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Influence of the liquid viscosity on the formation of bubble structures in a 20 kHz field

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ABSTRACT

The cavitation field in a cylindrical vessel bottom-insonified by a 19.7 kHz large area transducer is studied experimentally. By adding controlled amounts of Poly-Ethylene Glycol (PEG) to water, the viscosity of the liquid is varied between one- and nine-fold the viscosity of pure water. For each liquid, and for various displacement amplitudes of the transducer, the liquid is imaged by a high-speed camera and the acoustic field is measured along the symmetry axis. For low driving amplitudes, only a spherical cap bubble structure appears on the transducer, growing with amplitude, and the axial acoustic pressure field displays a standing-wave shape. Above some threshold amplitude of the transducer, a flare-like structure starts to build up, involving bubbles strongly expelled from the transducer surface, and the axial pressure profile becomes almost monotonic. Increasing more the driving amplitude, the structure extends in height, and the pressure profile remains monotonic but decreases its global amplitude. This behavior is similar for all the water–PEG mixtures used, but the threshold for structure formation increases with the viscosity of the liquid. The images of the bubble structures are interpreted and correlated to the measured acoustic pressure profiles. The appearance of traveling waves near the transducer, produced by the strong energy dissipated by inertial bubbles, is conjectured to be a key mechanism accompanying the sudden appearance of the flare-like structure.

1. Introduction

Acoustic cavitation depicts the appearance of a large number of radially oscillating micro-bubbles in a fluid irradiated with a high intensity ultrasonic wave [1]. Such bubbles self-organize into striking structures, such as cones, filaments, rings, among others [2]. In many cases, the cavitating bubbles appear preferentially in the vicinity of the fluid container edges or near the transducer. Particularly, the formation of conical bubble structures has been described by various authors [3–6].

The problem is further complicated by the existence of two distinct cavitating bubble populations, evidenced recently by spectroscopic studies [7,8]. Almost stationary hot bubbles whose collapse is highly symmetric were found preferentially near the ultrasonic horn, whereas far from the transducer, rapidly moving colder bubbles exhibit emission of non-volatile species. It is conjectured that such emission originates from the heating of liquid nanodroplets injected into the gas phase of the collapsing bubbles by non-symmetrical collapses, jetting, or coalescence events. Why the two populations of bubbles are spatially separated remains to be elucidated and constitutes an additional challenge for theorists.

Understanding the localization of the bubbles and the shape of the acoustic field is fundamental to control and optimize sono-reactors, and their scale-up for industrial applications. However, the physics underlying the formation of bubble structures is complex, because acoustic cavitation involves a large range of timescales (from the nanosecond scale for the bubble collapse, to the second for the typical motion of the bubble structures) and of spatial scales (from the micron-size bubble, to a few centimeters for the wavelength at low frequency). Self-organization of acoustic bubbles occurs through the coupling between the acoustic field and the bubble population. The acoustic field nucleates bubbles, promotes their growth by rectified diffusion and their coalescence, and induces their translational motion relative to the liquid under the influence of Bjerknes forces [2,9]. Conversely, owing to their radial motion, the bubbles modify the sound velocity in the liquid [10–12] and produce sound attenuation [13,14] and distortion [15,16].

The equations modeling this coupled interaction have been derived long ago [17] but their full resolution in the general case remains as a challenger. However, satisfactory results have been obtain under restrictive assumptions [18,19]. On the other hand, assuming a known shape of the sound field, particle models,

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simulating the paths of a large set of bubbles, have achieved remarkable agreement between some experimentally observed structures and theory [20–22,9]. Attempts to calculate the retroactive effect of the bubbles on the sound field have also been performed [23–25], but remains difficult in the range of acoustic pressures involved in sonochemistry, because of the short time scale involved in the bubble collapse. Conversely, linear theory yields unrealistically low attenuations of the wave [5]. Building a robust predictive model remains therefore a challenging task [26].

As for experimental results, very detailed descriptions of a large collection of bubble structures can be found in the literature [2]. However, the corresponding pressure fields are generally not known in detail, except for the cone bubble structure which has drawn specific attention over the last decade [5]. Moreover, experiments are generally performed in water, and the influence of the liquid physical properties such as surface tension or viscosity have been poorly explored.

In a recent work, a simple nonlinear model was proposed for low-frequency, high-amplitude acoustic fields in presence of cavitation, suggesting that the strong attenuation of the field observed in bubble clouds [13,14] was due to the large energy dissipated by individual inertial bubbles [27]. This attenuation was found to produce traveling waves near the transducer, strongly repelling the bubble nucleated on its surface, as originally suggested in Ref. [28]. The resulting bubble paths reproduced reasonably well the observed shape of conical bubble structures [29] and the so-called "*flare structures*", observed in ultrasonic baths [2].

