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Numerical simulation of aspherical collapses of vapor bubbles containing non-condensable gas

Theresa Trummler, Steffen J. Schmidt and Nikolaus A. Adams

Technical University of Munich, Department of Mechanical Engineering, Institute of Aerodynamics and Fluid mechanics

Boltzmannstrasse 15, Garching, 85748, Germany

theresa.trummler@tum.de

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Abstract

We investigate numerically the effect of non-condensable gas inside a vapor bubble on the bubble dynamics, the collapse pressure and the maximum pressure at the wall for aspherical collapses close to the wall. Free gas in the vapor bubble has a cushioning effect that can weaken the pressure wave and enhance the bubble rebound. In order to assess this effect numerically, simulations of collapsing vapor bubbles with different stand-off distances to the wall are performed. The bubbles contain either only vapor or vapor and a certain amount of non-condensable gas. For the cavitating liquid and the non-condensable gas we employ a homogeneous mixture model with a coupled equation of state for all components. The cavitation model is a barotropic thermodynamic equilibrium model. Compressibility of all phases is considered, in order to capture the shockwave of the bubble collapse.

Introduction

Liquids may contain dissolved gases that can be set free by pressure reduction or cavitation, leading to the presence of gas in vapor cavities. Gas inside a vapor bubble has a cushioning effect that can weaken the pressure wave and enhance bubble rebound. For spherical bubble collapses, this has already been investigated analytically and experimentally (e.g. Tinguely et al. (2012)). However, for more complex configurations, the effect of the gas is not yet clarified and can be investigated with three-dimensional time resolved numerical simulations.

In Trummler et al. (2018) we performed simulations of spherical bubble collapses and validated our approach against the experimental findings of Tinguely et al. (2012). The aim of the presented work is to numerically investigate the effect of free gas on an aspherical bubble collapse close to the wall.

Thermodynamical model

We employ a multi-component homogeneous mixture model (Örley et al. 2015). The cavitating liquid, with the liquid-vapor mixture (lv), and the non-condensable gas (g) are described with one mixture fluid, which is defined by the volume averaged density inside a computational cell

$$\rho = \sum \beta_\phi \rho_\phi . \tag{1}$$

β_ϕ denotes the volume fraction and ρ_ϕ the density of each component $\phi = \{\mathrm{lv},\ \mathrm{g}\}$. A coupled equation of state (EOS) gives the pressure as a function of the mean density $p = p(\rho)$ and is obtained by expressing the densities ρ_ϕ with the corresponding thermodynamic relations. The cavitating liquid is described with a barotropic EOS, derived by integration of the isentropic speed of sound. The non-condensable gas phase is described with an ideal gas law. In a bubble filled with vapor and gas the pressure in the bubble is the sum of both pressures and thus the pressure acting on the vapor is

$$p_{\mathrm{vap}} = p - p_{\mathrm{g}} = (1 - \beta_{\mathrm{g}})\, p \,, \tag{2}$$

which we include in our model (Trummler et al. 2018).

Viscous effects are considered in our simulations using a mixture viscosity.

The thermodynamic model is embedded in a density-based fully compressible flow solver (Schmidt 2015).

Setup of the simulations

A vapor bubble with an initial radius R_0 of $4 \cdot 10^{-4}\,\mathrm{m}$ is placed at different stand-off distances to the wall, as depicted in Fig.1. The driving pressure difference is $\Delta p = 1e5\,\mathrm{Pa}$ and the vapor bubble contains either no gas $p_{\mathrm{g},0} = 0\,\mathrm{Pa}$ or an initial gas content of $p_{\mathrm{g},0} = 160\,\mathrm{Pa}$.

The domain is discretized with an equidistant grid within the near bubble region and for the outer part grid stretching is applied. Simulations are performed on grids with 80 cells/R_0. To reduce the computational effort only one quarter of a bubble is simulated.

