Mitigation of Cavitation Damage in J-PARC Mercury Target Vessel

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The target vessel, which enclosing liquid mercury, for the pulsed spallation neutron source at the J-PARC is severely damaged by cavitation caused by proton beam-induced pressure waves in mercury. To mitigate the cavitation damage, we adopted a double-walled structure with a narrow channel for the mercury at the beam window of the target vessel. In addition, gas microbubbles are injected into the mercury to suppress the pressure waves. The narrow channel disturbs the growth of cavitation bubbles due to the pressure gradient. After finishing service operation, the front end of the target vessel was cut out, allowing us to inspect the effect of these cavitation damage mitigation technologies on the interior surface. The damage depth of the cutout specimens was quantitatively investigated by the replica method. The results showed that the erosion depth due to cavitation in the narrow channel is clearly smaller than on the wall facing mercury with injecting gas microbubbles.

KEYWORDS: mercury target, cavitation, pressure waves, microbubbles, narrow channel

1. Introduction

A pulsed spallation neutron source is used in the Japan Proton Accelerator Research Complex (J-PARC) to produce pulsed proton beams for research into innovative materials and life sciences [1]. The proton beam power of J-PARC is gradually being ramped up to achieve stable operation at the goal of 1 MW at 25 Hz with 1 µs pulse duration. High-power pulsed proton beams are injected into mercury to produce spallation neutrons. When the proton beam is injected, high-amplitude pressure waves are generated by the rapid deposition of heat into the mercury. The pressure waves cause cavitation, resulting in severe erosion damage to the mercury enclosure vessel, which is made of type 316L stainless steel. This is the so-called target vessel [2]. Since the beam window in the target vessel has a wall only 3 mm in thickness to reduce thermal stresses, cavitation erosion, which tends to be proportional to the beam power, hinders the realization of the high-power stable operation of the neutron source.

To minimize the cavitation damage, J-PARC adopted two cavitation damage mitigation technologies: (1) the injection of helium gas microbubbles into the mercury to suppress the pressure waves that causes cavitation and (2) a double-walled structure with a narrow channel at the beam window of the target vessel. The injected gas microbubbles absorb thermal expansion due to heating because they shrink. The pressure waves are attenuated by the bubble volume oscillation [3]. The gas microbubble generator which produces bubbles less than 100 µm in radius in mercury was developed and installed in the target vessel with a gas circulation system in 2012 [4, 5]. The double-walled structure has a narrow gap of 2.0 mm in width. It was adopted to produce a pressure gradient in narrow gap induced by the high-speed mercury flow. The pressure gradient is expected to deform the shape of growing cavitation bubble and reduce damage by changing ejection direction of microjet. The double-walled

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target vessel, coupled with the microbubble generator, was installed in 2013 [6]. The effect of these damage mitigation technologies was separately demonstrated through assessing the interior surface of the target vessel that was cut out from used targets. The effect of gas microbubble injection on pressure wave mitigation was recognized as the reduction in the displacement velocity of the vessel when the proton beam is incident. The damage visually observed in target No. 3 without double-walled structure was less than that predicted based on a previous target in which gas microbubbles were not injected (target No. 1) [7]. In contrast, the effect of a double-walled structure on damage was reported for the Spallation Neutron Source in the USA, which has a mercury target with a slightly different channel structure and operating conditions [8]. We confirmed the obvious mitigation of damage due to the double-walled structure by inspecting target No. 5 [6]. However, the damaged surface facing the gas microbubbles was not cut at the same time as the surface facing the narrow channel, due to a problem with the cutter.

This study aimed to investigate and compare quantitatively the effects of gas microbubble injection and the double-walled structure on the cavitation damage. The front end of a used target vessel were cut out using an improved cutting procedure, allowing us to assess the cavitation damage on the interior surface.

2. Double-walled target vessel

Figure 1 shows schematics of a double-walled target vessel (No. 8). The vessel has a water shroud and a mercury vessel. The gap between the water shroud and the mercury vessel is filled with helium gas. The front part of the mercury vessel has a double-walled structure separated by a narrow channel of mercury, 2 mm in width. The thickness of wall around the beam entrance portion, except for the inner wall of mercury vessel, is 3 mm to reduce thermal stresses due to the internal heat generation. The inner wall of the mercury vessel is 5 mm thick because it is cooled by the flowing mercury from double-side. The double-walled target vessel has a microbubble generator that injects helium gas microbubbles into the bulk side of the mercury.

