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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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