CAV2021
11th International Symposium on Cavitation
May 10-13, 2021, Daejon, Korea

Numerical study on the wall pressure caused by spark-generated underwater bubble near a hemispheric boundary

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Abstract: This study aims to numerically analyze the dynamics of an underwater explosion bubble near a hemispheric boundary with emphasis on the wall pressure characteristics. The coupling of a fully compressible multiphase mixture model and an interface capturing scheme is applied for numerical computations. The accuracy of the numerical model is verified by evaluations with experimental data regarding the bubble shape and wall pressure history. The numerical simulation is conducted for a spark-generated underwater bubble by 400 V high voltage (Maximum equivalent bubble radius is 30 mm) at a dimensionless stand-off distance of 0.67. Strong nonlinear interactions between the explosion bubble and the hemispheric target are well captured. Complex phenomena of bubble motions especially an annular residual formation and the high-velocity jet flow are reproduced by the numerical method. Especially, the pressure at the wall hemispheric center is predicted with an extremely high peak value during the bubble collapse process. The prediction results are also in good agreement with measured data. Afterward, the mechanisms of the wall pressure induced by jet impact are analyzed in detail.

Keywords: Cavitation bubble; Fully compressible; Hemispheric target; Wall pressure; Jet velocity

1. Introduction

The underwater explosion is an extremely complicated dynamic phenomenon involving multiphase flow, shock wave, interface deformation, jet velocity, and high wall pressure impact. Among them, the wall pressure loading is still a great difficult problem in numerical predictions due to the strong nonlinear interaction between the bubble and the wall. Thus, studies on wall pressure loading have been paid more attention in both experimental and numerical models. Recently, Ma et al. [1] developed an experimental measurement method to record the wall pressure loading subjected by a spark-generated underwater explosion bubble near a hemispheric target. Pressure loading induced by the shock wave and bubble collapse under different dimensionless stand-off distances was recorded in detail which useful for validation of other prediction methods. Yingyu et al. [2] based on experimental data to propose an analytical correlation for the prediction of the wall loading. They also estimated control parameters on the wall pressure loading by bubble collapse. Yuan et al. [3] conducted experiments to observe the floating ice cake damage by a violent high-speed jet and emitted shock wave. The mechanisms of wall pressure loading were analyzed by numerical simulations with high-fidelity to support for experimental methods. Tian et al. [4] based on the computational fluid dynamic method to study the shock wave propagation and bubble motions near a horizontal solid wall. They showed a good agreement with experimental observation and details of the wall pressure loading and space pressure distribution were presented. In our previous study [5, 6], the first shockwaves propagation features by an explosive bubble near a free surface or a rigid cylinder were numerically analyzed. In this paper, we focus on numerically analyze of wall pressure loading induced by the bubble collapse near a hemispheric target.

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2. Numerical Methods

A fully compressible multi-phases homogeneous mixture model is adopted to simulate the underwater explosion process of a spark-generated bubble near a hemispheric boundary. The numerical model adopted the Reynolds-averaged Navier–Stokes equation system with an assumption that all phases are in mechanical and thermodynamic equilibrium. To achieve the time accuracy solution, a preconditioning method adding a pseudo-time term is combined in the governing system. The bubble interfaces with large deformations during the bubble oscillations are maintained in shape interfaces by solving an additional interface advection equation. The compressibility effects on the vapor and water phases are treated where the properties are determined from the obtained local temperature and local pressure. Cut-off models for pressure and temperature fields are applied to prevent phase-change effects such as evaporation and condensation processes. For details of numerical discretization of the governing equations, the reader can refer to our previous studies [7, 8]. To obtain high-fidelity results, the Courant–Friedrichs–Lewy number of 0.2 is adopted in simulations.

