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Pressure wave reduction due to gas microbubbles injection in mercury target of J-PARC

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Abstract. We have developed a helium gas microbubbles injection system to reduce the pressure waves in mercury target of pulsed spallation neutron source of J-PARC (the Japan Proton Accelerator Research Complex). The reduction effect with the microbubbles injection was investigated to measure the displacement velocity of the target vessel with a novel diagnostic system using laser Doppler vibrometer. The measurement was carried out under the conditions that the proton beam power was from 60 kW to 300 kW and the injected gas fraction, β (ratio of injected gas flow rate to mercury flow rate), was from 0 to 4×10^{-3}. As results, we confirmed the pressure waves measured with bubbles injection of $\beta=4\times10^{-3}$ reduced to 1/4 of those without the microbubbles injection.

1. Introduction

At the Japan spallation neutron source (JSNS) of the J-PARC (Japan Proton Accelerator Research Complex) a mercury target system has been operated by bombarding pulsed proton beam to produce neutron beams for promoting not only researches of materials science, life sciences, etc. but also industrial applications [1]. The pulse duration and the repetition rate of proton beam are 1 μs and 25Hz, respectively. Hence the beam energy is 40 kJ/pulse in the rated beam power of 1 MW. Since the time duration is very short, mercury is rapidly heated and pressure waves are generated in mercury. They impose on the mercury target vessel which is made of Type 316L stainless steel, deforming it. Hence the reduction of pressure waves is important to reduce fatigue damage in the vessel. Furthermore, the deformation and inertia due to pressure wave propagation induce negative pressure at the vicinity of the target vessel, which causes cavitation. The cavitation induces erosion on the target vessel, shortening its lifetime significantly [2, 3]. At the spallation neutron source in US (SNS), the target vessel was damaged by cavitation induced erosion. As comparing the operational conditions between the JSNS and SNS, the repetition rates are 25 and 60 Hz, respectively. Therefore, since the energy of one proton beam pulse in the JSNS is 2.4 times higher, the target vessel in the JSNS receives higher pressure waves than those in SNS when the proton beam power is same.

We have been developing a microbubbles injection technique to reduce the pressure waves which cause cavitation erosion and fatigue damages on the mercury target vessel. Microbubbles in the mercury target are oscillated by the pressure waves and this oscillation dissipates the energy of pressure waves by changing kinetic energy to thermal energy. The bubble oscillation depends on the increasing time of pressure and bubble size. That is, the smaller bubbles are favorable to reduce the pressure waves which rapidly increase its amplitude. Numerical calculation showed that the microbubbles of 100 μm in radius mitigated efficiently the pressure wave in the mercury target [4].

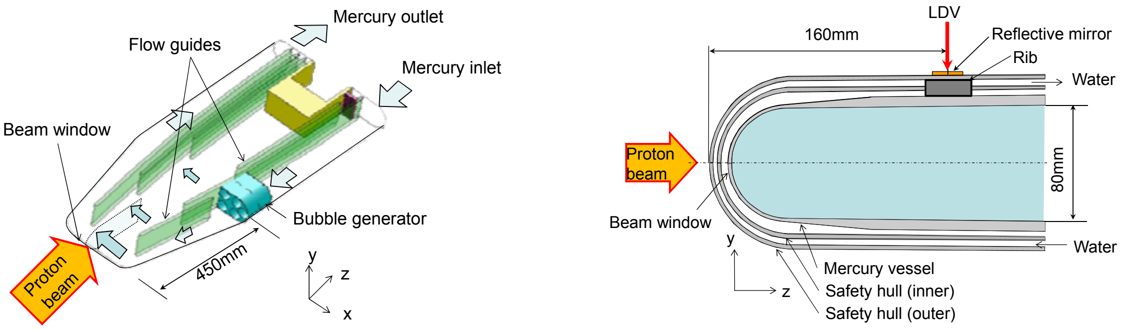
A microbubble generator [5] was installed into the mercury target system of J-PARC and the operation of the real target system with bubbling has been started since October 2012, which is the first operation in the world. During the operation, the proton beam power and beam profile, which change strength of pressure waves generated in mercury, and the bubbling condition were varied to estimate the effect under high power condition. In this report, the effect of bubble injection on pressure wave reduction is presented under the various proton beam and bubbling conditions.

