An experimental study on the cavitation of water with effects of SiO₂ nanoparticles

Youwei Gu, Buxuan Li, Min Chen *

Department of Engineering Mechanics, Tsinghua University, Beijing 10084, China

ABSTRACT

Cavitation pressure is a measure of liquid tensile strength, which determines the cavitation inception in hydrodynamics. The previously measured pressure is known to be significantly different because of the presence of solid impurities serving as nucleation sites. A recent study reported that water can be stabilized with solid impurities such as SiO₂ nanoparticles. These nanoparticles are supposed to form stabilized hydrogen bonds with water. In the present paper, the effects of SiO₂ nanoparticles on cavitation inception are investigated experimentally through acoustic method at 1 atm and temperatures from 0 °C to 80 °C. With diameters of 20, 50 and 100 nm, SiO₂ particles are dispersed into degassed water. The dimensionless free energy of critical bubble is also calculated. Both the cavitation pressure and the free energy of critical bubble of water with SiO₂ decrease when compared with those of ultrapure water. The increase of particle concentration further decrease the cavitation pressure and the free energy of critical bubble. Increasing particle size, the cavitation pressure has no measurable difference. Results show that SiO₂ nanoparticles are destabilizing impurities, which always promote the cavitation inception of water within current experimental conditions.

© 2016 Elsevier Inc. All rights reserved.

1. Introduction

Cavitation is one of the fundamental phenomena in fluid mechanics. It often occurs in a metastable state of liquid by stretching below the saturated vapor pressure (P_{sat}) of the liquid. In the past few decades, attentions have been focused on cavitation in pumps, screw propellers [1], and liquid jets [2]. Although cavitation involves negative aspects, such as degeneration of performance and vibration in pumps, noise and erosion on solid surfaces [3], this phenomenon provides prospective applications for surface cleaning or medical purposes [4]. All these issues require better understanding and control of the cavitation process.

Cavitation is essentially a first-order liquid-gas transition. An energy barrier caused by molecular attraction exists in liquid for the bubble nucleation to overcome. The stretched liquid can exist below its P_{sat} for a certain time before the gas phase occurs. The negative pressure below P_{sat} can be large. For example, theoretical analysis shows that pure water can be stretched down to at least −1000 bars at 20 °C when impurities and container walls are not considered [5]. However, the results are not consistent when people try to measure the cavitation pressure (at which the metastable

liquid is broken through bubble nucleation) by experiments. An extensive review of cavitation in water can be found in Refs. [6,7]. Different methods, such as Berthelot tube techniques, centrifugation, shock wave, mineral inclusions and acoustic wave have been adopted to measure this cavitation pressure. The values of cavitation pressure are scattered, even among similar experiments. Among the experiments, two kinds of methods are often adopted, namely, acoustic cavitation and cavitation in mineral inclusions.

For acoustic cavitation, negative pressure can be generated in a standing wave created by the resonance of the water-filled container. Before a cavitation experiment is performed, the liquid is usually pressurized to a large positive pressure to remove pre-existing bubbles that may be trapped on walls [8]. With this method, Bader et al. [9] obtained their largest value as P_{cav} = −31 MPa at room temperature. Herbert et al. [10] used bursts of focused ultrasound, thereby avoiding the effect of bubbles trapped at the container walls. They performed two independent pressure calibrations and obtained highly reproducible results: the cavitation pressure increases monotonically from −26 MPa at 273.15 K to −17 MPa at 353.15 K. Afterward, they used another method with a fiber-optic probe hydrophone and obtained the cavitation pressure from −34 MPa at 274 K to −25 MPa at 320 K [11]. There was one noticeable different from the experiments by Bader et al., P_{cav} was observed to be independent of the environmental

* Corresponding author.
 E-mail address: mchen@tsinghua.edu.cn (M. Chen).

pressure, even the liquid was pressurized to 20 MPa. Maxwell et al. [12] later followed this approach and obtained a result as P_{cav} = -27.4 ± 1.3 MPa at room temperature.

Angell et al. [13] initially adopted the method of mineral inclusions. A micrometer size water droplet was trapped in a quartz crystal. In the inclusion, the bubble in the liquid disappeared upon heating at temperature T_d. When the water sample was cooled down, liquid water followed a nearly isochoric path, until cavitation occurred at T_{cav}. They chose to extrapolate the Haar-Gallagher-Keel (HGK) equation of state (EOS) to calculate the negative pressure P_{cav}. They observed cavitation at a maximum tension of -140 MPa at 315 K. Recent experiments by Azouzi et al. [14] confirmed this value.