![Fig. 1. Schematic of the double-walled target vessel.](image)

Target No. 8 was operated from October 2017 to July 2018. The total proton beam energy was 1812 MWh for an average power of 434 kW. The beam power when in service was gradually ramped up from 300 kW to 500 kW (approximately 100 kW / 3 months). After finishing service, a 1 MW beam experiment at 25 Hz was performed for 1 hour to confirm the operation of the equipment at the rated beam power of J-PARC. It was confirmed for the mercury target vessel that the injection of gas microbubbles is effective in reducing pressure waves at 1 MW. The temperatures of the mercury and target vessel were well within with the designed values [9].
3. Cutting and inspection of the used target vessel

3.1 Beam window cutting

After finishing service, the front end of the mercury target vessel, the so-called beam window, was cut using an annular cutter by full remote handling to investigate the cavitation damage on the inner surface [10]. In our previous research, we could not completely cut the double-walled target vessel due to the friction heat in dry cutting [6]. Therefore, the cutting conditions were optimized through cold cutting tests. We used a lubricant to reduce the friction heat. The optimized cutting conditions are a cutter rotation speed of 250 rpm and a cutter feed rate of 0.017 mm/s. Every 3 s we cut through 0.1 mm followed by a break of 3 s with intermittently spraying lubricant.

Prior to cutting, a numerical simulation focusing on the negative pressure distribution predicted that the most severe cavitation damage would occur in the off-center portion of the beam window [6]. Hence, we cut out two areas: the center of the beam window and off-center on the side opposite to the bubble generator.

3.2 Damage inspection procedure

After cutting, the specimens were extracted from the annular cutter and cleaned in an ultrasonic bath with water for 60 minutes to remove the mercury and radioactive products. Finally, an ethanol was sprayed onto the specimens to remove the oil from the lubricant. To assess the cavitation damage on the mercury vessel, the surface of the specimens was directly observed using a digital video camera held by a master/slave manipulator. The dose rate for the specimen is higher than 10 Sv/h. Therefore, it is difficult to directly observe the surface of the specimens outside a hot cell. To measure quantitatively the cavitation damage on the mercury vessel, the surface of the specimens was replicated using silicone rubber (Struers, RepliSet-F5). To minimize the adhesion of radioactive products onto the replica, the replication was performed several times. The replica was packed in a transparent box and the surface was measured using a 3D laser scanner (Keyence, VR-3200). The depth resolutions of the replica and laser scanner are 0.1 µm and 1 µm, respectively.

4. Results and discussions

4.1 Cavitation damage on channel and bubbly mercury

Figures 2 and 3 are photographs of the cutting machine, the holes in the beam window, and the specimens cut from the center and off-center of target No. 8. Note that the bulk side surface faced the bubbly mercury and the surface of the narrow channel faced the high-speed mercury flow, which had a mean velocity of approximately 4 m/s. The surfaces B and E are the outside of the inner wall, C and F are the inside of the inner wall. The off-center surfaces (D, E, and F) have glossy surfaces whereas the center specimen surfaces (A, B, and C) have relatively matte surfaces. However, during fabrication, the same surface finish was applied for the both locations. There is clear damage around the center of surface from the bulk side (C). The original surface finish, recognized as the lay of machining, can be seen on the narrow channel surface (A and B), although there is a matte surface at the middle and top.

Figure 4 is a typical example of the cavitation damage measured with the replica narrow channel (A) and the bulk side (C). There are relatively small pits distributed on the narrow channel. On the other hand, there are deep pits distributed along with the lay of machining on the bulk side. Furthermore, the lay of machining still remains on the surfaces of the narrow channel and bulk sides. The maximum depths of damage in the narrow channel and bulk side are 17.5 µm and 250 µm, respectively. In cavitation damage, localized pits tend to form on top of any homogeneous erosion, which is generally assessed using a mass-loss measurement as the mean depth of erosion (MDE). In our previous study, we proposed that the maximum depth of cavitation erosion \( D_{\text{max}} \) can be estimated...
Fig. 2. Photographs of cutting machine and cutout holes of the beam entrance portion.