2. Mercury target system in JSNS

Figure 1 shows schematic of the mercury target vessel of JSNS. Proton beam bombards at nose of the target vessel which is called as a beam window. The mercury target vessel consists of a mercury vessel and surrounding safety hull to prevent the mercury spill to the outside if the mercury vessel is broken. Figure 2 shows the heat density distribution for the 1 MW beam injection calculated with the Particle and Heavy Ion Transport code System (PHITS) [6, 7]. At present, the beam power has been reached to 300 kW. The beam power, the peak heat density and the distributions of heat density in x- and y-direction in mercury as shown in Figure 2 were changed to investigate the effect of beam condition on the generated pressure waves. To remove efficiently the generated heat, there are flow guide inside of the mercury target vessel as show in Figure 1 (a). These flow guides have roles of not only controlling mercury flow pattern in the vessel but also has restriction of a deformation of the vessel due to the pressure wave. Mercury comes into an inlet pipe, and then it flows perpendicularly to the proton beam injecting direction as its flow rate is distributed to much the heat density distribution by a flow guides. In the case of the beam condition as shown in Figure 2, pressure of ca. 40 MPa and stress of 150 MPa will be generated at the peak heat position and the beam window, respectively.

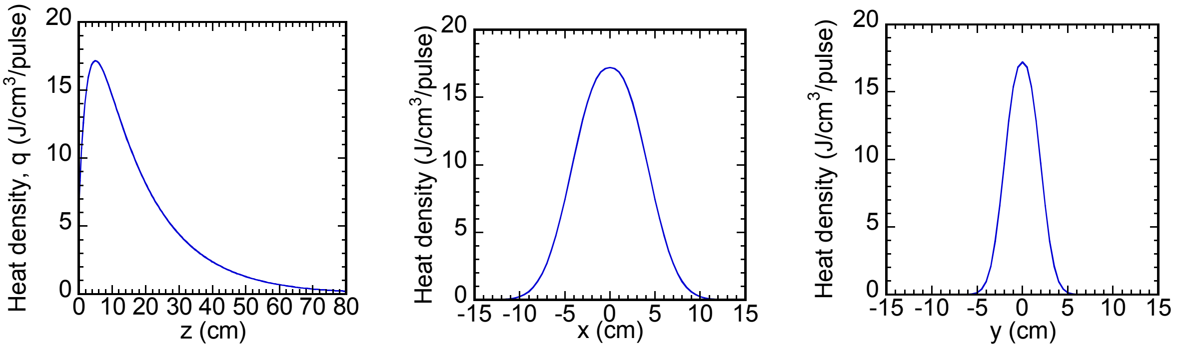
The pressure waves could be measured indirectly by the deformation of the target vessel in the JSNS. A laser Doppler vibrometer (LDV) was installed in the JSNS. The LDV measures the displacement velocity in the direction of the laser beam injection. The reflective mirror is set on the top of the target vessel to reflect the laser beam efficiently as show in Figure 1 (b). The mercury vessel and the safety hull are connected by the ribs and the mirror set on the rib, so that the mirror can follow the vibration of the mercury vessel due to the pressure.

Bubble generator is set in the target vessel, which injects microbubbles to mercury. The bubble generator was set in the inlet pipe at 450 mm apart from the beam window to realize both of many bubbles passing near the peak heat position and the beam window and the structural integrity of the bubble generator against the thermal stress due to the temperature rise in the bubble generator itself. This bubble generator generates microbubbles of 90 μm in radius. In this study, not only the beam condition but also the bubbling condition was changed to investigate the effect of the bubbles on the pressure wave reduction. Actually we were troubled on that injected gas could not be increased up to summer in 2013 because mercury came into a gas supplying line and injected gas fraction, β, which is defined as the value of the injected gas flow rate, Q_{He}, divided by the mercury flow rate, Q_{Hg}, was 9×10^{-4} in user operation. In summer shutdown 2013, a liquid-gas separator was installed and the injected gas fraction could be increased to 4×10^{-3}.



(a) Mercury vessel (Bird view) (b) Target vessel (cross sectional view)

Figure 1. Schematic of mercury target vessel.



(a) (b) (c)

Figure 2. Distribution of heat density in mercury under 1 MW proton beam condition;(a) Along the beam injection direction (z) at x=y=0 cm, (b) Along x-direction aty=0 cm z=4 cm, (c) Along x-direction at x=0 cm z=4 cm.

