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Intense cavitation at extreme static pressure

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ABSTRACT

Cavitation is usually performed at hydrostatic pressures at or near 0.1 MPa. Higher static pressure produces more intense cavitation, but requires an apparatus that can build high amplitude acoustic waves with rarefactions exceeding the cavitation threshold. The absence of such an apparatus has prevented the achievement of intense acoustic cavitation, hindering research and the development of new applications. Here we describe a new high-pressure spherical resonator system, as well as experimental and modeling results in water and liquid metal (gallium), for cavitation at hydrostatic pressures between 10 and 150 MPa. Our computational data, using HYADES plasma hydrodynamics code, show that, under these conditions, the formation of dense plasma reaches peak pressures of about three to four orders of magnitude greater than the hydrostatic pressure in the bulk liquid and temperatures in the range of 100,000 K. Passive cavitation detection (PCD) data validate both a linear increase in shock wave amplitude and the production of highly intense concentrations of mechanical energy in the collapsing bubbles. High-speed camera observations show the formation of bubble clusters from single bubbles. The increased shock wave amplitude produced by bubble clusters, measured using PCD and fiber optic probe hydrophone, was consistent with current understanding that bubble clusters enable amplification of energy produced.

1. Introduction

Acoustic cavitation is the growth and collapse of cavities in a liquid driven by an acoustic wave: the growth is caused by the negative pressure, and the subsequent inertial collapse is driven by the combination of the positive-pressure phase of the wave and hydrostatic pressure [1]. Even at a hydrostatic pressure of 0.1 MPa, the pressure inside the collapsing bubbles can rise to more than 100 MPa and the temperature can reach several thousand degrees [1–8]. These conditions enable the cavitation bubbles to act as micro reactors with rapid heating and cooling rates to initiate, speed up, or enhance chemical reactions and provide a range of capabilities including producing allotropic transformations and synthesizing novel materials [5–11]. It is reasonable to expect that these transformational capabilities will be increased with more intense cavitation. Previous studies have shown that cavitation intensity can be increased by producing cavitation at high static pressures [12–19]. Here we describe a system to produce cavitation at extreme static pressures and provide illustrative experimental and numerical results of this system between static pressures of 10 and 150 MPa.

2. Materials and methods

2.1. Acoustic resonators

To achieve cavitation at extreme static pressures, we significantly changed our previous designs [12–19] of high-quality-factor spherical resonators that, with relatively small consumption of power, produce high-amplitude standing acoustic waves. Resonators have varied between 6-in. (15.24 cm) and 15-in. (38.1 cm) outer diameter (OD), with larger ODs operating at lower frequencies for stronger cavitation. The state-of-the-art is the 15-in. OD resonator operated at 16 kHz. The quality factor of the resonators is affected by the number, position and design of the access ports (e.g., for filling and draining, inserting hydrophones and other probes), windows and acoustic drivers. All of these components were significantly changed following numerous tests and modeling with COMSOL multiphysics.

The resonators were pressurized using high-pressure generators (HiP, High Pressure Equipment Company), which are essentially manually operated piston screw pumps. For the experiments above 30 MPa static pressure, we motorized the HiP

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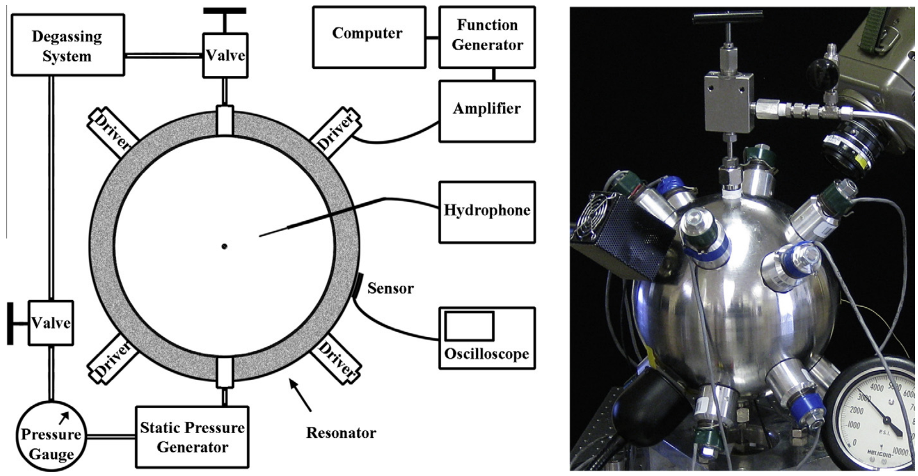

Fig. 1. Schematic of a typical experimental configuration and a photograph of a 9.5-in. windowed resonator used for experiments with a high-speed camera (top right).

generator and controlled the static pressure using a program written in IGOR Pro (IGOR Pro 6, WaveMetrics, USA). In these experiments, static pressure was monitored using two calibrated pressure transducers (PX91N0-60KSV, OMEGA Engineering, USA and AST47HPX60000P2D0123, American Sensor Technologies, USA) with digital panel meters M20020DCV1 (Micron Meters, USA). In the experiments below 30 MPa, we used analog gauges (10,000 psi, ACCO Helicoid Gauge, USA), as shown in the bottom right of Fig. 1, as well as digital gauges (MP40A series, Micron Instruments, USA).

