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Numerical Investigation on Underwater Explosion with Thermodynamic Cavitation Process

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Abstract: This work presents computational results of cavitation phenomena during the underwater explosion (UNDEX). As the primary blast wave reflects at the free surface, the vapor phase is generated due to the local pressure drop. When the cavity region collapses, the bulk cavitation loading arises, which is comparable to shock loading in certain conditions. Based on the homogeneous mixture framework, compressible Euler equations are adopted for computations. Thermodynamic cavitation model that can describe the generation of actual vapor mass is employed, which is known to be critical for capturing the phase change process in UNDEX. Preliminary simulation on small scale UNDEX is carried out for the in-house solver validation. The main simulation is carried out with 10kg of TNT located 3m beneath the free surface. The computation results show that the bulk cavitation loadings are only observed in the case where the thermodynamic cavitation model is applied, whereas only primary shock loading is captured with a simple pressure-cut model. The effect of different equations of state for explosion gas bubble is also compared. The numerical framework in this work shows the capability in predicting cavitation loads. Further investigation will be carried out for the cases with actual experimental data.

Keywords: Underwater explosion; Cavitation loads; Compressible multiphase flow; Thermodynamic cavitation model, Computational Fluid Dynamics (CFD)

1. Introduction

Underwater explosion (UNDEX) refers to the detonation of explosive charges immersed in water. The physical scenario of UNDEX seems simple, but it is complicated. As a blast wave reaches the free surface, rarefaction waves are reflected back, while a weaker shock is transmitted to the air. As the rarefaction waves propagate in the water, cavitation occurs in the low-pressure region beneath the free surface. When the cavitation bubbles collapse, bulk cavitation load arises which sometimes could reach a comparable magnitude of the primary blast wave depending on the conditions [1,2].

Investigations on UNDEX have been conducted since the nature of these phenomena is intricate and can potentially be applied to safety purposes as well. Several numerical studies adopted a boundary integral method (BIM), but it has limitations in predicting the whole flow fields with shock and phase change due to the potential flow assumption [3]. Other numerical studies, based on more realistic Euler or Navier-Stokes equations, still have limitations since they mostly used simplified pressure-cut or mechanical cavitation model. These models consider the growth/collapse of cavities due to pressure variations only, without liquid-vapor transition. In order to predict the cavitation loads accurately, the thermodynamic cavitation process needs to be taken into account [4].

In this study, CFD-based numerical simulations will be carried out by solving compressible Euler equations with thermodynamic cavitation models, which has not been attempted for UNDEX simulations. During the computations, liquid water is vaporized and condensed back according to the local pressure

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and temperature through the thermodynamic cavitation model, with latent heat going in and out along the process. Based on the simulation results, the efficacy of the thermodynamic cavitation model in predicting the bulk cavitation load will be examined.

2. Numerical Methods

The homogeneous mixture model, also known as a four-equation model is adopted to describe multiphase flows. The compressible Euler equations are employed as governing equations. This system of conservation equations is comprised of mixture mass, momentum, energy, and two additional mass fractions that can describe three different phases and/or species: liquid water, water vapor, non-condensable explosion gas. The air above the free surface is also considered the explosion gas in atmospheric conditions.

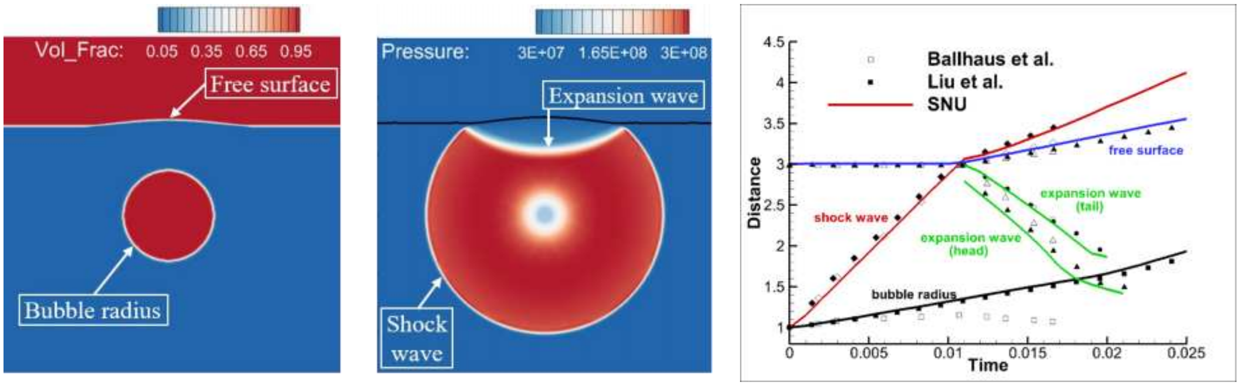
The equation system is closed using EOS for each phase, which can represent disparate thermodynamic characteristics over fluids, and the mixture properties are calculated based on Amagat's law. Simple stiffened-gas EOS and ideal gas law are adopted for liquid water and water vapor, respectively. Explosive material is modeled by Trinitrotoluene (TNT), where the detonation products are calculated by ideal gas law and Jones-Wilkins-Lee (JWL) EOS [5, 6]. The effect of different explosion gas EOS is omitted for the brevity of this paper.

