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# An investigation on the flow physics of bubble implosion using numerical techniques

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A B S T R A C T

In this paper, implosion of a micron-sized air bubble was studied numerically using OpenFoam software package. Then a parametric investigation on the flow physics of the problem was performed. The results show that as the initial pressure of the liquid increases, the pressure and the temperature inside the bubble increases such that in some cases, the temperature is as high as the one required for luminescence. Also, increasing the density and the temperature of the liquid solely, decreases the intensity of the collapse.

## 1. Introduction

In physics, bubble implosion is of high importance since, it has a significant role in many phenomena such as sonoluminescence in which micron-sized bubbles excited by the sound waves emit flashes of light during strong collapse (Barber et al., 1991). Also, due to destruction caused by cavitation, bubble implosion is of great interest in engineering and industry.

It is now a century that Rayleigh first described the pressure developed in a liquid during the collapse of spherical cavities (Rayleigh, 1917). Although he assumed the liquid to be as inviscid and incompressible and ignored surface tension which is a significant parameter especially in microscale, his results formed bubble dynamics basis. Later, Plesset tried to improve Rayleigh's theory by taking into account for the effects of viscosity and surface tension which led to the well-known Rayleigh-Plesset equation (Hickling and Plesset, 1964). Experiments such as (Cole, 1949) showed that the energy of the exploded bubble vanishes gently during bubble beat. In order to find the reason behind the energy dissipation of the exploded bubble, many researchers also considered the compressibility of the liquid surrounding the bubble (Keller and Kolodner, 1956; Prosperetti and Lezzi, 1986; Lezzi and Prosperetti, 1987; Nigmatulin et al., 2000). The mentioned studies assumed the collapse of the bubble as spherical, but practically, due to huge compression of the materials inside the bubble and large velocities during the last steps of the collapse, bubbles never collapse completely spherical. In this regard, researchers studied the shape stability of the bubble and found that the spherical symmetry hypothesis cannot be precisely true, particularly, at the last step of the collapse (Plesset and Prosperetti, 1977; Bogoyavlenskiy, 2000). In other studies, Brennen (2013) and Hilgenfeldt et al. (1996). declared that the Rayleigh-Taylor shape instabilities may cause the extinction of sonoluminescence.

Most of the phenomenon related to the bubble implosion such as sonoluminescence or cavitation damage occur so rapid that in spite of using high-tech equipment, experimental researchers are not easily able to investigate the bubble implosion phenomenon and providing accurate data. Hence, numerical simulations serve as an efficient tool for studying bubble dynamics. Wu and Roberts (1993), using the Rayleigh-Plesset equation and considering the collapse as spherical, suggest the formation of a shock inside the bubble. Moss et al. (1994), utilizing a finite difference technique, studied the hydrodynamics of the liquid around the bubble time-dependently. However, their investigation was in one dimension and lacked surface tension and viscous effects. In a later study, Yu et al. (1995), by solving three-dimensional Navier-Stokes equations using a finite difference/front-tracking method and ignoring thermal effects, investigated the collapse of a cavitation bubble in shear flows. However, in their simulation, the surrounding liquid was incompressible.

During the past two decades, many numerical techniques have been proposed by the researchers for studying bubble dynamics. For example, boundary element method (BEM) (Best and Kucera, 1992; Zhang and Liu, 2015; Li et al., 2016; Xiao et al., 2016), boundary integral method (BIM) (Blake et al., 1986, 1987; Wang, 2013; Wang, 2014) or smoothed particle hydrodynamics method (SPH) (Ming et al., 2016) were used to investigate non-spherical bubble dynamics. Also, researchers utilized Level-set method to describe the bubble motion (Nagrath et al., 2006; Lauer et al., 2012).

