410  Numerical study on gas bubble formation in stagnant and flowing mercury

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A high-power liquid mercury target system for spallation neutron source is being developed in Japan Atomic Energy Agency. Cavitation will be induced by pressure waves which are caused by high intense proton beam injection into mercury. Injection of microbubbles in mercury with 50 to 200 μm in diameter may be effective to mitigate the cavitation. The effectiveness is dependent on bubble size and population. To investigate the behavior of bubble formation in mercury from a nozzle and develop microbubbles injection technique, numerical simulations on bubble injection in stagnant and flowing mercury were carried out using a Computational Fluid Dynamics (CFD) code. The simulation in stagnant showed that bubble grew around the outer wall of the nozzle. Bubble computed under flowing condition was smaller than that in stagnant due to the drag and shearing forces induced by mercury flow.

Key Words : Mercury, Pressure wave, Microbubble, bubble formation, Computational Fluid Dynamics.

1. Introduction

The Japan Atomic Energy Agency (JAEA) is developing MW-class spallation neutron sources, which are installed in Japan Proton Accelerator Research Complex (J-PARC). The target for spallation neutron sources will be liquid mercury taking into account benefits of self-circulating heat removal and neutron yield. The injected proton beam into the target results in rapid thermal expansion which generates pressure waves in the mercury. Pressure waves will induce cavitation in the mercury, which may result in pitting damage on the wall surface. A technique of microbubbles injection into the mercury to minimize wall damage has been proposed. The effectiveness is dependent on bubble size and population.

Studies focusing on the bubble formation in liquid metals are few. Kogawa et al. observed gas bubble formation from a micro-nozzle of 100 μm in inner and 200 μm in outer diameters in stagnant mercury by X-rays. The bubble size was estimated from the captured frames of the detached bubbles and found to be about 2.5 mm in diameter at gas flow rate of 10 cm³/min.

In this study, we applied numerical simulation to understand the effect of flowing mercury on bubble generation and predict bubble sizes generated from a micro-nozzle.

2. Numerical simulation

In order to carry out simulation for the dynamics of gas bubble formation at the gas nozzles in liquid mercury, we used STAR-CD code to solve a free-surface flow problem using the volume of fluid (VOF) methodology. For incompressible flow, the code assumes that densities of both heavy (liquid) and light (gas) fluids are constant. The volume fraction of each fluid is tracked as solving the computational cells. Tetrahedral cells were used to create the three dimensional (3D) model shown in Fig. 1.

To investigate the effect of mercury flow, U_L, on the bubble formation, the bubble injection was carried out under stagnant and mercury flowing condition with 0.4 and 1.0 m/s. Contact angle related with wettability is set to be 130° in mercury in contact with stainless steel, based on experimental results. Needle type nozzle of outer, D_out, and inner, D_in, diameters of 200 and 100 μm, respectively, was set in the bottom of the model. The number of cells and the minimum size are 126800 and 25 μm, respectively. The chamber was filled with mercury, and helium was injected at various flow rates from 0.1 to 10 cm³/min.

For the boundary conditions of the numerical model in this study, the inlet of gas and the free surface were set at the bottom of the nozzle and the top of the model, respectively. All walls were defined to be no-slip. Initial conditions of mercury were set to 0.1 MPa and 293 K for pressure and temperature, respectively.

Fig. 1 A schematic drawing of the 3D model in this work

3. Results and Discussion

To verify the simulation code, Fig. 2 shows comparison between generated bubbles in mercury at the tip of the needle observed by X-rays by Kogawa et al. and numerical bubble growth in stagnant condition at gas flow
Fig. 2. Observed and computed bubble growth in mercury at contact angle, $\theta = 130^\circ$.

rate of 10 cm$^3$/min. The numerical shape of bubble in mercury agrees well with the experimental. Liquid mercury has poor wettability and its contact angle is large which makes the bubble to form surrounding the nozzle.

Figure 3 shows the numerical results of generated bubble diameter under flowing mercury condition against the injected gas flow rate. Bubble diameter became smaller under the flowing of mercury. The numerical bubble diameter decreased to 580 $\mu$m under flowing mercury of 1.0 m/s condition at 10 cm$^3$/min from 2.5 mm in stagnant condition. Figures 4 (a) and (b) show numerical flow patterns of mercury around the bubble at the moment of detachment in stagnant and flow of 0.4 m/s, respectively. In Fig. 4 (a-2), the bubble in stagnant detached after forces on it became into balance. But as shown in Fig. 4 (b-1), the mercury flow helps bubble separation to make smaller bubbles by shearing force. Mercury flow could help to make small bubbles not only due to the increase in the drag force on the bubble but also with the effect of the shearing force on it.

4. Conclusion

Numerical simulation was carried out for bubble injection in mercury to investigate the effect of mercury flow on bubble formation and size. The simulation showed good agreement with bubble formation in stagnant mercury observed by X-rays from the viewpoint of bubble size and growth behavior. The formation showed that the bubble is growing around the outer surface of the nozzle due to poor wettability of mercury. The numerical results showed that shearing force of the mercury flow on the bubble helps to make smaller bubbles.

References