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Numerical investigation of the time-resolved bubble cluster dynamics by using the interface capturing method of multiphase flow approach*

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Abstract: The present paper proposes a multiphase flow approach for capturing the time-resolved collapse course of bubble clusters in various geometrical configurations. The simulation method is first verified by computing the dynamic behavior of an isolated vapor bubble placed in a uniform ambient pressure. The comparison between the numerical result and the theoretical solution indicates that the method can accurately capture the bubble shape, the characteristic time and the extremely high pressure induced by the collapse. Then the simulation method is applied to investigate the behavior of two kinds of bubble clusters in hexagonal and cubic geometrical configurations. The predicted collapsing sequence and the shape characteristics of the bubbles are generally in agreement with the experimental results. The bubbles transform and break from the outer layer toward the inner layers. In each layer, the bubbles on the corner first change into a pea shape and cave before collapsing, then the bubbles on the sides begin to shrink. It is also found that, in comparison with the case of an isolated single bubble, the central bubble in the cluster always contracts more slowly at the early stage and collapses more violently at the final stage.

Key words: Bubble cluster, collapse, numerical simulation, cavitation model

Introduction

Cavitation often occurs in a wide range of hydraulic devices when the static pressure in the fluids drops greatly due to the local high speed. The cavitation erosion effect is caused by the cyclic impact loads of the bubble cluster collapse acting on the tiny area of the solid surface in a very short time. The cavitation erosion was extensively studied, especially, experimentally. It has been a common sense that the internal structure of the bubble cluster inside the cavitation cloud and its collapse process should be more precisely studied, if one intends to go further in the erosion mechanism research. However, the microscopic scale of the bubbles makes experimental techniques impractical in studying the interaction between the bubbles in the course of collapse.

In these days, numerical approaches are playing a key role in the bubble cluster dynamics investigation. A great deal of numerical studies of the bubble evolution were based on solving the Rayleigh-Plesset equation or its modified forms[1,2]. In the cavitating flows, the local vapor fraction often exceeds the dilute limit and the Rayleigh-Plesset equation does not hold true. Therefore the bubble-bubble interaction is an important effect in the bubble flows, as shown by the studies of Seo et al.[3]. Also, some studies concentrated on how the collapse of the neighboring bubbles is affected by their conjunct interaction[4]. Nevertheless, the bubble dynamics equations alone are not enough to well resolve the interaction between the bubbles.

The boundary element method (BEM) based on the inviscid fluid model was widely used for the computation of the bubble dynamics and the bubble-boundary interaction in axisymmetric cases[5-7] and in full 3-D geometric configurations[8,9]. In the multiphase flow framework, the mixture models based on the macroscopic conservation laws coupled with simplified bubble equations were used to simulate the bubble cluster behavior[10]. The most essential issue for such methods is the technique of capturing the bubble surfaces, such as with the VOF method, the level-set method, and the front-tracking method. They were used

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to study dilute bubbly flows and were shown to be capable of resolving the flow features. The radial dynamics of the bubbles in compressible fluids were also studied extensively[11-14], where the main focus is on the final stage of the collapse. Recently, Zhang et al.[15] developed a complete model for studying the mutual interaction between cavitation bubbles with the effects of liquid compressibility fully included.

In this paper, the multiphase flow approach based on the homogeneous cavitation model is used to capture the collapse course of the bubble clusters in various geometrical configurations. The primary objective is to investigate the dynamic behavior of the bubble clusters during their collapse and the interaction between the bubbles.

1. Multiphase flow approach

1.1 *Volume fraction function*

In the traditional bubble dynamics approach, the differential equation for the bubble size or even its spatial distribution function is directly solved, the results obtained are not field-resolved and the bubble surface is regarded as a discontinuous interface. In real flows, the finite distance between the bubbles and the non-symmetric environment invalidate the basis upon which the bubble dynamics equation is founded. Furthermore, the deformation of the bubbles is hard to be taken into account in the traditional way.

This shortcoming can be overcome by using the multiphase flow approach. The transient location and shape of each bubble surface in the cluster are interpolated from the vapor's volume fraction function, $\alpha(\boldsymbol{r},t)$, which denotes the local proportion of the vapor phase inside the liquid/vapor mixture at the coordinates $\boldsymbol{r}$ and at any given instant t. The distribution of $\alpha(\boldsymbol{r},t)$ in the 3-D domain is directly resolved and can be written as:

$$0<\alpha(\boldsymbol{r},t)<\alpha_0 \quad \text{inside bubble} \tag{1a}$$

$$\alpha(\boldsymbol{r},t)=\alpha_0 \quad \text{bubble surface} \tag{1b}$$

$$\alpha_0<\alpha(\boldsymbol{r},t)<1 \quad \text{outside bubble} \tag{1c}$$

where $\alpha_0\in(0,1)$ is a selected value which determines the geometry of the bubble surfaces.

In another way, the discrete bubble surface Γ encircling any vaporous region can be instantaneously constructed from the continuous distribution of $\alpha(\boldsymbol{r},t)$:

$$\int_\Gamma \nabla\alpha\times\boldsymbol{n}\mathrm{d}\Gamma=0 \tag{2}$$

$$\frac{\partial^2\alpha}{\partial n^2}=0 \tag{3}$$

where α_0 is not required to be explicitly specified.

Equation (2) reveals the fact that the gradient of $\alpha(\boldsymbol{r},t)$ across the bubble surface always vertically points out. Numerous contour lines of α can be determined in this way. Using Eq.(3) we can select the most reasonable contour line from those described by Eq.(2). This is because that the change rate of $\partial\alpha/\partial n$ along the radial direction of any bubble reaches its inflection point in the middle of the density transitional region around the bubble interface. Therefore a middle surface for the bubble is picked out through Eq.(3). Additionally, the influence of the interaction between the bubbles on the bubble shapes is also directly observed.

1.2 *One-fluid homogeneous model*

The volume fraction function $\alpha(\boldsymbol{r},t)$ is governed by a phase change process suggested by Zwart et al.[16], and is derived from the Rayleigh-Plesset bubble dynamics equation. A transport equation of the volume fraction is solved, where the mass transfer between the liquid and vapor phases is modeled through the evaporation and condensation source terms:

$$\frac{\partial(\rho\alpha)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j\alpha)=S_e+S_c \tag{4}$$

$$S_e=C_e\frac{3\alpha_0(1-\alpha)\rho_v}{R_B}\left[\frac{2}{3}\max\left(\frac{p_v-p}{\rho_l},0\right)\right]^{1/2} \tag{5}$$

$$S_c=C_c\frac{3\alpha\rho_v}{R_B}\left[\frac{2}{3}\max\left(\frac{p-p_v}{\rho_l},0\right)\right]^{1/2} \tag{6}$$

$$\rho=\alpha\rho_v+(1-\alpha)\rho_l \tag{7}$$

$$\mu=\alpha\mu_v+(1-\alpha)\mu_l \tag{8}$$

where C_e and C_c are the empirical constants, which are chosen as 50 and 0.01, respectively, α_0 denotes the initial void fraction of the water due to the dissolved gas nucleus, and R_B denotes the nucleus radius.

With this model, the evolution of the bubble shapes is computed according to the time-dependent dynamic equilibrium between the non-uniform ambient pressure outside any bubble and the vapor pressure inside the bubble. When the local ambient pressure p becomes lower than the vapor pressure p_v, the evaporation source described in Eq.(5) works. In this way, the