], where it is considered that the induced velocity in the case of a plane wave in an infinite medium, is proportional to the square of the acoustic pressure. Lighthill [16] established that this steady streaming motion is due to the Reynolds stress created by the viscous dissipation of the acoustic energy per unit volume, and added the hydrodynamic non linearity term in the Navier-Stokes equations. Besides, in the case where the acoustic beam does not interact with the medium lateral walls, no acoustic boundary layer is present in the problem and Rayleigh streaming (which is boundary layer driven streaming inside a standing wave resonator where the shear viscosity close to a solid boundary is responsible for the induced flow [17]), is negligible compared to the Eckart streaming.

In both cases, limiting the analysis to an incompressible and Newtonian fluid in a steady state streaming flow, the streaming motion can be described by the following equation [16,18]:

$$\rho_0 u_j . \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + F_{aci}, \tag{1}$$

based on a Reynolds-like decomposition of the velocity field into $u_{i\ tot} = u_i + u_{i\ ac}$, where $u_{i\ ac}$ is an oscillating component whose average value over a period of the ultrasonic wave is zero, and u_i corresponds to the average of the velocity field $u_{i\ tot}$ over one period of the ultrasonic field. The same decomposition is applied to the pressure $p_{tot} = p + p_{ac}$. The density ρ_0 is the equilibrium density of the fluid and μ is its dynamic viscosity. The obtained equation describes the average behavior of the fluid submitted to the acoustic volume force associated with the Reynolds stress given by $\overline{(\rho_0 u_{aci} u_{acj})}$:

$$F_{aci} = -\rho_0 \frac{\partial \overline{u_{aci} u_{acj}}}{\partial x_j}, \tag{2}$$

the overbar denoting here the averaging over one acoustic period. This average behavior of the fluid corresponds to the streaming flow.

Streaming flows produced by acoustic beams result generally in shear flows with hydrodynamical aspects controlled by the mean-velocity difference with the surrounding fluid at rest, the mean velocity being predominantly in the axial direction. This situation is very similar to a jet flow, and few studies already compared streaming flows to jet flows in the case of plane sources [19,20].

The free circular jet is an axisymmetric three-dimensional flow, where the fluid is ejected through a circular nozzle and mixes with a surrounding identical fluid at rest at infinity. It should be noted that, in this kind of free flows, the radial flow dimension is smaller than the longitudinal one (flow direction), and the gradient with respect to the radial scale is dominant. Thus, this flow is characterized by a boundary-layer nature flow, and thus the use of boundary layer equations (Prandtl's mixing length theory) is justified [21].

Free circular jets, whether they are laminar or turbulent, have been the subject of many studies, whose pioneering works date back to 1944 [22–24]. It has been shown that beyond an initial development region, where properties of the flow depend on the injection velocity profile and shape, the jet flow reaches a region characterized by more generic behaviors with the mean-velocity profile becoming self-similar. In this self-similarity region, the jet spreads linearly, and the decay of the mean-velocity on the axis is inversely proportional to the axial distance.

In the present study, the acoustic streaming flow produced by a focused ultrasound field is measured using a Particle Image Velocimetry (PIV) technique previously validated in this context [25]. A brief description of the method is given in Section 2. In Section 3, measurements of the mean-velocity distributions are given for several acoustic pressure amplitudes, and their main properties are discussed. Scaling analysis is proposed to understand the behavior of the mean-velocity evolution on the acoustic axis and its dependence with regards to acoustic pressure amplitudes. Then, a comparison with a free circular jet flow provides additional characterizations of the streaming flow beyond the transducer focus.

2. Experimental procedure and methods

Experiments were carried out in a 60-l tank (0.58 × 0.38 × 0.27 m (LxWxH)), filled with degassed and filtered water (oxygen concentration < 2 mg L^{-1}). The tank walls were made of glass to allow optic access, and water was seeded with 0.09 g m^{-3} of spherical Polyamide Seeding Particles (Dantec Dynamics) whose diameter is 5 μm and whose density, close to that of water, is 1030 kg m^{-3} [26]. These seeding particles are shown to be reliable and appropriate to characterize the streaming flow under the experimental conditions of the study and to be free of any bias due to acoustic radiation pressure [25]. To generate the ultrasonic waves, a piezoelectric focused transducer (Imasonic) with a 10 cm diameter and a 10 cm focal length was used. The transducer was immersed 15 cm deep into the water tank and was fed at its resonance frequency of 550 kHz. The driving signal of the transducer was induced by a generator (Tektronix AFG3102, 100 MHz) which supplies an input voltage amplitude from 25 to 175 mV in continuous mode to a power amplifier (Prâna DP300, 53 dB gain), generating an acoustic pressure amplitude at the focus ranging from 2.6 to 18.4 bar. This pressure amplitude was measured by a hydrophone (MÜLLER-PLATTE NEEDLE PROBE, M60-1L) whose sensitivity was 1.14 mV bar^{-1}. An ultrasound absorber was placed at the end of the tank in front of the source in order to avoid standing wave generation.

Fig. 1 shows the generated acoustic pressure field along the acoustic axis direction and in the transverse focal plane. From this figure we can notice that the pressure field at the focus has a nearly-Gaussian profile along the propagation axis with a full-width half-maximum about 10 times the wavelength λ.

Velocity measurements were performed using the Particle Image Velocimetry (PIV) technique. The PIV system used a laser source (Changchun New Industries Optoelectronics MGL-F-532-2W) with a wavelength of 532 nm, operating in continuous mode and generating a 2 mm-diameter light beam. The laser beam was converted, using an optical system consisting of a lens assembly, to a 20 cm-wide and 250 μm-thick laser sheet, and then positioned to illuminate the measuring area including the focal zone. Due to the light scattered by the seeding particles, particle flow was recorded by a CMOS-based camera (Vision Research Phantom V12.1). 1280 x 800 pixel resolution images were acquired at a rate of 24 frames per second with an exposure time of 41.7 ms. The resulting field of view dimensions were 9 cm × 5.6 cm. The experimental set up is illustrated in Fig. 2.

To solve the seeding particle velocity field, each pair of images was cross-correlated using PIVlab (a set of routines built in MATLAB [27]) and adopting an algorithm using Fast Fourier Transform. This algorithm is adaptive and based on an initial assessment of velocity vectors on large interrogation windows (128 pixels × 128 pixels). Interrogation area size is gradually reduced to reach ultimately a size of 32 × 32 pixels (about 2.2 by 2.2 mm). It is generally required that the interrogation window comprises more than 5 particle images [28]: This condition is no more fulfilled below 32 × 32 pixel windows with the above mentioned quantity of introduced particles, and for smaller windows, decorrelation due to the lack of particles in the interrogation window deteriorates the quality of the velocity measurement. Frame time step was also tested to carry out correlation with an optimal one that takes into account the velocity scales. This convergence test led us to choose a 83.3 ms time step between two images, which is two times the original recording time step (41.7 ms). Images were recorded 60 s after the beginning of the ultrasound shot, ensuring the steady state of the flow in our case.

To get a properly averaged velocity field, it has been shown in a previous study that averaging over a number of 50 image-pairs was sufficient for an acoustic pressure amplitude at the focus of 5.2 bar [25]. However, in the present study, higher acoustic pressure amplitudes are