Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2012,24(4):569-578
DOI: 10.1016/S1001-6058(11)60279-5
www.sciencedirect.com/science/journal/10016058

NUMERICAL SIMULATION OF SPHERICAL, CYLINDRICAL AND AXIAL BUBBLE CLOUDS COLLAPSE*

MAHDI Miralam, EBRAHIMI Reza, SHAMS Mehrzad
Faculty of Mechanical Engineering, K.N.Toosi University of Technology, Tehran, Iran,
E-mail: miralam_mahdi@yahoo.com

(Received August 28, 2011, Revised May 1, 2012)

Abstract: The nonlinear dynamics of a spherical, cylindrical and axial cloud of cavitation bubbles were numerically simulated in order to learn more about the physical phenomena occurring in the cloud cavitation. The simulations employed the fully nonlinear continuum mixture equations coupled with the Gilmore equation for the dynamics of bubbles by considering the compressibility of liquid. A set of the Navier-Stokes equations was solved for the gas inside a spherical bubble, considering heat transfer through the gas inside the bubble and the liquid layer. The flow field around the cylindrical and axial cloud was obtained by solving the Navier-Stokes equations using a finite volume method and a dynamic layering mesh scheme. The calculated strength of shock wave in the liquid around the cloud was of the order of 1×10^6 Pa and the propagation of this shock wave lasted for 10 μs. The conducted investigations illustrate that the shock wave propagates before the cloud has completely collapsed. A good agreement with experimental data was observed.

Key words: cloud cavitation, shock wave, spherical cloud, cylindrical cloud, axial cloud

Introduction

Cloud cavitation is a periodic phenomenon occurring in a body which involves formation and collapse of sheet cavities. Experimental studies of cloud cavitation have shown that noise, erosion and vibration are mainly caused by the shock wave emission due to cloud cavitation collapses[1,2].

The earliest analytical study of the dynamics of cloud bubbles were conducted by Van Wijngaarden[3]. Van Wijngaarden used the continuum mixture models in the study of the behavior of a collapsing layer of bubbly fluid next to a flat wall. Agostino and Brennen[4] analyzed the linearized dynamics of a spherical cloud of bubbles using a continuum mixture model coupled with the Rayleigh-Plesset equation for the dynamics of the bubbles. Morch[5,6] and Hanson et al.[7] studied the collapsing cloud based on the energy transfer theory. They speculated that the collapse of a cloud proceeded layer by layer from the outside layer of the cavity cloud towards its inner part. Zhang et al.[8] used the idea proposed by Hanson to simulate cloud cavitation collapses in a Venturi tube. Wang and Brennen[9] investigated the fully nonlinear dynamics of spherical bubbles and found that a bubbly shock wave developed as a part of the nonlinear collapse of the bubble cloud. Mahdi et al.[10,11] demonstrated that both thermal conduction and liquid compressibility has great effects on bubble dynamics and shock wave strength due to bubble collapses, but radiation heat transfer effect is negligible. Wu and Lu[12,13] used the Homogenous Equilibrium Model (HEM) for simulating laminar cavitating flows around the 2-D hydrofoil and 3-D axis-symmetric body. The so-called homogeneous equilibrium model is based on a single fluid approach, in which the relative motion between liquid and vapor is neglected. Fu et al.[14] have calculated the cavitating flow around a revolution body with the HEM approach of void fraction transport equation. Reisman et al.[15] measured very large impulsive pressures on the suction surface of an oscillating hydrofoil experiencing cloud cavitations and demonstrated that these pressure pulses were associated with the propagation of the bubbly shock waves. Konno et

* **Biography:** MAHDI Miralam (1980-), Male, Ph. D., Assistant Professor
Corresponding author: SHAMS Mehrzad,
E-mail: shams@kntu.ac.ir

al.[16] showed that cloud cavitation collapses in spherical, cylindrical and axial features. Duration of collapse was the order of 10 to 100 microseconds and the maximum pressure generated by this collapse related to the collapse type. In their experiment, the peaks of impulsive force did not meet the instant of final collapsing, but were often some 10 to 100 microseconds earlier than the final collapsing.

