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Characterizing the cavitation development and acoustic spectrum in various liquids

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ABSTRACT

A bespoke cavitometer that measures acoustic spectrum and is capable of operating in a range of temperatures (up to 750 °C) was used to study the cavitation behaviour in three transparent liquids and in molten aluminium. To relate these acoustic measurements to cavitation development, the dynamics of the cavitation bubble structures was observed in three Newtonian, optically transparent liquids with significantly different physical properties: water, ethanol, and glycerine. Each liquid was treated at 20 kHz with a piezoelectric ultrasonic transducer coupled to a titanium sonotrode with a tip diameter of 40 mm. Two different transducer power levels were deployed: 50% and 100%, with the maximum power corresponding to a peak-to-peak amplitude of 17 μm. The cavitation structures and the flow patterns were filmed with a digital camera. To investigate the effect of distance from the ultrasound source on the cavitation intensity, acoustic emissions were measured with the cavitometer at two points: below the sonotrode and near the edge of the experimental vessel. The behaviour of the three tested liquids was very different, implying that their physical parameters played a decisive role in the establishment of the cavitation regime. Non dimensional analysis revealed that water shares the closest cavitation behaviour with liquid aluminium and can therefore be used as its physical analogue in cavitation studies; this similarity was also confirmed when comparing the measured acoustic spectra of water and liquid aluminium.

1. Introduction

Acoustic cavitation involves the formation, growth, pulsation, and collapse of micro-bubbles in liquids under high-intensity ultrasound waves. Cavitation is initiated when the amplitude of the acoustic pressure exceeds a threshold e.g. ~0.15 MPa for liquid glycerine [1], 0.06–0.1 MPa for distilled water [2], and ~0.7 MPa for molten aluminium [2] for driving frequencies around 20 kHz. With further increase in acoustic pressure, there is a transition to the developed cavitation regime where thousands of micro-bubbles are formed. These bubbles expand during the rarefaction phase and rapidly collapse during the compression phase of ultrasound, thereby producing high-speed jets (300–1000 m/s) and local hydrodynamic impact pressures in the range of GPa [3]. These phenomena are believed to be responsible for mixing, fragmentation, erosion, wetting, sono-capillary, and other effects that have various practical industrial applications [2–4].

Multi-bubble systems have been vigorously studied in recent years. However, the dramatic fluctuations of bubble ensembles, the complex interactions between bubbly clouds, and their non-linear cavitation activity make it difficult to observe and model cavitation in a consistent and thorough manner [5]. Nevertheless, with suitable cavitation detectors [6,7], broadband acoustic emissions from micro-bubbles undergoing acoustic cavitation can be detected. High-order resolution of the frequency spectrum allows the determination, characterization, and quantification of the cavitation regime with great accuracy.

Key features of a typical acoustic spectra include:

(i) sharp peaks corresponding to harmonics and ultra-harmonics of the acoustic driving frequency with further contributions from the non-linear dynamics of cavitation bubbles;
(ii) sub-harmonics related to the excitation of bubbles at sub-harmonic resonances that indicates the inception of cavitation regime [8]; and

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(iii) a continuous broadband component, commonly known as "white noise" or "cavitation noise", which is linked to the occurrence of violent inertial cavitation at large acoustic intensities [9].

The choice of the driving frequency, and consequently the size range of cavitating bubbles, is very important for both physical and chemical effects. Specifically, it is shown that driving frequencies in the low frequency range (i.e. 20 kHz) are associated with larger and violently collapsing bubbles that are mostly responsible for mechanical effects such as surface deformation, erosion, de-agglomeration, and fragmentation while driving frequencies in the MHz range are associated with a shorter life cycle of smaller cavitation bubbles that affect chemical reactions and cleaning [10]. The frequency spectrum analysis provides substantial information on the characteristics of cavitation in a liquid volume. By analysing the prominent peaks across the frequency spectrum as has been done in Refs. [11,12], regions of higher cavitation activity can be revealed and the mean size of active cavitation bubbles can be estimated.

In this work, we examined the effects of liquid properties on the development of the cavitation zone, the behaviour of the cavitation cloud, and the corresponding acoustic emissions. To identify the characteristic frequencies due to cavitation development at two acoustic powers, a detailed analysis of three liquid environments with distinctly different properties – water, ethanol, and glycerine – was conducted by observing the cavitation structures and analysing the frequency spectra received by a bespoke cavitometer capable of working in a range of temperatures [6]. Active cavitation bubbles and bubble cloud formation were observed macroscopically using a high definition digital camera. The magnitudes of broadband cavitation noise of the tested liquids were compared. To the authors' knowledge, this is the first attempt of systematic characterization and comparison of cavitation development in these three liquids. The results were analysed with dimensionless parameters, and the acoustic spectra for water and liquid aluminium were compared. The results of this study may be useful for the selection of a transparent analogue for opaque liquids such as molten aluminium, which are now in the focus of technological development of ultrasonic processing [2,4,11,12].

