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Cavitation erosion induced by proton beam bombarding mercury target for high-power spallation neutron sources

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ABSTRACT

A liquid mercury target system for a megawatt-class spallation neutron source is being developed in the world. Proton beam is injected to the mercury target to induce spallation reaction. The moment the proton beams bombard the target, pressure waves are generated in the mercury by the thermally shocked heat deposition. The pressure waves excite the mercury target vessel and negative pressure that may cause cavitation along the vessel wall. Gas-bubbles will be injected into the flowing mercury to mitigate the pressure waves and suppress the cavitation inception. The injected gas-bubbles conditions were examined and the effects were predicted experimentally and theoretically from the viewpoints of macroscopic time-scale and microscopic time-scale, i.e. in the former is dominant the interaction between the structural vibration and the pressure in mercury, and in the later is essential the pressure wave propagation process.

1. Introduction

Neutrons are used for the innovative research that will bring about breakthrough in scientific and engineering research fields, i.e. fuel cell, hydrogen embrittlement, protein structure, medicine, etc. Mercury has the benefits for pulse spallation neutron sources because of the high neutron yielding efficiency and usage as a coolant, and is available as target material to produce neutrons by spallation reaction that is caused by the bombardment in mercury with high-energy protons. The pulsed spallation neutron sources are being operated at the Materials and Life science experimental Facility (MLF) in the Japan Proton Accelerator Research Complex (J-PARC) in Japan [1] and the Spallation Neutron Source (SNS) in the USA [2], which are standing on the way to increase the power up to megawatt-class. However, the higher the proton beam power, the severer the mercury cavitation problems become apparent.

At the moment that the proton beam bombards in the mercury, thermal shock is generated in the mercury and the pressure waves are induced [3–5], whose amplitude is dependent on the proton beam power. On the process of the pressure wave propagation aggressive cavitation generates in the mercury, which imposes damage on the solid wall of the target vessel. Therefore, the cavitation phenomenon gets to be a crucial issue to increase the power in the mercury target for the pulsed spallation neutron sources. Theoretical and experimental investigations were carried out to understand the relationships among pressure wave conditions, mercury cavitation aggressiveness, and damage growth behaviors on some solid materials [6,7].

Surface hardening treatments of the target vessel wall by coatings and/or surface improvements, Kolsterising®, nitriding, etc., were tried to reduce the cavitation damage formation [8,9]. These techniques were not sufficient to protect the vessel wall against damages due to very violent mercury cavitation. On the other hand, microbubble injection for softening mercury is investigated from the viewpoint of pressure wave mitigation. However, such technique is not straightforward because of complicated phenomenon on interaction between injected gas bubbles and cavitation bubbles under dynamic pressure responses, which are very dependent on the interaction between the solid vessel wall and the impulsive pressure induced by protons injection. As well, it was not easy to make the microbubbles in flowing mercury which are theoretically predicted to mitigate the pressure: i.e. the diameter of bubbles is less than 100 μm and the void fraction larger than 10^{-3} [10], because mercury exhibits high surface tension, high density, low wettability, etc. An innovative microbubble generator, therefore, a so-called swirl bubbler was developed to inject microbubbles into flowing mercury [11].

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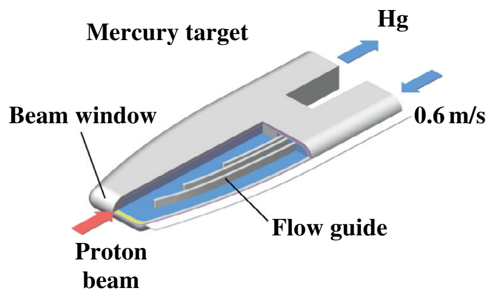

Fig. 1. Mercury target at J-PARC. The drawing illustrates the inner wall of target vessel: i.e. the vessel consists of multi-wall structure to protect from the mercury leakage into the outside of vessel.

In this paper, the gas-bubbling mitigation effects are discussed based on the experimental observation and the numerical simulation on the interaction between the gas-bubbles and the cavitation bubbles.