The present work describes the non-equilibrium phase change process for cavitation phenomena, by adding source terms. The vaporization and condensation rates are calculated by well-known Schnerr-Sauer's model [7]. The effect of the thermodynamic cavitation process is compared with the simple pressure-cut model, where the lowest local pressure is limited by saturation pressure, and described in section 3.2. More descriptions of the flow solver can be found in [8, 9].

3. Results

3.1. Flow solver validation

For the validation of the in-house flow solver, a preliminary UNDEX simulation is conducted. Initial conditions and computational grid are the same as the work of Liu et al. [10]. Figure 1(a), (b) shows contours of volume fraction and pressure at 0.016s, and the discontinuity comparison between theoretical [11] and previous simulation result [10] is presented in Fig. 1(c). The y-directional distance from the center of the initial gas bubble is measured by time. These results indicate that the major flow structures including blast wave, expansion wave, and bubble radius are well predicted by the in-house solver.



(**a**) (**b**) (**c**)

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Figure 1. Preliminary UNDEX simulation results: (**a**) Contour of vapor volume fractions; (**b**) Contour of pressure; (**c**) Discontinuity comparison of the present simulation (solid line), previous simulation of Liu et al. [10] (filled square) and theoretical result of Ballhaus and Holt [11] (blank square).

3.2. UNDEX near free surface

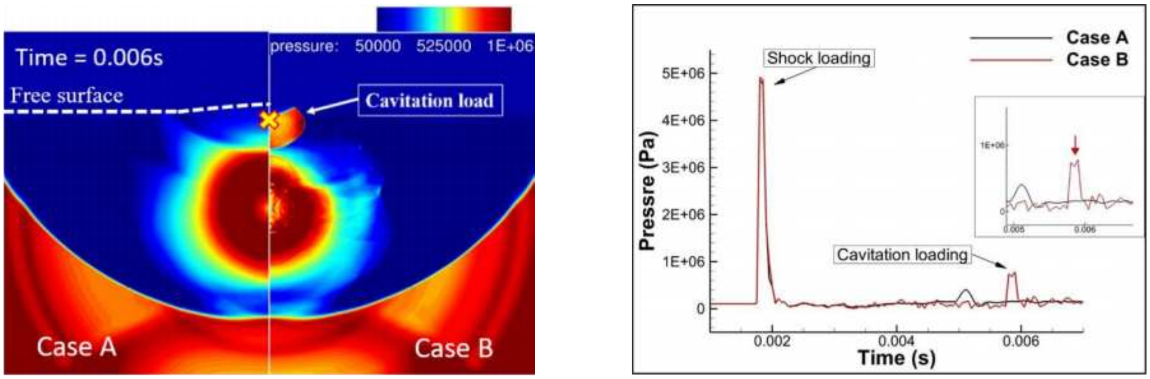
A number of previous works on UNDEX have been conducted on a laboratory scale, in terms of depth and weight of explosives. This kind of small explosions produce weak blast wave, in turn, local pressure drop induced by expansion is not enough to be cavitated. To focus on the phase change process near the free surface, a larger scale of underwater explosion is adopted in this study. Therefore, a single explosion gas bubble is generated by TNT with the weight of 10kg at a depth of 3m. Table 1 summarizes the computational cases.

To determine the initial condition of this scenario, empirical formulas of maximum bubble radius $R_{\max}$ and initial bubble pressure P_0 are adopted [12]. By employing the Rayleigh-Plesset equation [13, 14], an initial bubble radius R_0 can also be derived. However, there is no particular relation between the temperature and the density inside the explosion gas bubble. Though the explosion gas bubble is modeled by ideal gas law, JWL EOS is temporarily cast in to determine the initial bubble temperature. First, the initial bubble temperature is casually set to 2,000 K, and the initial bubble density is calculated from JWL EOS. Then, by matching the bubble pressure and density, the bubble temperature is calculated back using the ideal gas law. The influence of the guessed value of 2,000 K will be examined in the presentation.

Figure 2(a) shows the pressure contour of case A, B at the moment of cavity collapse, t = 0.006s. It is clearly seen that the pressure wave, which is the bulk cavitation loading, occurs and propagates from the collapsed cavity region of case B. The case with the simple pressure-cut model (case A) couldn't predict any noticeable pressure waves except the primary shock loading.

Table 1. Computational cases with initial bubble conditions.

Case	Radius	Pressure	Density	Temperature	Bubble EOS	Cav. model
A	0.254 m	70.26 MPa	356.27 kg/m^3	5,387 K	Ideal gas law	Pressure-cut
B						Schnerr-Sauer



(**a**) (b)

Figure 2. Main UNDEX simulation results: (**a**) Contour of pressure at 0.006 s (left: case A, right: case B); (**b**) pressure-time history gauged at 0.1m beneath the free surface.

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Figure 2(b) is the pressure-time history gauged at 0.1m beneath the free surface (the location marked with yellow-colored cross). Primary shock arrives at the same time incident for both cases, and the cavitation load is observed only at the case B. However, there is a slight pressure rise at 0.0052s in case A. After the initial explosion, the expansion wave is generated near the free surface and bumps into the explosion gas bubble. The pressure rise at 0.0052s in case A indicates the history pressure wave reflected back from the explosion bubble, which is distinguished from the cavitation load. In this scenario, approximately 15.54% of the primary shock load is generated from the cavity collapse, which is small yet hard to be ignored.

Table 2. Comparison of shock and cavitation loadings.

Primary shock load (MPa)	Bulk cavitation load (MPa)	Percentage (%)
5.02	0.78	15.54

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