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Numerical investigation of an interaction between shock waves and bubble in a compressible multiphase flow using a diffuse interface method

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ABSTRACT

The shock-bubble interaction in a compressible multiphase flow was investigated using a diffuse interface method (DIM) consisting of seven equations. To achieve detailed flow structures and mass transfer information, high-order numerical schemes, including the fifth-order MLP and a modified HLLC Riemann solver, were implemented. The numerical methods were verified via a flow structure comparison of the high-pressure water and low-pressure air shock tubes. A two-dimensional air-helium shock-bubble interaction at the incident shock wave condition (Mach number 1.22) was numerically solved and verified using the experimental results. A very detailed deformation was observed, so unsteady shock patterns such as the incident, transmitted, and reflected shocks could be identified. In addition, the air–water shock-bubble interaction at the same Mach number condition (1.22) was analyzed via the observation of detailed flow structures such as the reflection and transmitted shock inside and outside of the water bubble.

1. Introduction

A cavitation is a rapid evolution of vapor bubbles in a fluid due to very low pressures. The sudden appearance of bubbles and subsequent collapse causes a sudden change in pressure, which can lead to severe mechanical damage. Damage is known to occur through two mechanisms [1]. First, the strong shockwaves generated by the bubble collapse can interact with the surface. The second mechanism occurs when the bubble is very closely attached to the wall. This leads the jet to impact the wall directly, causing erosion. This phenomenon is called a 'water hammer' [2] and is understood to be the more potent mechanism.

High-speed vehicles can suffer damage via collisions with several millimeters of liquid droplets present in the atmosphere, called hydrometers [3]. In this case, the water droplets collide with the surface after undergoing deformations such as shape changes and mass reductions due to the shock waves generated in front of the body. The state of the water droplets deformed by the shock waves is a factor to be considered because the damage can be serious when the surface changes according to the deformation strength of the water droplet [3,4]. The deformation of water droplets due to shock waves occurs under the interaction of complex phenomena such as incident, transmitted, and reflected shocks. A precise numerical technique to account for compressible multiphase flows is required to analyze these phenomena numerically.

There are two schemes for mathematically capturing the interface of a multiphase flow – the sharp interface method (SIM) and diffuse interface method (DIM). The SIM includes the typical volume of fluid (VOF) [5] and level-set [6] methods, and these methods are based on incompressible governing equations. Moreover, the SIM has complex algorithms and is expensive. On the other hand, the DIM is based on the Baer-Nunziato equation [7], which is a compressible flow equation. This makes the DIM simpler than the SIM. Therefore, in this study, the DIM was implemented to solve compressible multiphase flows such as shock-bubble interaction problems.

There have been several numerical studies on shock-bubble interactions. Quirk and Karni [8] conducted a numerical analysis of an air-helium bubble. Terashima and Tryggvason [9] performed a numerical analysis of air-helium and air-water bubble shocks using five equations with front-tracking and ghost fluid methods. Yeom and Chang [10] modified the HLLC method to simulate bubble-shock wave interactions with six equations and compared

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Nomenclature

c	speed of sound
E	specific total energy
e	internal energy
$\boldsymbol{F}$	inviscid flux vectors of x directions
$\boldsymbol{G}$	inviscid flux vectors of y directions
$\boldsymbol{H}$	non-conservative of x direction
$\boldsymbol{I}$	non-conservative of y direction
n	normal vectors
p_I	interfacial pressure
p	pressure
Q	primitive variables
r	coefficient of MLP
S	cell face area
s	fastest wave speed
$\boldsymbol{U}$	conservative matrix
u	x velocity
u_I	interfacial x velocity
V	contravariant velocities
v	y velocity
v_I	interfacial y velocity
p_∞	infinite pressure parameter of EOS

Greek

α	volume fraction
ρ	density
φ	coefficient of MLP
γ	specific heat ratio
Ω	cell volume
λ	artificial drag coefficient

Superscripts

$\bar{}$	averaged value
$*$	state at the intermediate or step in RK

Subscripts

i	notation of x-direction
j	notation of y-direction
k	phase
L	left state
R	right state

the results with previous studies to confirm that their results had fewer numerical errors. Daramizadeh and Ansari [11] used the MUSCL and HLLC methods to calculate a shock-bubble. Sembian et al. [12] conducted experiments on the interaction of shocks with cylinder water columns in the air, and they compared the results with numerical results. Wang et al. [13] conducted a shock-bubble numerical analysis using the MUSCL-Hancock scheme and the second-order upwind scheme for helium bubbles of various shapes. Recently, Haimovich and Frankel [14] performed bubble arithmetic using the TENO reconstruction method and compared the results of the WENO and MUSCL. Yoo & Sung [15] conducted a numerical analysis of a two-dimensional air-helium shock-bubble interaction at the incident shock wave condition (Mach number 1.22) using the diffuse interface method and modified HLLC and then compared it with experimental results.