The model of Ref. [27] showed that for inertial bubble oscillations, viscous dissipation in the radial motion of the liquid around the bubble was the dominant source of dissipation, contrarily to the linear prediction for which thermal gradients in the bubble were the prevailing dissipation mechanism at low frequency [30]. The power dissipated by viscous friction in the radial motion of the liquid around a single bubble, averaged on one acoustic period, can be estimated once the bubble dynamics is known, by [27]:

$$\Pi_v = \frac{1}{T}\int_0^T 16\pi\mu_l R\dot{R}^2\, dt \qquad (1)$$

where μ_l it is the viscosity of fluid and $R(t)$ is the bubble instantaneous radius.

The liquid viscosity appears therefore as a potentially important physical parameter, through its action on the energy dissipated by the bubbles, and therefore on the wave attenuation and the shape of the acoustic field. This raises the natural question of how bubble structures observed in a given geometry would be modified by variations of the liquid viscosity. Moreover, acoustic cavitation in highly viscous liquids deserves specific interest for applications in food industry [31], sludge treatment [32] and polymers degradation [33], among others. This issue is also relevant for the interpretation of recent experiments on multi-bubble sonoluminescence in highly concentrated sulphuric or phosphoric acid [34,7], which are ten-folds more viscous than water at the concentrations used.

The motivation of the present paper is to examine experimentally the shapes of the bubble structures and of the acoustic field obtained in a given ultrasonic setup, for different liquid viscosities. The viscosity of the liquid was changed by adding given amounts of Poly-Ethylene Glycol (PEG-8000) to water and the amplitude of the transducer tip is varied. The output variables are the bubble structures observed and the acoustic pressure profile in the insonified vessel.

2. Materials and methods

The experimental set-up consists of a cylindrical vessel of 90 mm inner diameter and 150 mm height, built in 5 mm thick borosilicate glass (Fig. 1). The vessel is filled with 500 ml of fluid, resulting in a level of 80 mm. The fluid is insonified by an 19.7 kHz transducer located at the bottom of the vessel. The radiant face of the transducer has a diameter d = 50 mm. Because the studied phenomena is highly temperature-dependent, and cavitation noticeably heats the liquid, a special excitation strategy was developed to avoid excessive heating of the liquid: ultrasound is turned on during about 2000 cycles, after which the system is left still during 6 s. Preliminary trials have established that this strategy allows the realization of cavitation experiments while keeping the temperature constant within 1 °C.

The emitter amplitude was characterized by monitoring the peak displacement U_0 of the transducer during the experiments. The latter can be obtained by monitoring the current I feeding the transducer, and a calibration curve of U_0 *vs.* I was drawn. The current I was measured using a high frequency Hall-effect probe, while the displacement of the transducer radiant face U_0 was measured with a laser-Doppler system. The resulting calibration curve is shown in Fig. 2. It can be seen that the relationship between U_0 and I is quite linear, and we checked that this linear relationship remained unchanged even if the impedance loading the transducer was varied. This justifies our method to monitor the displacement amplitude of the transducer face during the experiments.

On the other hand, the acoustic pressure in the chamber was measured with a home-made PVDF hydrophone [35], which was calibrated by using a non-linear calibration system [36]. The sensitivity of the probe at the fundamental frequency was found

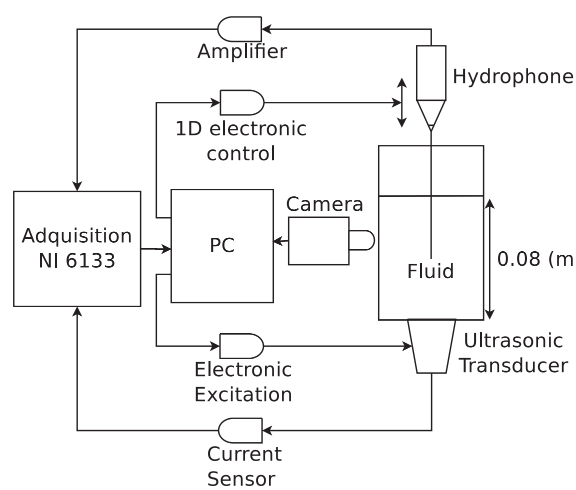

Fig. 1. Schematic experimental set-up.

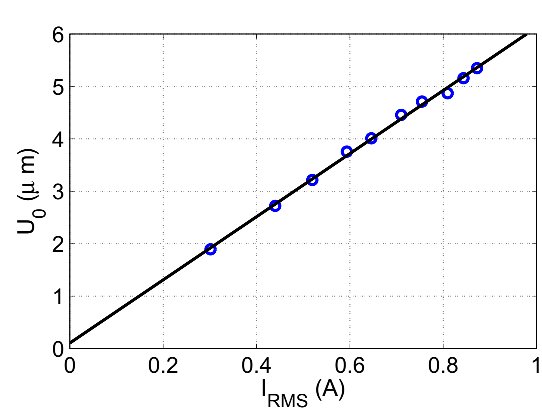

Fig. 2. Displacement amplitude of the transducer as a function of the feed current.