3. Reduction of pressure wave by bubbling

Figure 3 compares time history of displacement velocity between the cases without and with bubbling under the beam condition of 300 kW and 3.0 J/cm^3/pulse. With bubbles injection, the maximum velocity decreased to 1/3 of the case without bubbling. And high frequency components caused by the shaking of the mirror, which appears in the case without bubble, was attenuated by the injecting bubbles. Figure 4 compares the maximum velocity among various beam conditions and with or without bubbling. Comparing with the cases without bubbling, the maximum velocity has lager variation in the case with bubbling. This is caused by the variation of the injected gas amount. In the same power, the maximum velocity increases with the heat density. The averaged maximum velocity generated in the bubbling condition is ca.2/3 of that in without bubble.

Reduction of the pressure waves depends not only on the injected bubble size but also amount of the injected gas [4]. The injected gas fraction was changed. Figure 5 shows the reduction of the maximum velocity as a function of the amount of injected gas fraction. The vertical axis represents the averaged maximum velocity obtained with the bubbling condition, which is normalized by that obtained under the same proton beam condition without bubbling. It is noted that the results shown in Figures 3 and 4 are obtained when the injected gas fraction is ca. 9×10^{-4}. The normalized maximum velocity decreased with increase of the injected gas fraction. The normalized velocity was reduced by increasing the injected gas fraction. When the injected gas fraction was increased to 1.7×10^{-3} and 4×10^{-3}, the averaged maximum velocity reduced to 1/3 and 1/4 of that without bubbling, respectively.

4. Discussion –Estimation of bubbling effect under the high power condition-

As shown in Figures 4 and 5, the maximum velocity induced by the pressure wave depends on the beam condition and the injected gas fraction. Since the beam power will be increased from 300 kW to 1MW, we estimated the velocity for high-power beam-condition.

As shown in Figures 4, the maximum velocity, $V_{\max}$, increases as a function of the maximum heat density $q_{\max}$,

$$V_{\max} = A \times q_{\max}^{B} \tag{1}$$

where, A is the constant depending on the beam power and B the constant depending on the bubbling condition. Furthermore, the constant A increases as follow;

$$A = C \times W^{D} \tag{2}$$

where, W [kW] is the beam power in 25 Hz operation. Table 1 shows the B, C and D values obtained from Figure 4.

At present, operation is possible with the injected gas fraction, β, of 4×10^{-3}. Supposing that the

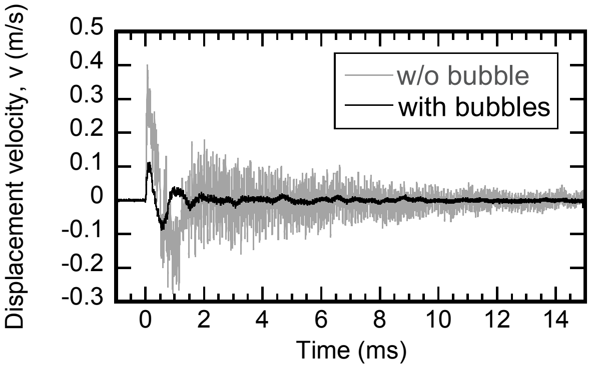


Figure 3. Comparison of the time history of the displacement velocity between cases without bubbling and with bubbling under the 300 kW and 3.0 J/cm^3/pulse.

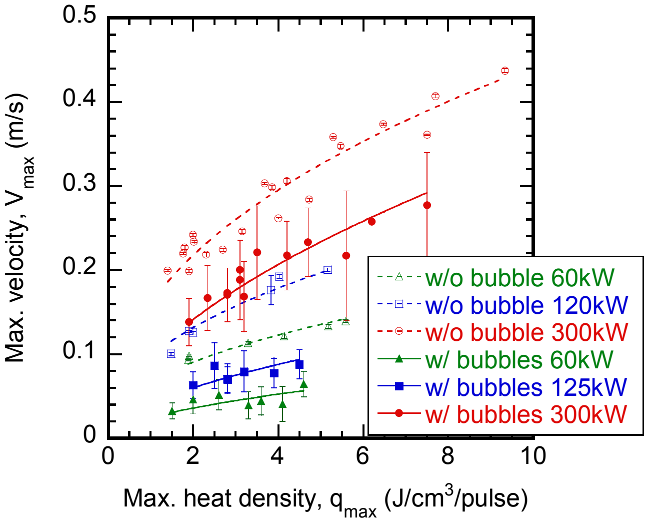


Figure 4. Comparison of the maximum velocity between the bubbling condition (β=9×10^{-4}) and without bubble.