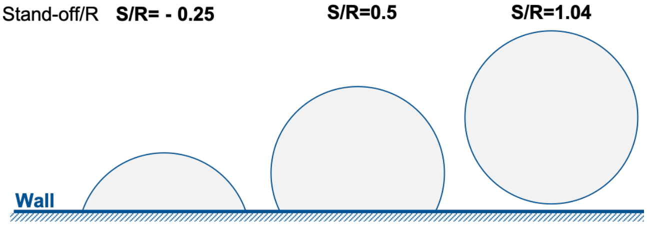

Figure 1: Sketch of the investigated configurations.

Results and Discussion

In the investigated configurations we observe the same collapse behaviors as found by Lauer et al. (2012) for bubbles with various stand-off distances. We now focus on a bubble cut in the lower hemisphere. Fig. 2 shows the temporal evolution of the void fraction for collapses with and without gas and Fig. 3 depicts a corresponding time series. At the beginning there is an indentation of the bubble, then the bubble is penetrated by a jet directed towards the wall leading to the formation of a toroidal structure, then the first collapse takes place, afterwards a rebound in the form of a toroidal vapor structure is observed followed by the second collapse.

When non-condensable gas is present, the rebound is slightly stronger and the second collapse is delayed. The monitored pressure maximum in the domain is damped by 6.6 % when gas is present.

We plan to further investigate the effect of free, non-condensable gas inside a vapor bubble on the collapse and rebound behavior of aspherical collapses close to a wall as well as on the pressure impact on the wall.

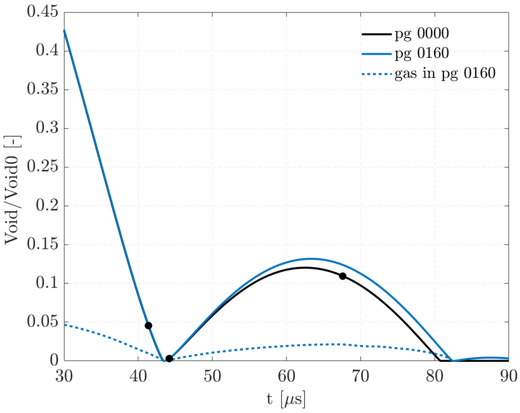

Figure 2: Temporal evolution of the void fraction for the bubble containing only vapor and the bubble with $p_{g,0} = 160\,\mathrm{Pa}$. Time instants shown in the time series are marked by dots.

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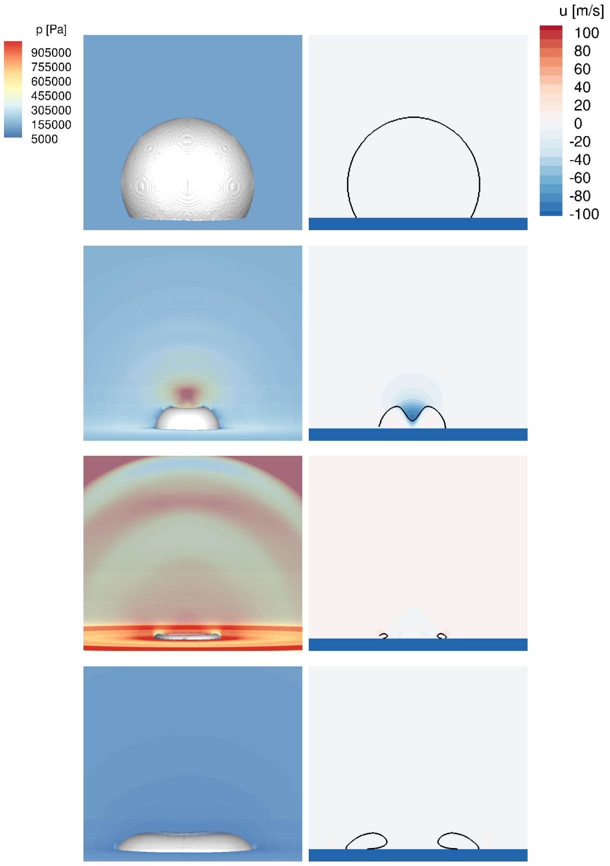

Figure 3: Time series for the bubble without gas. Left column: pressure; right column: velocity in wall normal direction. Time instants are marked in Fig. 2.

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