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Dynamic responses of a solid wall in contact with a bubbly liquid excited by thermal shock loading

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ABSTRACT

Several MW-class spallation neutron sources are being developed in the world. Specifically, intensive and high energy protons are injected into heavy liquid metals (mercury, lead or lead–bismuth eutectic) to induce the spallation reaction that produces neutrons. At the moment when the proton beams are injected, thermal shock occurs in the liquid metal, causing pressure waves to propagate in the liquid metal, collide against the container and damage it.

It is proposed that microbubbles are injected into the liquid metal to mitigate the impulsive pressure waves by means of absorption and attenuation effects. These effects are dependent on the relationship between bubble size and the rate of pressure increase. In the present experiment, a very rapid rise in pressure in the order of MPa/μs, equivalent to the rise in pressure due to proton beam injection, was simulated by the electric discharge method in a water loop test to investigate the impulsive pressure mitigation effect of injected microbubbles. The solid wall response was measured using an accelerometer, and the dynamic responses of microbubbles were observed using an ultra-high-speed camera filming at 5×10^5 frame/s. The sound velocity in bubbly water was estimated using a differential image technique. It was confirmed from the experimental results that microbubbles are effective in reducing impulsive pressure waves and to suppressing the impact vibration of the solid wall in contact with the liquid.

1. Introduction

The Japan Spallation Neutron Source (JSNS), a high-power pulsed neutron source, has been installed at the Materials and Life science experimental Facility (MLF) in the Japan Proton Accelerator Research Complex (J-PARC) [1]. The first proton beam was injected into the mercury target in May 2008, the power of the beam increasing up to 1 MW (3 GeV, 333 μA, 25 Hz) within about 5 years. The mercury target has benefits in terms of realizing the high-power pulsed neutron source, namely excellent cooling performance, sufficient neutron production, non-existent radiation damage and liquid phase at room temperature. On the other hand, MW-class pulsed proton beam bombardment repeatedly brings about high-intensity impulsive pressure waves in the mercury [2]. The pressure waves induce cavitation in the mercury through propagation inside it and by interaction with the solid wall of the stainless steel target vessel. The cavitation damage (“pitting damage”) degrades structural integrity and significantly reduces the lifetime of the target vessel [3,4]. The development of pressure wave mitigation technology is therefore needed to realize the mercury target for 1 MW proton beams injection [5].

Microbubble injection into mercury is a possible technique for reducing the pressure wave and pitting damage. In general, the interaction between shock waves and bubbles with a radius of sub-millimeter order, which is a relatively large bubble size, has been investigated experimentally and theoretically [6–12]. For example, Kameda and Matsumoto discussed it based on experimental results in water with homogeneously distributed bubbles [10]. Gas bubbles in a liquid markedly increase the compressibility of the liquid and reduce sound velocity in a range lower than the resonance frequencies of the bubbles [11,12]. Through the numerical calculations carried out by the authors to date [13,14], the gas microbubbles are expected to effectively mitigate the pressure waves in the mercury target by means of three mechanisms, namely, *i.e.* absorption, attenuation and suppression: (1) thermal expansion of mercury is absorbed by the contraction of the bubbles, (2) pressure waves are attenuated by thermal dissipation of kinetic energy in the bubbles, and (3) cavitation inception is suppressed by compressive pressure emitted by the expansion of the gas-bubbles. These effects are very dependent on bubble conditions (bubble size and void fraction) as well as the rate of rise in pressure.

In order to evaluate the mitigation effects experimentally, the authors carried out water tests by using a spark discharge technique to generate a very rapid rise in pressure. Microbubbles were injected into the flowing water while the bubble conditions were

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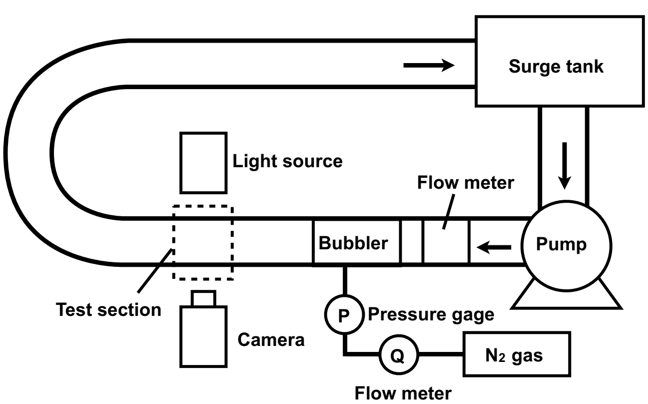
controlled using a swirled bubbler. The dynamic responses of pressure waves and microbubbles were observed using an ultra-high-speed video camera, while the time responses at the solid wall excited by the pressure waves were measured using an accelerometer and the pressure in water by a PVDF-type pressure transducer. From the optical images and measured signals the authors confirmed that the microbubbles were very effective in mitigating pressure waves and reducing sound velocity.