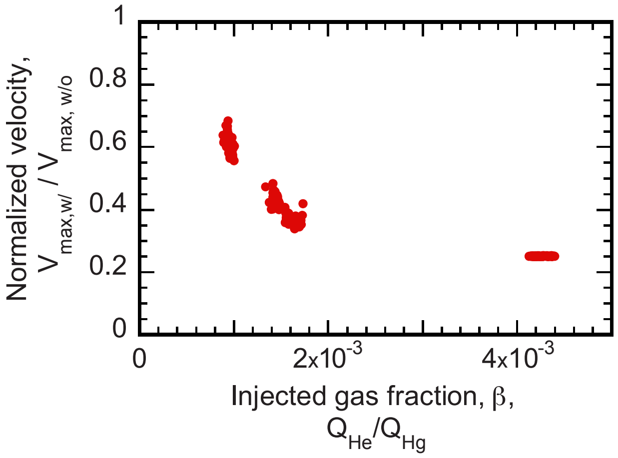


Figure 5. Effect of the injected gas fraction on the reduction of the maximum velocity (W=300 kW).

maximum heat density, $q_{\max}$, will be 0.011×W [J/cm^3/pulse] in the future operation for the user program, the maximum velocity estimated by using the equations (1), (2) and Figure 5 is shown in Figure 6. In the case of $\beta=4\times10^{-3}$, the maximum velocity under 1 MW beam condition is estimated to be 0.33 m/s which corresponds to 315 kW beam condition without bubble. This is expected to mitigate the cavitation induced erosion on mercury vessel. The effect of bubble injection on mitigation of cavitation induced erosion will be evaluated by observing the target vessel cut after its service operation.

Table 1 *B* and *C* values for equations (1) and (2)

	B	***C***	***D***
Without bubble	0.44	0.0075	0.56
With bubbles ($\beta=9\times10^{-4}$)	0.55	0.00096	0.8

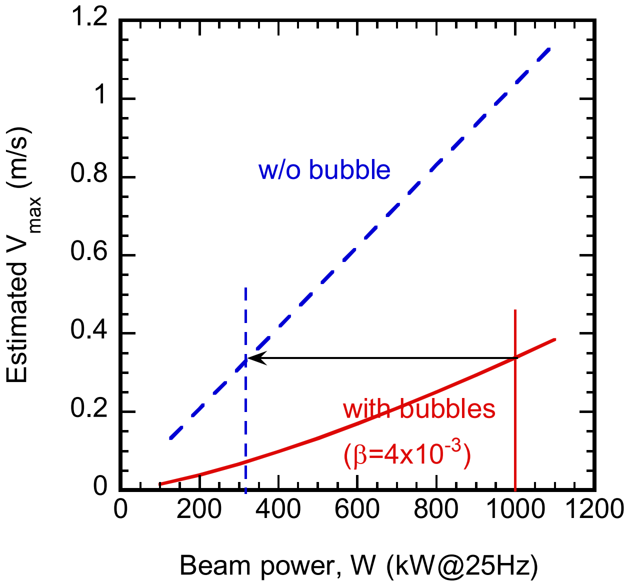


Figure 6. Estimated maximum velocity comparing the bubbling case to the case without bubble.

5. Summary

The effect of the bubble injection on reduction of the pressure waves was confirmed by the test operation in the JSNS, J-PARC. The bubble generator installed into the JSNS mercury target generates the microbubbles of 90 μm in radius. The injected gas fraction, β, was varied from 9×10^{-4} to 4×10^{-3} comparing with the case without bubble injection. To estimate the bubble effect under high-power proton-bema condition, the proton beam power bombarding the mercury target was changed from 60 kW to 300 kW and the displacement velocity which indicates the strength of the pressure wave of target vessel was measured with novel diagnostic system using the laser Doppler vibrometer.

In the case of $\beta=9\times10^{-4}$, the maximum velocity of the target vessel was reduced to 1/3 of that without bubbling in the best case. The averaged result shows the velocity reduction of 2/3. The averaged maximum velocity was reduced by the increase of the injected gas fraction. That is, when the injected gas fraction was increased to 1.7×10^{-3} and 4×10^{-3}, the averaged maximum velocity reduced to 1/3 and 1/4 of that without bubbling, respectively.

Effect of bubble injection on the pressure wave reduction under high-power proton-beam condition was estimated based on the measured result. The estimation indicated that the maximum displacement velocity generated in 1 MW beam operation with bubbles of $\beta=4\times10^{-3}$ corresponds to that in 315 kW operation without bubbles. This is expected to mitigate the cavitation induced erosion on mercury vessel to prolong its lifetime. The effect of bubble injection on mitigation of cavitation induced erosion will be evaluated by observing the target vessel cut after its service operation.

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