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Numerical analysis of mercury cavitation in MW-scale spallation neutron source system

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Abstract

We are developing a new numerical analysis method for elucidating and predicting the cavitation phenomena in mercury, which make a controversial impact on the development of the MW-scale spallation neutron source systems. The method is a unified methodology for liquid–gas two-phase problem based on the Cubic Interpolation Volume/Area Coordinates (CIVA) method. Since the Combined Unified Procedure (CUP) method is used for basis algorithm and the finite volume method for discretization, the method enables the numerical analysis of multi-phase flow in technologically complex systems. With the aim of the cavitation analysis, the method introduces the following two methods into the code: a generalized equation of state, which unifies the liquid and gas equations of state, and a model that can represent a pressure change caused by the phase change. We analyze the cavitation problem in mercury and compare the results with the Rayleigh–Presset theoretical solution.

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1. Introduction

The development of MW-scale spallation neutron source systems is being carried out throughout the world. In Japan, the high-intensity proton accelerator driven neutron scattering facility is under construction for the implementation of Japan Proton Accelerator Research Complex (J-PARC), which is a joint project between Japan Atomic Energy Research Institute (JAERI) and High Energy Accelerator Research Organization (KEK). With the facility, pioneering researches of material and life sciences shall be challenged using pulsed neutrons produced by bombarding the liquid mercury target with intense proton beams. When this facility is used, there is apprehension that cavitation in the liquid mercury target of MW-scale spallation neutron source may cause the erosion of the solid metal container [1]. However, when a mercury target is bombarded by a pulsed proton beam, expansion waves are produced through the abrupt exothermic reaction process in the target container while neutrons are produced through the spallation nuclear reaction process. Expansion waves changes into pressure waves to propagate in the liquid mercury toward the inner wall of the container with the sound velocity and to apply impact loads to the container wall. The impact pressure causes pitting damage caused by the formation and collapsing of cavitation at the interface between the container wall and mercury, leading to the reduction of the life of the metal container.

To predict and prevent cavitation problems, we are expected to apply computational fluid dynamics. To deal with some difficulties originating from mercury cavitation such as more than 1000 times larger difference in the density between liquid and gas phases, and high surface tension, we have developed a high accuracy numerical analysis method for solving multi-phase flow, using the Cubic Interpolation Volume/Area coordinates (CIVA) method [2] in concert with the Combined Unified Procedure (CUP) method [3]. The CIVA method is a high accuracy interpolation method, and the CUP method is a

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unified methodology for solving compressible and incompressible fluids. The combination of CIVA and CUP enables flexible and highly accurate simulation of multiphase flow in the engineering fields [4,5]. In this study, we verified the usefulness of the method by introducing a phase change model for the analysis of cavitation. In addition, we performed a numerical analysis of the above mentioned mercury cavitation and compared the results with the Rayleigh–Presset solution.

2. Numerical approaches to cavitation

2.1. Fundamental equations and analytical method

As the basis algorithm for analysis code, this study uses the Thermo-CUP (TCUP) method [6], which is a reconstructed CUP method for the thermohydraulic analysis through the thermodynamical interpretation. The TCUP method evaluates the fundamental equations by dividing it into advection, diffusion, and acoustic phases according to the characteristic time. The fundamental equations are given by

$$\partial\rho/\partial t + \mathbf{u}\cdot\nabla\rho = -\rho\nabla\cdot\mathbf{u} + \Omega \tag{1}$$

$$\rho\partial\mathbf{u}/\partial t + \mathbf{u}\cdot\nabla\mathbf{u} = \nabla\cdot\mathbf{\Pi} + \mathbf{F} \tag{2}$$

$$\rho\partial e/\partial t + \mathbf{u}\cdot\nabla\mathbf{u} = \{\nabla\cdot\mathbf{\Pi}\}\cdot\mathbf{u} - \nabla\cdot\mathbf{q} + Q_S \tag{3}$$