The significant difference in the results of acoustic cavitation and the method of mineral inclusions remains unclear. People doubt the inclusion method because of two defects. On the one hand, the HGK EOS used in this method is a multiparameter EOS, which is fitted on the data where the liquid is stable. The validity of extrapolating it to metastable water has not been proved [15]. On the other hand, the water in the inclusions can be affected by SiO_2 walls. A recent study [16] stated that the majority of acoustic, centrifugal and shock wave experiments are correct. The authors [16] further speculated that an impurity stabilizing water exists in quartz inclusions. This stabilizing impurity can be attributed to SiO_2 clusters, which may stabilize the neighboring hydrogen-bond network. In the experiments on cavitation of nanofluids in water pumps [17,18], SiO_2 nanoparticles have been observed to postpone cavitation inception. However, in other experiments of nanofluids, cavitation in water was observed to be promoted when SiO_2 nanoparticles were added [19–21]. To date, the effects of SiO_2 nanoparticles on the cavitation remains unclear.

In the current study, we use a focused high-frequency pulsed ultrasonic wave to measure the cavitation pressure in ultrapure water, as well as in water with SiO_2 nanoparticles. Water samples with different concentrations and sizes of SiO_2 nanoparticles are studied. Possible reasons on the discrepancy between our data and those of other experiments are discussed.

2. Experimental setup

The experimental setup is shown in Fig. 1. Acoustic waves are generated by a piezoelectric transducer with a 16 mm inner diameter and 20 mm outer diameter, made of Saint-Gobain Quartz. The focal length (radius of curvature) is 46 mm and its working frequency is 1 MHz. The transducer is driven using a radio-frequency amplifier (North Star SWA200A, 70 kHz to 5 MHz), which is primarily designed to operate a 50 Ω resistive load. The matching network with a high-power downstep transformer and a resistor bridge is constructed in-house [22]. The waveform generator (ATANA AT3020) offers a sinusoidal signal (5–15 cycles duration of a single pulse) to the amplifier for all experiments. The amplifier then drives the transducer to generate acoustic waves. The root mean square voltage (U_{rms}) is measured as the excitation voltage to characterize excitation. Ultrasound pressure waveforms are measured in water samples by using a needle-shaped piezoelectric hydrophone (Precision Acoustics, 0.8–15 MHz), which is made of a 9 μm-thick gold electrode polyvinylidene difluoride film. The disk diameter of the hydrophone is 200 μm. The manufacturer provides calibration data for the whole hydrophone system with an uncertainty of 14% from 1 MHz to 20 MHz.

The needle hydrophone is inserted along the axis of the transducer. We repeat a given low amplitude acoustic wave to determine the position of the focus, which corresponds to the maximum of the peak-to-peak voltage of the hydrophone. A typical signal in the focus is shown in Fig. 2. From the view point of vertical and horizontal distances, the focusing region is very narrow (an ellipsoidal region with 15.2 mm³ in volume).

The experimental cell is made of polymethyl methacrylate with a volume of 150 ml. Care is taken to avoid pollution in the connections. Before filling, the cell and tubes are evacuated using a vacuum pump. Water or solution can then be sucked into the cell under vacuum. The valve near the cell is closed once the system is filled with liquid.

We used two different water samples: degassed ultrapure water (with a resistivity of 18.2 MΩ cm and a total oxidizable organic carbon less than 2 ppb) and colloid with SiO_2 nanoparticles. The diameters of SiO_2 particles used in colloid are 20, 50, and 100 nm. These particles, which are produced by the Institute of Chemistry of Chinese Academy of Sciences, exhibit a purity and density of 99.9% and 2143 kg/m³, respectively. The base liquid for solvent is degassed water with a mass fraction of 0.1% Na_2CO_3. The volume fraction of SiO_2 nanoparticles in the prepared samples are 1.5% ml SiO_2/ml water and 0.15% ml SiO_2/ml water for different concentrations. Fig. 3 shows the scanning electron microscope (SEM) images of 20 nm SiO_2 nanoparticles and the size distribution in the sample. The SiO_2 nanoparticles are uniformly spherical.
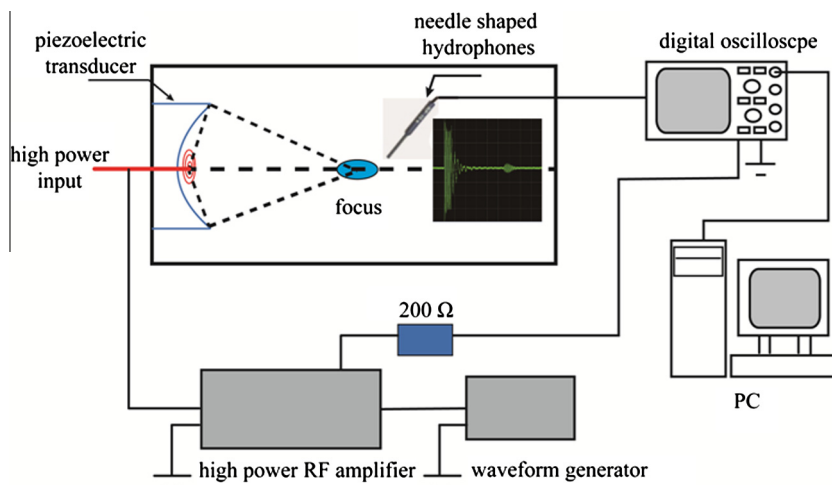

Fig. 1. Experimental system.