This study, however, used the Baer-Nunziato's seven equations and fifth-order multi-dimensional limiting process (MLP) reconstruction scheme, and the modified Harten–Lax–van Leer-Contact (HLLC) Riemann scheme to achieve more detailed characteristics of the bubble-shock interaction.

2. Governing equations

2.1. The governing equation

The two-dimensional seven-equation model proposed by Baer and Nunziato [7] is as follows.

$$\frac{\partial \alpha_1}{\partial t} + u_I \frac{\partial \alpha_1}{\partial x} + v_I \frac{\partial \alpha_1}{\partial y} = 0$$

$$\frac{\partial \boldsymbol{U}_k}{\partial t} + \frac{\partial \boldsymbol{F}_k}{\partial x} + \frac{\partial \boldsymbol{G}_k}{\partial y} = \boldsymbol{H}_k \frac{\partial \alpha_1}{\partial x} + \boldsymbol{I}_k \frac{\partial \alpha_1}{\partial y} \tag{1}$$

where $k = 1, 2$ corresponds to the gas and liquid phases, respectively. The vectors are defined as:

$$\boldsymbol{U}_k = \begin{pmatrix} \alpha\rho \\ \alpha\rho u \\ \alpha\rho v \\ \alpha\rho E \end{pmatrix}_k \boldsymbol{F}_k = \begin{pmatrix} \alpha\rho u \\ \alpha\rho u^2 + \alpha p \\ \alpha\rho u v \\ \alpha u(\rho E + p) \end{pmatrix}_k$$

$$\boldsymbol{G}_k = \begin{pmatrix} \alpha\rho v \\ \alpha\rho v u \\ \alpha\rho v^2 + \alpha p \\ \alpha v(\rho E + p) \end{pmatrix}_k \boldsymbol{H}_1 = \begin{pmatrix} 0 \\ p_I \\ 0 \\ p_I u_I \end{pmatrix} \boldsymbol{I}_1 = \begin{pmatrix} 0 \\ 0 \\ p_I \\ p_I v_I \end{pmatrix} \tag{2}$$

$\boldsymbol{H}_k$ and $\boldsymbol{I}_k$ are non-conservative matrices, and $H_2 = -H_1$, $I_2 = -I_1$. The two volume fractions satisfy $\alpha_1 + \alpha_2 = 1$. Saurel and Abgrall [16] determined that the interfacial velocity could be estimated as it corresponded to the center of mass velocity and pressure, which equals the mixture pressure, as follows.

$$u_I = \frac{\alpha_1\rho_1 u_1 + \alpha_2\rho_2 u_2}{\alpha_1\rho_1 + \alpha_2\rho_2},\ v_I = \frac{\alpha_1\rho_1 v_1 + \alpha_2\rho_2 v_2}{\alpha_1\rho_1 + \alpha_2\rho_2} \tag{3}$$

$$p_I = \alpha_1 p_1 + \alpha_2 p_2 \tag{4}$$

To solve Eq. (1), eight primitive variables are used, as follows.

$$Q_k = (\rho, u, v, p)_k \tag{5}$$

where $k = 1$ and 2. The velocity and pressure relaxation process described in Eqs. (3) and (4) yields the same speed and pressure for each phase. The governing system solves the seven equations of Eq. (1), but consequently has five primitive variables, $Q = (\rho_1, \rho_2, u, v, p)$.

2.2. Equations of state

Each phase governed by the stiffened equations of state (EOS) is well-matched for the liquid phase in a large pressure differential environment.

$$p_k = (\gamma_k - 1)\rho_k e_k - \gamma_k p_{k,\infty} \tag{6}$$

where γ_k and $p_{k,\infty}$ are empirically determined as the constant parameters of each phase. Eq. (6) becomes equal to the EOS for the gas phase if $p_{k,\infty}$ is zero. Then, the specific total energy becomes $E = \frac{p+\gamma p_{k,\infty}}{\rho(\gamma-1)} + \frac{1}{2}(u^2 + v^2)$. The velocity of sound in a stiffened EOS is as follows.

$$c_k = \sqrt{\frac{\gamma_k p_k + p_{k,\infty}}{\rho_k}} \tag{7}$$