2. Experiment

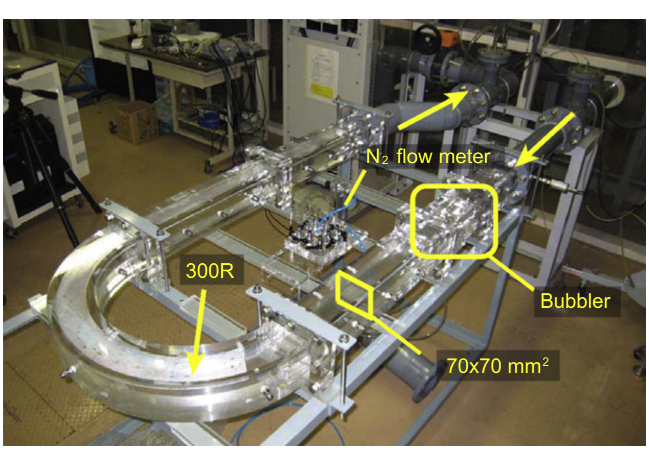
Fig. 1 shows a schematic view of the water loop used to investigate impulsive pressure mitigation by microbubbles. The loop consisted of straight and curved transparent acrylic pipes with a cross section of 70 × 70 mm^2 and a thickness of 20 mm, used to visualize bubble formation and motion. Water and gas flow rates were measured using mass flow meters (YAMATAKE, KID1B for water, HORIBA STEC, SEF-E40 for gas), respectively. Bubble size distribution was calculated from 2D images taken at each position on the straight pipe using a digital still camera (NIKON, D200).

In this experiment, the bubbler was the most important element in systematically investigating the bubbling effect on pressure wave mitigation. The authors developed a swirl-type bubbler with a relatively small flow resistance in order to produce microbubbles 50 μm in radius [15]. The void fraction was calculated as the ratio of N_2-gas to water flow rates and controlled by the gas flow rate, independently of the bubble size.

Fig. 2 shows the experimental setup of the Impulsive Pressure Generator (IPG), consisting of a spark discharge system (NORTH-TECH, AUTOLITH) to supply high voltage (maximum 6 kV) to two electrodes made of copper rods of 6.35 mm in diameter with hemi-spherical ends. The pressure propagation in water was measured using a PVDF-type pressure transducer (MÜLLER, Platte-Gauge). Beside this, the solid wall response against the pressure waves was measured using an accelerometer (RION, PV-90B) fixed on a sidewall of the square pipe. Both signals were recorded on a digital scope (YOKOGAWA, DL-9040) with sampling rates at 62.5 MHz for pressure and 1.25 MHz for acceleration. Images of the dynamic responses of bubbles against the pressure waves generated by the IPG were visually taken using an ultra-high-speed video camera with a maximum frame rate of 10^6 frame/s (SHIMADZU, HPV-1).



(a) Schematic drawing of the water loop



(b) Experimental setup of the loop

Fig. 1. Water test loop to investigate the effect of microbubbles on pressure waves.

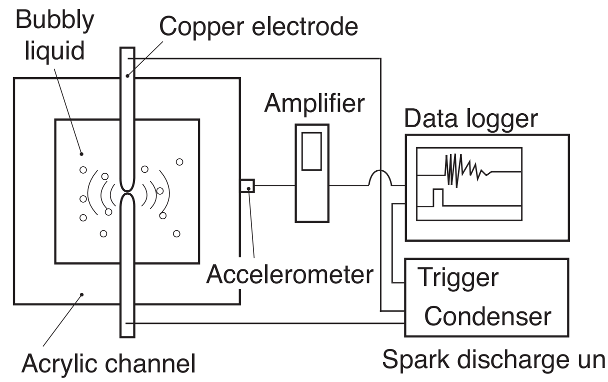


Fig. 2. Experimental setup for causing pressure in flowing bubbly water.

3. Results

3.1. Impact and bubble conditions

The mechanism of pressure wave generation by the spark discharge in water is given by the following equations:

$$Q = \int I^2(t)\mathcal{R}\,dt, \quad (1)$$

$$\Delta T = \frac{\eta Q}{\rho C_p}, \quad (2)$$

$$\Delta P = \Delta T \beta K, \quad (3)$$

where K is the bulk modulus, β is the volumetric expansion coefficient, P is the pressure rise, T is the temperature rise, Q is the total joule heating rate, η is the thermal efficiency of the spark, ρ is the density of water, C_p is the specific heat, $\mathcal{R}$ is the electric resistance of water, I is the current, and t is time. The very rapid rise in pressure is caused by thermal shock due to electric discharges between the two electrodes in the water.

The typical time responses of current discharge and measured pressure are shown in Fig. 3. The pressure was measured using the PVDF pressure transducer at a distance of approximately 3 mm from the electrode sparking point. The electric noise was recorded just after sparking. It was confirmed that the pressure rising incident occurred rapidly within a few μs and decayed exponentially within approximately 10 μs, which shows very good coincidence with the electronic discharge response. In other words, the pressure was definitely generated by electric discharge in water.

Fig. 4 shows the relationship between the bubble size and the number of bubbles counted from the images in the cases of 10^{-4} and 10^{-3} of void fractions estimated from the ratio of the N_2-gas flow rate to the water flow rate. The bubble size distribution was almost independent of the void fraction and the peak was 50 μm in radius.