$$\partial\alpha/\partial t + \mathbf{u}\cdot\nabla\alpha = \Gamma \tag{4}$$

where ρ is the density, $\mathbf{u}$ the velocity vector, $\mathbf{\Pi}$ the viscous stress tensor, e the internal energy, $\mathbf{q}$ the heat flux, α the void fraction, Γ and Ω the rate of change in the void fraction and density, respectively, caused by the phase change, Q_s the latent heat effect caused by the phase change, and $\mathbf{F}$ the external force such as the gravity and surface tension. This study introduced the continuum surface force (CSF) method [7] proposed by Brackbill et al. for evaluating the surface tension effect. Eqs. (1)–(4) were evaluated by using hexahedral grid and the collocation grid. In the collocation grid, all physical quantities are assigned to the centroids of control volumes.

To address complicated shape problems, we use the finite volume method for discretization and the CIVA method for the evaluation of advection term, which enables a high accuracy analysis even for unstructured grids. In the CIVA method, the interpolation is made by using triangles or tetrahedrons, and the cubic interpolation is achieved by using spatial derivatives as the variables in the same way as the CIP method. The interpolation using the CIVA method needs to construct the tetrahedral elements from neighboring centroids where physical quantities are defined. For that purpose, the octahedral element surrounding an intended centroid needs to be constructed from the eight centroids of the control volumes sharing boundary surfaces with the control volume containing the intended centroid. Then, the eight tetrahedral elements are constructed from the octahedral element and the intended centroid so that each of the eight octahedral elements has the intended centroid as one of its vertices.

2.2. Equation of state and phase change model

In this section, we describe the equation of state introduced in the TCUP method. The generalized equation of state proposed by Shin et al. [8,9] adopts the equation of state of ideal gas for the gas phase and the Tammann-type equation of state for the liquid phase (the ideal gas model is not correct under a high pressure and will be replaced by the higher EOS in future). A weight is assigned to each equation of state and they are combined. As a result, the generalized equation of state is given by

$$\rho = (1-\alpha)(p+p_c)/R_l(T+T_c) + \alpha p/R_g T \tag{5}$$

where p_c, R_l, R_g, and T_c are the pressure, liquid, gas, and temperature constants, respectively. They are determined by the physical properties. Considering that cavitation is sort of phase change induced by the pressure drop, the calculation is performed through the following procedure. First, the calculation is carried out without considering the phase change. For the cells including liquid with pressure lower than the saturation pressure, the change during the calculation step is assumed to be isothermal, and the void fraction is changed so that the pressure reaches the saturation pressure with keeping the density constant. Under the condition $\rho_{f\geqslant}\rho_g$, the source of density, Ω, is given by $\Omega = \rho_l\Gamma/(\alpha+\Gamma\Delta t)$. The latent heat effect caused by the phase change is given by $Q_s = \rho\Gamma L$, where L is the latent heat.

3. Numerical analysis of mercury cavitation

In making the spallation neutron source high-powered, the important factor is to clarify how the deterioration behavior of the target container differs with the condition of proton beam power and incident period. Among its deterioration causes, the above mentioned cavitation in mercury is to be specified. To clarify the cavitation phenomena produced in the target, we have been conducting experiments of impact erosion at liquid/solid metals interface with a magnetic impact testing machine. The machine was used to apply the impact pressure to the mercury/solid metal interface by forcibly giving the displacement with electromagnetic forces. As a consequence, he succeeded in reproducing erosion phenomena induced by pressure waves on the solid/liquid interface. We shed the light on the cavitation damage process [1], in which submicron-sized pits were produced and cracks produced at the bottom portion of the pits. However, the experimental approach has limitations to the visibility experiments for the elucidation of the damage mechanism because of the opacity of liquid mercury. Therefore, the numerical analysis is expected to elucidate and predict the cavitation phenomena. As a first step, this study performed