2. Methods and materials

2.1. Experimental setup

A 1-kW piezoelectric transducer (Hielscher UIP1000HD) operating at 20 kHz induced ultrasonic oscillations continuously in three transparent liquids, i.e. de-ionised water, ethanol and glycerine, via a cylindrical titanium sonotrode of 40-mm diameter. These three liquids were not degassed prior to the experiments. The tested liquid was contained in a rectangular, glass-walled tank with the base area 290 mm × 210 mm. The liquid height was 110 mm. The radiating surface of the vertically mounted sonotrode was immersed 20 mm below the liquid surface. There is a limited choice of variables that can be kept constant in the experiment: one is the frequency (20 kHz), another is either the input power or the oscillation amplitude. In this work, we have selected to keep the amplitude constant for comparison of different liquids (albeit we performed two series of comparison at two levels of constant amplitude). The amplitude of the vibrating surface was 17 μm peak-to-peak in all liquids when the sonotrode operated at 100% power (and 8.5 μm peak-to-peak at 50%). The acoustic power at the tip of the sonotrode was monitored by subtracting the input electric power of the transducer when sonotrode operates in the studied liquid from that measured in the reference medium (air). This value was recorded using a wattmeter integrated to the transducer device. The acoustic powers of the sonotrode were 90 ± 3 W, 78 ± 2 W and 230 ± 5 W for water, ethanol, and glycerine, respectively, when operating at 100% power. The temperature was continuously monitored during the experiments and was maintained at 21 ± 1 °C.

The cavitation and flow patterns were recorded using a high definition digital camera at 30 frames per second. Each experiment was repeated at least five times with very good reproducibility of the observed effects.

The cavitometer probe [6] with a spatial resolution of about 50 mm and a bandwidth of up to 10 MHz captured the acoustic spectra. Measurements of the acoustic emissions with this probe were performed at two points as shown in Fig. 1: i) below the sonotrode and ii) near the edge of the tank (110 ± 2 mm off the sonotrode axis).

The cavitometer consists of a 4 mm diameter tungsten waveguide that can be submerged into the liquid up to a depth of 100 mm; at the other end, the waveguide is connected to a piezo-electric sensor that converts the mechanical vibrations into an electrical signal. This signal is acquired by the measuring device after amplification. The waveguide of the cavitometer probe was submerged 40 ± 2 mm below the liquid free surface. The probe calibration has been performed in collaboration with the National Physical Laboratory (Teddington, UK) using independently calibrated vessels, sources, and hydrophones. A full account of the cavitometer design and performance can be found elsewhere [6].

Finally, cavitation emissions in liquid aluminium and water were compared. For this comparison, both liquids were sonicated

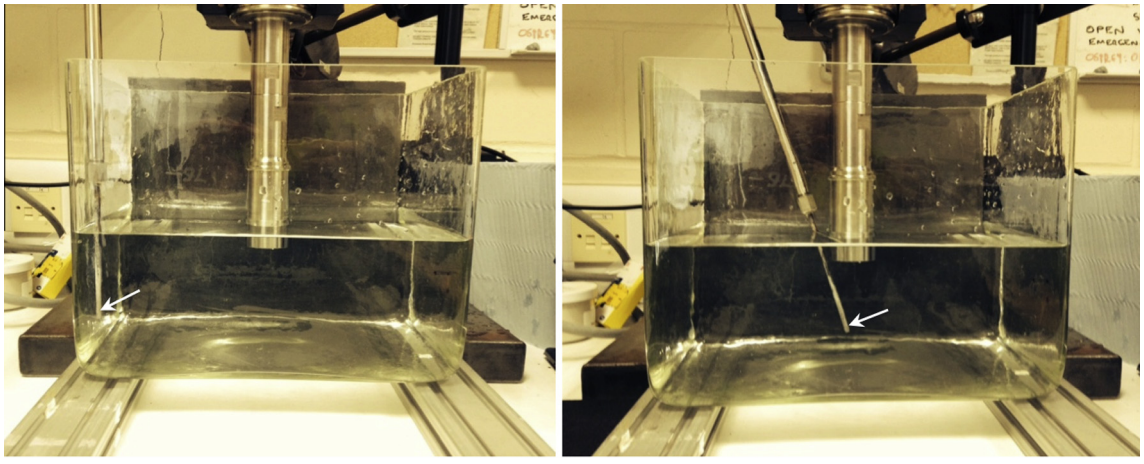

Fig. 1. Experimental test rig: a cavitometer (tip is shown by the arrow) placed a) nearby the edge of the vessel and b) below the sonotrode.