In the present paper, with considering liquid compressibility, heat transfer through the gas inside the bubble and the liquid layer, the nonlinear dynamics of spherical, cylindrical and axial cloud of cavitation bubbles were studied. For a spherical cloud, the time-dependent boundary condition at the surface of cloud can be obtained using the Bernoulli equation in the spherically symmetric incompressible liquid outside the cloud. A CFD program is developed to compute pressure field on the surface of cylindrical and axial clouds.

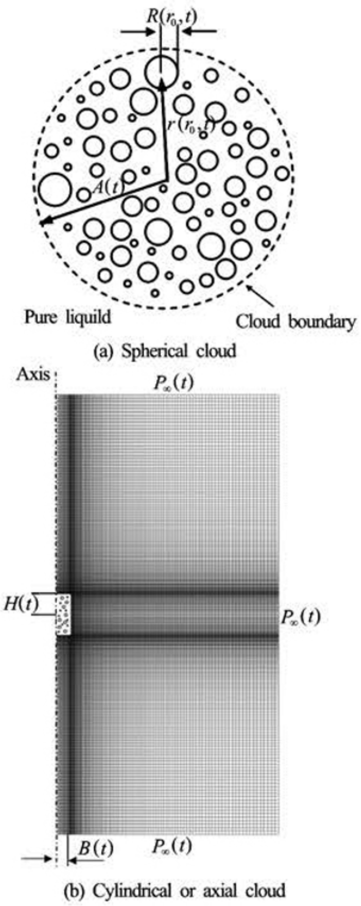

Fig.1 Schematic of physical model

1. Physical model

Bubble cloud consists of a limited number of cavitation bubbles. The bubble cloud may be spherical (Fig.1(a)), cylindrical or axial (Fig.1(b)). This cloud is surrounded by the liquid, and compared with the compressibility of the cloud, the compressibility of the liquid is neglected. First, η bubbles per unit liquid volume inside the cloud are uniformly distributed. The mass transfer between two phases of liquid and gas is neglected and no coalescence or breakup occurs in the bubbles. Therefore, the value of η is always constant and uniform within the bubble cloud.

Applying an order of magnitude analysis[17] indicates that, for the present flows, relative motion of two phases can be neglected. However, a homogeneous continuum bubbly mixture model can be used for analyzing the problem. The spherical bubbles are uniformly distributed with equal initial radius within the bubble cloud and an amount of air and vapor exists within the bubbles. Over time, the bubble radius $R(r,t)$ changes as a function of time and radial coordinate r relative to the bubble cloud center. The radius of the spherical cloud $A(t)$ is time dependent. $B(t)$ and $2H(t)$ are the radius and height of the cylindrical (axial) cloud, respectively. When the cloud behaves cylindrically, H is constant and $B(t)$ changes with time and, in the axial cloud, B is constant and $H(t)$ changes with time. At the moment $t=0$, the cloud and liquid are in equilibrium. Over time, the far-field driving pressure of the liquid, $P_\infty(t)$, changes. In this paper, the cloud response to $P_\infty(t)$ is investigated.

2. Mathematical model

2.1 *Single bubble*

The Gilmore equation describes the behavior of a spherical bubble within a static, compressible and inviscid liquid subjected to a sinusoidal wave. As no gravity or other asymmetrical disturbing effects are considered, the equation describing the evolution of bubble radius as a function of time is[18]

$$R\ddot{R}\left(1-\frac{R}{C}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{R}{3C}\right)=H_b\left(1+\frac{\dot{R}}{C}\right)+ \frac{R\dot{H}_b}{C}\left(1-\frac{\dot{R}}{C}\right) \tag{1}$$

The dots in Eq.(1) refer to the first and second order time derivations. C and H_b are the speed of sound and the liquid enthalpy at the interface between the gas-filled bubble and liquid, respectively.

$$H_b=\frac{1}{\rho_l}\left(\frac{\tilde{A}}{\tilde{A}-1}\right)\left(\frac{1}{P_0+\tilde{B}}\right)^{-\tilde{A}^{-1}}\left[\left(P_{bl}+\tilde{B}\right)^{(\tilde{A}-1)/\tilde{A}}-\right.$$