3. Results and discussion

In this paper, the numerical simulation of the spark-generated underwater explosion bubble near a hemispheric boundary is performed. To validate numerical results and investigate the bubble collapse pressure, the experimental work by Ma et al. [1] is adopted. In their study, an underwater explosive bubble was generated by an electric discharge of 400 V near a hemispheric target with a diameter of 50 mm. The whole process of the bubble dynamics and the history of wall pressure-induced bubble collapse were recorded which useful to verify the accuracy of the numerical model. According to the experimental condition, a computational domain is presented as shown in Figure 1a. A dimensionless standoff distance parameter, $\gamma = d/R_m = 0.67$, is adopted. d presents the distance between the initial explosive bubble and the bottom of the hemispheric target and R_m is maximum bubble radius in free-field condition ($R_m = 30\ mm$). By ignoring the effects of swirls, an axisymmetric domain includes half of the hemispheric shape and an axisymmetric line at the left is used. The simulation domain has a radius of $15R_m$ and a height of $30R_m$. To capture the strong bubble-wall interactions and wall pressure with high accuracy, a quite resolution mesh near ($N/R_0 = 50$) the bottom of the hemispheric target is adopted as shown in Figure 1b. The whole process from the expansion to the collapse of the bubble is simulated from a spherical with high pressure inside the bubble. The initial conditions of the bubble including bubble radius and pressure are determined by applying the Rayleigh-Plesset equation [7, 8]. The obtained values for initial bubble radius and pressure are $R_0 = 2.69$ and $P_0 = 50.66$ Mpa, respectively. To simply the model, the effects of phase change and non-condensable gas are not considered in the present simulation.

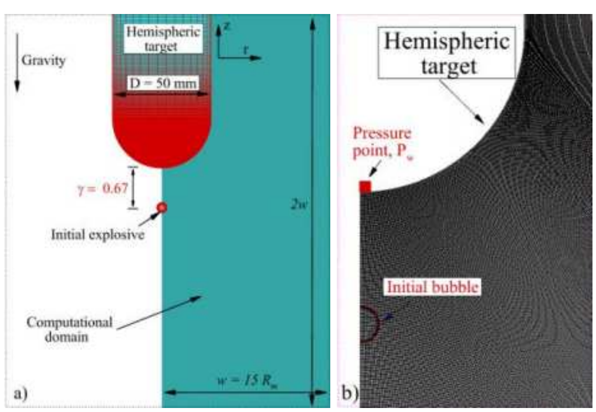

Figure 1. Schematic diagram of an explosive bubble near a hemispheric boundary; (a) Computational domain; (b) Mesh distribution near a rigid wall

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Figure 2 shows a comparison between predicted numerical results (Middle line) and experimental observation (Top line) for the evolution of the bubble shape. As we can see that the bubble interfaces during the strong interaction processes are well captured with high-resolution. Owing to the high pressure at the initial condition (Figure 2a), the bubble immediately expands toward and the top bubble surface is closer to the hemispheric boundary. The bubble further expands and then the top bubble surface begins to be contacted to the wall. Therefore, the bubble shape at the top part is relatively straight, while at the bottom part is still maintain in its spherical shape (Figure 2b). As time goes up, the bubble reaches the maximum stage with partially wrapped at the bottom hemispheric boundary (Figure 2c). Subsequently, the bubble begins the collapse process by reducing the bubble radius. During the bubble shrinking, the bubble is observed as an oval-like shape with strong interaction along with the hemispheric boundary. Especially, around the top part of the bubble, an annular residual is formed and well captured by the present numerical model shown in Figure 2d, which was also observed in the experiment [1]. Without any interactions, the bottom bubble surface is maintained a spherical shape during the early collapse stage. Afterward, the bubble changes into a slender shape (Figure 2e). At the same time, a high-velocity jet liquid flow forms, develops and penetrates the top part of the bubble with generating an extremely high peak pressure value at the hemispheric target. Afterward, the bubble rebounds in toroidal shape and enters the second expansion and collapse stages. The sub-figure at the bottom line shows the temperature field (left side), pressure field and velocity vectors (right side) at specific stages during the interaction process. The temperature inside the collapsing bubble increased significantly and reached a maximum value of approximately 1,000 K at its final stage. From the above numerical observations, the complex and strong interaction between a spark-generated explosive bubble and a hemispheric target are captured well with experimental results.