2. Pressure waves in mercury target

2.1. Rapid thermal expansion by proton injection

Fig. 1 shows the target vessel for the spallation neutron source at the MLF. The target vessel is filled with the mercury circulating at approximately 1 m/s as flowing along the beam window. The spallation reaction is induced when accelerated protons (1 MW, 3 GeV, 25 Hz, and 1 μs pulse duration) are bombarded in mercury and approximately a half of the power is dissipated for rapidly heating in the mercury [3,4,12]. Temperature rising ΔT in the mercury is given by

$$\Delta T = \frac{\Delta Q}{\rho C_V}, \quad (1)$$

where T is the temperature, Q is the heat density, C_V is the specific heat capacity, ρ is the density of mercury. As a result, pressure rapidly rises following the pressure waves in the mercury. Pressure rising ΔT in the mercury is given by

$$\Delta P = \beta_p K_T \Delta T, \quad (2)$$

where P is the pressure, β_p is the thermal expansion, K_T is the bulk modulus. Nuclear heat generation of the JSNS was calculated with the Particle and Heavy Ion Transport Code System (PHITS) [13] using the cross section data of Japanese Evaluated Nuclear Data Library (JENDL) Ver. 3.2. Nuclear heat distribution is very dependent on proton beam profiles. The maximum nuclear heat density (Q_{max}) in the mercury is associated with the proton current density: Q_{max} is the liner function of the proton current density. As assumed Gaussian distribution at 1 MW proton beam, the maximum heat density is approximately 12 J/cc with 1 μs pulse duration. The maximum pressure become approximately 30 MPa. Pressure propagation behavior is considered dividing into two time scales phenomena as followings.

2.2. Macroscopic time-scale

Nuclear heat distributions ΔQ in the mercury target is very dependent on the proton beam profiles and the maximum peak pressure attributes to a peak heat deposition of the beam profile. In order to investigate the pressure propagation and the dependency of pressure waves on the beam profiles, FEM analyses were carried out using an explicit code LS-DYNA. The 1/4 symmetrical model was used for the FEM. Mercury and stainless steel vessel were meshed as solid and shell elements, respectively. The cut-off pressure model is applied to mercury to simulate the tension failure in mercury due to cavitation [14]. In the cut-off pressure model, a relationship between volumetric strain and pressure is linear elastic when pressure larger than a certain value (the cut-off pressure), but the mercury has no stiffness when the pressure is less than it. We used the cut-off pressure of −0.15 MPa, whose suitability was confirmed experimentally. The boundary condition along the interface between solid wall and liquid mercury was tied. Pressure distribution in mercury due to the thermal expansion resulting from the proton beam injection was applied for the initial condition.

Fig. 2 shows the pressure time response nearby the beam window in liquid mercury along the center axis in the proton beam injection direction under 1 MW power. After the strong compressive pressure appears, the long period of negative pressure is 5 ms approximately, and the pressure increases gradually after around 8 ms. The negative pressure with a relatively long period is induced by the interaction between the solid wall and the liquid mercury.

The damage is dependent on the cavitation bubble growth and collapse behaviors, i.e. cavitation intensity, which are affected by the amplitude and the time-response of pressure waves. In the macroscopic view, it can be said that the liquid failed at the pressure lower than a critical tensile pressure to induce the cavitation bubbles, i.e. so-called the Blake threshold, which is equivalent to the cut-off pressure used in the pressure wave propagation analysis in the target [14]. The period of negative pressure, therefore, seems to be one of crucial factors related with the cavitation intensity. The relationship between bubble growth behavior and pressure waves was investigated by using Rayleigh–Plesset equation. The results showed that the cavitation inception is very dependent on the amplitude of negative pressure, and if the negative pressure exceeds the threshold, the maximum bubble size increases with the amplitude and imposing period of negative pressure.

2.3. Microscopic time-scale

The strong compressive pressure waves propagate toward the beam window from the highest heat deposition area around 30 mm in downstream of the beam injection direction with sound velocity in mercury. The compressive pressure waves are reflected and the phase might be changed by the acoustic impedance difference between the wall and the mercury so that the negative pressure occurs. Fig. 3 shows the microscopic time-scale model, Pressure wave propagation Analysis Code in Mercury Target (PAC-MT) [10], to evaluate the effects of acoustic impedance of solid wall and the injected gas-bubbles, which is expected as one of the mitigation techniques to suppress the cavitation damage.

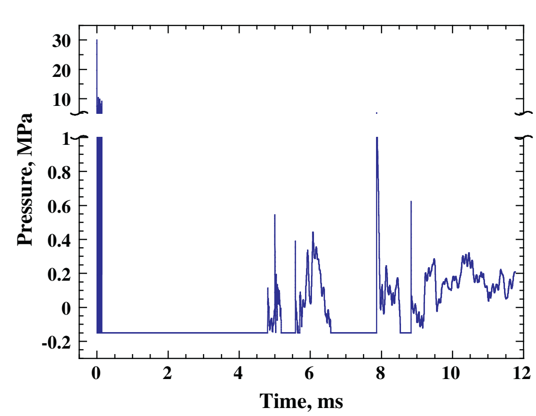

Fig. 2. Time-response of pressure waves nearby mercury target.