Fig. 3. Photographs of the specimens cutout from used mercury target vessel No. 8.

Fig. 4. Depth contours and depth profiles of pits between the arrows of the replicated surfaces for the narrow channel and the bulk side.

4.2 Narrow gap effect

Through inspection, we confirmed that the damage in the narrow channel is dramatically less than that for the bulk side. Furthermore, the damage depth of the outer wall of the mercury vessel faced the narrow channel (A in Fig. 3) for target No. 8 is smaller than what was predicted based on inspecting the damage to target No. 5. Figure 5 shows the photographs of the outer wall of the narrow channel cut from target No. 5 and No. 8. The total proton beam energy and average beam power of target No. 5 were 670 MWh and 400 kW. It operated for approximately 63% less total

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D_{\text{max}} = \text{MDE} + S_Z = 8\text{MDE},
\]

where \( S_Z \) is the peak to peak roughness on surface. Based on this equation, the maximum depth of damage of the bulk side including homogeneous erosion was estimated to be 286 \( \mu \text{m} \). The estimated damage depth that faced bubbly mercury corresponds to the damage formed at approximately 40% of the beam power without injecting gas microbubbles. Details will be discussed elsewhere.
Comparisons of the cavitation damage distribution of the outer wall of mercury vessel for target No. 5 and No. 8. The total operating time was 2.5 times longer for No. 8. The damage to target No. 5 is concentrated around the center, whereas the damage is more widely distributed in target No. 8. However, the maximum damage depth of target No. 5 is slightly more than that of target No. 8 despite that the total energy and average power were lower. A possible reason for this is due to the difference in the width of narrow channel. For example, the gap at the center of the beam window for the target No. 5 was 2.33 mm whereas for the target No. 8 it was 1.19 mm. In our previous study, we have confirmed that the flow velocity is increased approximately 25% when the gap width reduces 1 mm through the numerical simulation [11]. The actual mean flow velocity in the narrow channel for the target No. 5 and No. 8 were roughly estimated to be 3.2 m/s and 4.0 m/s, respectively. It is thought that the growth of cavitation bubble around wall boundary deforms due to the pressure gradient produced by high-speed flow [12]. Furthermore, the direction of microjet which ejects during cavitation bubble collapsing and impose the impact pressure to the wall might be changed by pressure gradient. It is also reported that the cavitation damage tends to be reduced with increasing in flow velocity [13]. In contrast, the effect of gap width on damage under flowing condition was hardly recognized whereas the damage reduced with reducing in gap width under stagnant condition [13]. Therefore, the damage difference between the target No. 5 and No. 8 was thought to be caused by both of the differences of the flow velocity and the gap width. The relationship among the gap width, the beam power, and the damage degree will be investigated in future work.

4.3 Bubble effect

Cavitation damage to the inner wall of the mercury vessel facing the bubbly mercury was more severe than that to the outer wall in the narrow channel. The mitigation of cavitation damage due to injecting gas microbubbles was due to a suppression of the pressure waves, which was confirmed by measuring the displacement velocity in the target vessel [5]. The details are not shown this paper, but the reduction in the displacement velocity due to the injection of gas microbubbles compared to without bubble was by a factor of approximately 0.3~0.4 during service. Moreover, the measured damage depth was in the range predicted by considering the reduction in the displacement velocity. In future work, we will improve the prediction of cavitation damage by considering bubble effect.

5. Summary

The double-walled mercury target vessel No. 8 with the gas microbubble generator operated for a total energy of 1812 MWh (434 kW average power). It was cut open to allow us to inspect the cavitation damage on the interior surface. The inspection showed that the erosion damage was clearly
shallower on the outer wall of the mercury vessel facing the narrow channel than that for the inner wall facing the bubbly mercury. Through this inspection, we quantitatively observed for the first time the mitigation of cavitation damage due to the injection of gas microbubbles. A maximum erosion depth of approximately 18 $\mu$m was measured on the outer wall of the mercury vessel, whereas it was 286 $\mu$m on the surface of the bulk side. The measured depth of the damage on the outer wall was slightly smaller than the predicted depth based on inspection of target No. 5. The results suggest that the damage depends on the gap width and/or the flow velocity.

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