Volume of fluid (VOF) is a finite volume based method that has been

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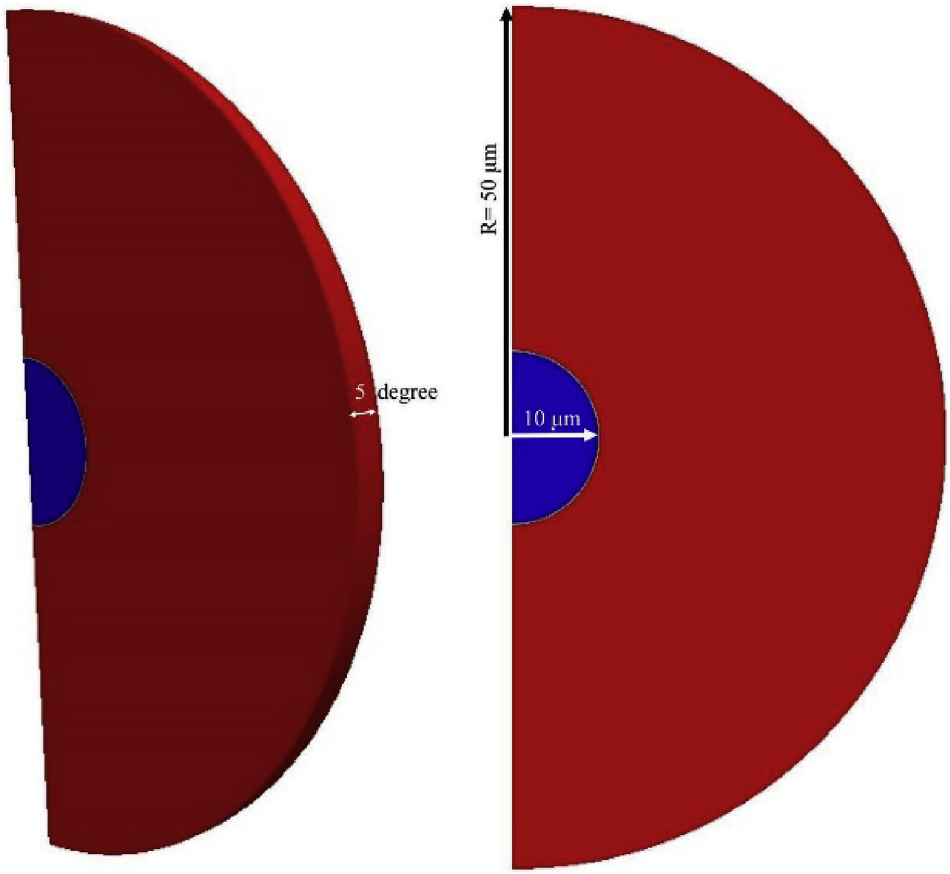


**Fig. 1.** The geometry of the underwater bubble implosion problem (air-blue color, water-red color). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

used widely for dealing with multiphase flows (details about the VOF method, can be found in (Hirt and Nichols, 1981)). Many of the researchers implemented this method for studying the bubble dynamics especially in the recent years. Passandideh-Fard and Roohi (2008) utilized a modified VOF for studying cavitating flows. Osterman et al. (2009) used VOF to study near-wall bubble collapse under the influence of acoustic fields. More recently, Koch et al. (2016), using open source software package OpenFoam, numerically modeled laser generated cavitation bubbles. They were able to capture shock waves by implementing Tait equation of state for the liquid phase. Koukouvinis et al. (2016a) used VOF to study the non-spherical collapse of a laser-generated bubble subject to gravitational force. They found that during the expansion, the bubble shape is highly spherical, but at the final stages of the collapse, a jet emerges at the axis of symmetry. Also, in another study (Koukouvinis et al., 2016b), they investigated a laser-generated bubble interacting with a free surface using VOF.

Since bubble implosion is a highly interested area of research, especially for sonoluminescence studies and based on our literature review, there is not sufficient information about the environmental conditions that affect the bubble implosion, this paper aims to focus on the physics of bubble implosion under different environmental conditions. Volume of fluid method of open source software package OpenFoam is used to handle interactions of the liquid and the gas. Both the liquid and the gas phases are treated as compressible; surface tension, viscous and thermal effects are taken into account. As given in (Koch et al., 2016), there is no need to include phase transition and therefore there is no mass transfer between the phases.

## 2. Numerical procedure

The volume of fluid method of OpenFoam is used to deal with the interface between the liquid and the gas (OpenFoam et al.) and both phases are treated as compressible. In the following, the governing equations and the methodology used in the present simulation are discussed in detail.

### 2.1. Governing equation

The governing equations solved in OpenFoam are as follows:
The continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \tag{1}$$

The Navier-Stokes equation:

$$\frac{\partial(\rho U)}{\partial t} + \nabla.(\rho UU) = -\nabla\left(P + \frac{2}{3}\mu\nabla.U\right) + [\nabla.(\mu\nabla U) + \nabla U.\nabla\mu] + \rho g + \sigma\kappa(\alpha_1)\nabla\alpha_1 \tag{2}$$

In which $\sigma$ is the surface tension, $\kappa$ is the curvature of the surface and $\alpha_1$ is the phase fraction of phase 1. The curvature of the surface can be obtained as:

$$\kappa = \nabla.\left(\frac{\nabla\alpha_1}{|\nabla\alpha_1|}\right) \tag{3}$$

### 2.2. Equation of state for the liquid and gas phase

For the liquid and gas phases, a linear equation of state is used as follows:

$$\rho_i = \psi_i P + \rho_{0i} \tag{4}$$

Where, $i$, is the phase liquid ($l$) or gas ($g$) and $\psi_i$ denotes the compressibility and is equal to $1/c_i^2$ where $c_i$ is the sound speed. For the