The resonators were driven by piezoelectric transducers, connected to RF power amplifiers (1140LA, Electronic Navigation Industries, USA). The amplifiers were fed by a function/arbitrary waveform generator (33120A, Agilent, USA) controlled by a computer using a program written in IGOR Pro.

The resonators were filled with filtered and degassed liquids. In selected experiments, argon or deuterium gas was added to the system. For experiments from 30 to 150 MPa the resonators were filled with a liquid metal, gallium, maintained at temperature around 40 °C. The photography and high-speed imaging data are from water-filled, windowed resonators operated at room temperature at 10–30 MPa static pressure, which is the safety limit of the sapphire windows required for visual observations.

2.2. High-speed imaging and shadowgraph photography of shock waves

High-speed videos were recorded using a Phantom v710 camera (Vision Research, USA) with 16 GB memory. The images were recorded either at 210,526 frames per second (fps) with 128 × 128 pixel resolution or at 397,660 fps with 128 × 64 resolution. In one sequence, the camera captures about 342,000 consecutive frames at 210,526 fps or 685,000 frames at 397,660 fps, producing videos of about 1.6–1.7 s.

The images were taken using a Nikon 50 mm F1.8 lens and 13 mm extension tube. Illumination (Fig. 1, right panel) was provided using a 250 W gooseneck photo light (North Star, USA) for side lighting and a 50 W light with a diffusion disc for backlighting. Shadowgraph photography of shock waves was performed using a parallel beam of light produced by a 5 mW laser (532 nm, LightVision Technologies) and a 10× beam expander (Melles Griot). Propagation speeds of shock waves from collapsing bubbles were determined by measuring the radial expansion of shock waves seen as expanding shadowgraphic circles between the consecutive frames. To reduce the uncertainty of the measurements, we used average values of circle diameters measured at different angles.

2.3. Measurements of absolute pressure

Absolute pressure was measured using a self-calibrated fiber-optic probe hydrophone (FOPH-2000, RP acoustics, Germany) [20]. The sensitivity of the hydrophone was determined by measuring a DC photodetector signal at normal atmospheric pressure without acoustic signal and using an internal light scattering factor of the fiber-optic system that was measured at regular intervals. The photovoltage-pressure relation (provided by the manufacturer) was derived using isentropic Tait parameters for water and Gladstone–Dale relation between refractive coefficient and density, as well as correction factors for compression of glass and water temperature. Since the FOPH shows the absolute pressure, we also checked FOPH readings of static pressure against calibrated pressure gauges (20,000 psi, McDaniel Controls, Inc., USA) in 0.1–138 MPa pressure range. The readings agreed with an accuracy of 5%.

The FOPH uses a 140-μm diameter glass fiber with a 100-μm diameter sensitive core, making the hydrophone virtually omnidirectional up to MHz range. The FOPH fiber was inserted in high-pressure resonators through a 3/8-in. NPT port using 1/16-in. OD stainless steel tubing. To minimize acoustic interference from the tube, the fiber tip typically extended about 3 cm beyond the end of the tube. Recorded traces were deconvoluted with the FOPH impulse response provided by the manufacturer and processed using programs written in LabVIEW (National Instruments, USA).

2.4. Passive cavitation detection

Passive cavitation detection [21,22] was performed using polyvinylidene fluoride (PVDF) sensors (LDT0-028 K/L, Measurement Specialists, USA). The PVDF sensors are 28 μm piezoelectric films with rectangular (10 mm by 14 mm) sensitive elements and silver ink screen-printed electrodes, laminated to a 125 μm polyester layer with crimped–on solder tabs for electrical connections. The PVDF sensors were mounted on the outer surface of the resonators and had the same spherical curvature as the resonator shell, thereby focusing the sensors to the cavitation zone at center of the resonator (Fig. 1). This focusing ensured that shock waves radiated by cavitation bubbles reached different parts of the sensor at the same time, allowing us to maximize signal detection.

2.5. Laser nucleation

In some experiments, bubbles were nucleated using a Q-switched Nd:YAG laser (Minilite 1, Continuum) with a wavelength