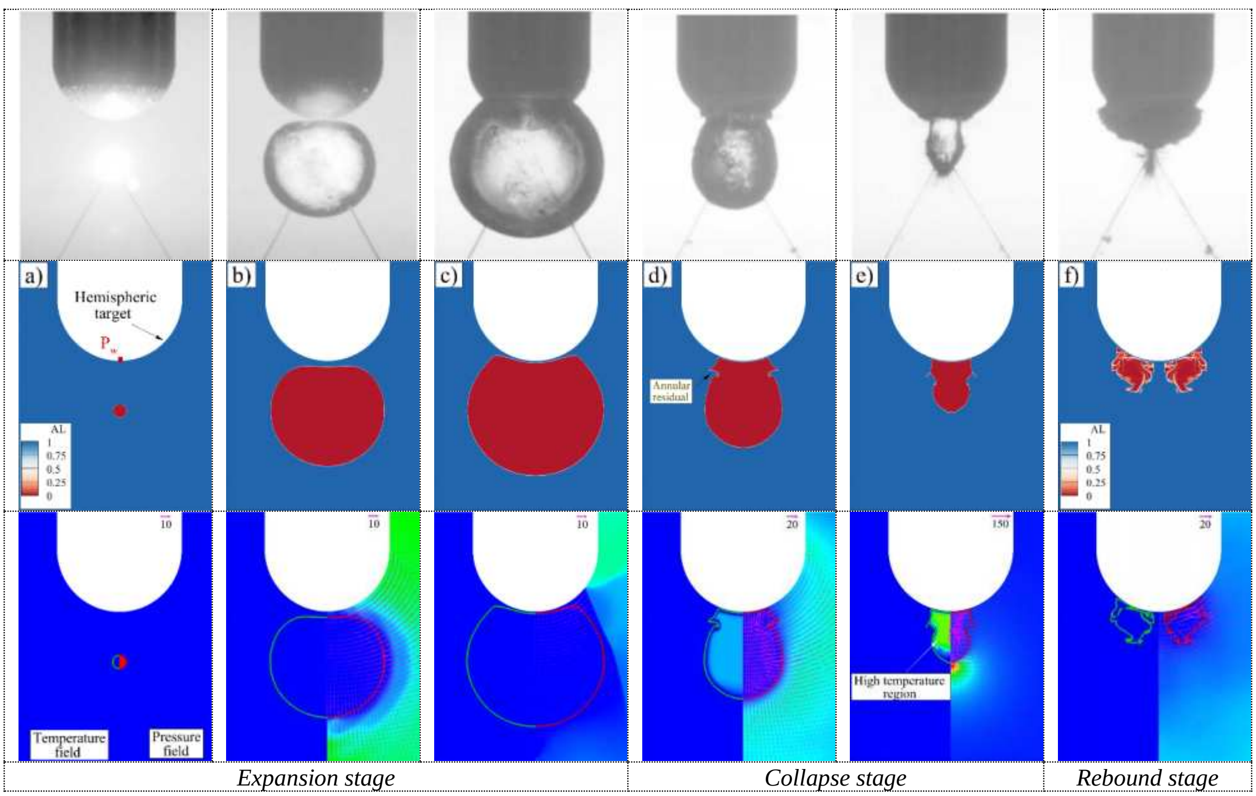

Figure 2. Evolution of bubble shapes during the interaction of an explosive bubble near a hemispheric boundary for $\gamma = 0.67$ and $R_m = 30\ mm$

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Figure 3 shows the time history of the pressure at the bottom hemispheric wall, point P_w, during the whole interaction process. According to the pressure profile, there are two significant pressure peaks during the first cycle of bubble oscillation. As the bubble expands with high pressure inside, a shock wave is generated and propagated as a radial shock wave. Then, the shock wave interacts with the bottom part of the hemispheric target after t = 0.032 ms and the first pressure peak of approximately 7.830 MPa is predicted at the wall center. The measured time and pressure peak values of the first shock wave in the experimental study [2] were 0.00112 ms and 8.936 MPa, respectively. The shockwave loading decrease as it spreads on the target. The second peak pressure is observed when the bubble re-entrant jet acted on the hemispheric target. Its peak pressure value has reached the value of 43.4 MPa in our numerical simulation which slightly higher in comparison with the measured data of 42.3 Mpa. Based on numerical observations, the second peak pressure is mainly induced by bubble collapse load in the presence of very high-jet velocity flows. The maximum jet velocity can reach the peak value of up to 250 m/s is found in our simulation. Figure 3b presents an enlarged view of wall pressure and equivalent radius histories during the end of the first collapse stage. The jet impact load occurs before the bubble reaches a minimum equivalent radius is observed. After the jet impact, the wall pressure dramatically decreases, and the multiple pulsating collapse load of the bubble.

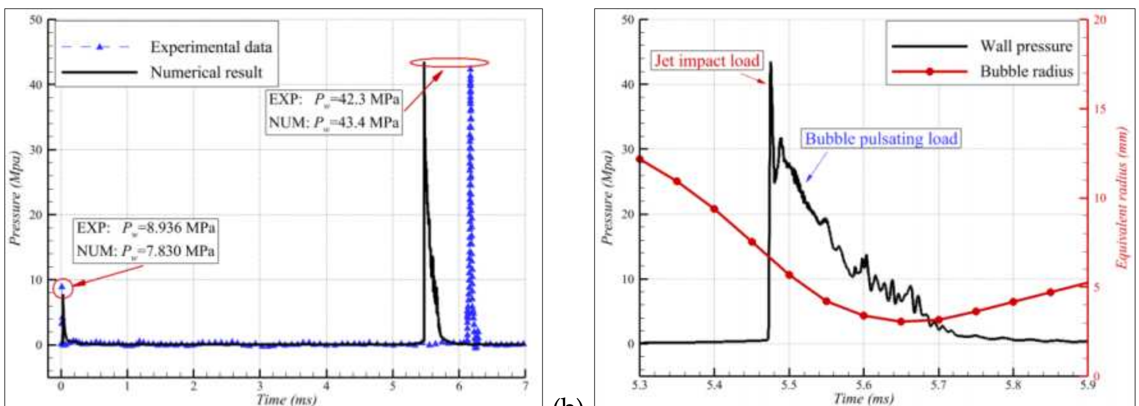

Figure 3. Time evolution of (a) the wall pressure during the first cycle and (b) enlarged view of pressure during the first bubble collapsing stage

Figure 4 shows the evolution of the bubble and pressure fields during the high-velocity jet impact stages. During the bubble collapse stage, a high-pressure region is formed at the bottom of the bubble, pushes the bubble, and results in the development of a high-speed upward jet to the hemispheric target. The jet impact with a very localized pressure region on the wall is observed. Then, the toroidal bubble continues to rebound in the radial direction.

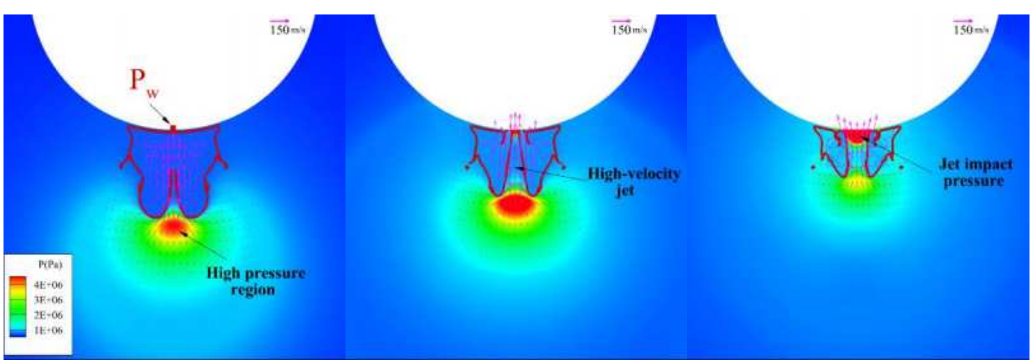

Figure 4. Evolution of pressure distribution during high-velocity jet impact to the hemispheric wall

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4. Conclusions

In this paper, numerical analyzes on the wall pressure caused spark-generated underwater bubble near a hemispheric boundary under $\gamma = 0.67$ were presented. Complex deformation bubble interfaces were well captured by the present numerical model in comparison with experimental data. The time history of wall pressure on the bottom of the hemispheric target was in good agreement with recorded data. There were two wall pressure loading during the first cycle bubble oscillation caused by shock wave propagation and bubble collapse with jet impact. According to numerical predictions, a high-velocity jet impact with a value up to 250 m/s and jet impact to the wall before the bubble reaches a minimum equivalent radius was observed. The wall loading caused by the jet impact was found in a very localized region and then dramatically decreases.

Acknowledgments: This study was supported by two Basic Science Research Programs through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (no. 2020R1I1A1A01071163) and (no. 2020R1I1A3067229).

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