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# A level-set method for bubble growth in acoustic droplet vaporization

Sungwook Cho, Gihun Son*

*Department of Mechanical Engineering, Sogang University, Seoul, South Korea*

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ABSTRACT

A level-set method is presented for computation of bubble growth in acoustic droplet vaporization (ADV) including the interactions between the liquid-vapor interface and the liquid-liquid interface as well as the effects of vapor compressibility and liquid-vapor phase change. The ghostfluid and semi-implicit pressure correction methods are implemented into the level-set method for compressible bubble growth with phase change. The numerical results for several test cases show good agreement with the analytical solutions. The level-set method is applied to investigate the effects of wall and ambient temperature on the droplet and bubble motion in the ADV condition.

## 1. Introduction

Acoustic droplet vaporization (ADV), in which volatile droplets immersed in another immiscible liquid are vaporized into bubbles by means of ultrasound, is of great interest in medical diagnostic and therapeutic applications [1,2]. Despite extensive experimental studies of the ADV process, its general predictive model has not yet been developed due to the complexity of the associated liquid-vapor and liquid-liquid interfacial flows including heat transfer and phase change.

One-dimensional theoretical or numerical models were proposed by several researchers. Qamar et al. [3] developed a predictive model for the dynamics of ADV in a rigid tube assuming that the vapor bubble follows the ideal gas law, the evaporation rate at the interface is constant, and the droplet and bubble motion remains spherical for all time. Their results for the time evolution of bubble compared well with the experimental data for dodecafluoropentane (DDFP) droplets of 10–20 μm radius. While predicting the bubble growth in a DDFP droplet, Shpak et al. [4,5] evaluated the heat transfer rate from the surrounding liquid, which determines the bubble growth rate, from the effective thermal boundary thickness or the energy equation in the liquid. However, their model has limitations by further assuming that the droplet is an infinite medium of liquid DDFP. A somewhat different model was presented by Pitt et al. [6] assuming that a vapor bubble is formed around a droplet rather than inside the droplet. Doinikov et al. [7] developed an improved model for the vaporization of octafluoropropane (OFP) and decafluorobutane (DFB) droplets, which does not have the limitations that the evaporation rate is constant and that the droplet size is infinite. Their results for the bubble growth inside a droplet and the subsequent bubble overexpansion showed good agreement with the experimental data for OFP and DFB droplets of 1–4 μm radius [8].

The first multi-dimensional computational model for ADV was presented by Ye and Bull [9] considering the expansion of a DDFP bubble located in the center of a cylindrical tube. The bubble expansion and the associated wall shear stress were computed by a sharp-interface moving boundary method. However, their model did not include the effect of phase change at the liquid-vapor - interface. Subsequently, Qamar et al. [10] combined the computational model for non-spherical bubble expansion during the late period of ADV with their theoretical model [3] that includes phase change of the DDFP droplet during the initial period.

Extensive numerical simulations were performed for incompressible or compressible bubble growth with phase change using a moving-grid method [11,12], the front-tracking method [13,14], a level-set (LS) method [15-19], the volume-of-fluid (VOF) method [20,21], and the coupled LS and VOF method [22,23]. However, the numerical simulations were not extended to the bubble growth in a deformable droplet immersed in another liquid.

In this work, the LS method is extended to bubble growth in the ADV condition including the interactions between the liquid-vapor interface and the liquid-liquid interface as well as the effects of vapor compressibility and liquid-vapor phase change. The numerical method is validated through computations of several test cases. The effects of wall and ambient temperature on the droplet and bubble motion in the ADV condition are quantified.

* Corresponding author at: Department of Mechanical Engineering, Sogang University, 35 Baekbeom-ro, Mapo-gu, Seoul 04107, South Korea.
*E-mail address:* gihun@sogang.ac.kr (G. Son).

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**Nomenclature**

| | |
|---|---|
| $a$ | speed of sound |
| $c$ | specific heat at constant volume |
| $f_a$ | frequency of acoustic pulse |
| $F$ | fraction function |
| $h$ | grid spacing |
| $h_{lv}$ | latent heat of vaporization |
| $H$ | domain height |
| $\dot{m}$ | mass flux across the interface |
| $\mathbf{n}$ | unit normal vector |
| $p$ | pressure |
| $P_a$ | amplitude of acoustic pressure pulse |
| $r$, $y$ | cylindrical coordinates |
| $R$ | radius |
| $R_g$ | gas constant |
| $t$ | time |
| $t^*$ | artificial time |
| $T$ | temperature |
| $\mathbf{u}$ | flow velocity vector, $(u,v)$ |
| $W$ | domain width |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | step function |
| $\beta$ | $\rho_v^{-1} - \rho_l^{-1}$ |
| $\gamma$ | specific heat ratio |
| $\kappa$ | interface curvature |
| $\lambda$ | thermal conductivity |
| $\mu$ | dynamic viscosity |
| $\rho$ | density |
| $\sigma$ | surface tension coefficient |
| $\boldsymbol{\tau}$ | viscous stress |
| $\phi$ | distance function from the liquid-vapor or liquid-liquid interface |

*Subscripts*

| | |
|---|---|
| $ac$ | acoustic |
| $b$, $d$ | bubble, droplet |
| $e$ | equilibrium state |
| $f$ | fluid |
| $I$ | interface |
| $l$, $v$ | liquid, vapor |
| $o$ | initial |
| $s$ | solid wall |
| $sat$ | saturation |
| $w$ | water |
| $\infty$ | ambient |

*Superscripts*

| | |
|---|---|
| $G$, $R$ | ghost, real |
| $n$ | time step |
| ^ | effective property |
| * | intermediate step |

## 2. Numerical analysis

The present numerical approach is based on the sharp-interface LS formulation developed in our previous studies [18,19] for compressible bubble growth with phase change. The LS method is extended to the ADV case where a volatile droplet immersed in another liquid is vaporized into a bubble. In this work, we consider an OFP droplet, whose boiling point −36.8 °C at 1 atm, immersed in a liquid water. The bubble and droplet surfaces are tracked by the LS functions $\phi_b$ and $\phi_d$, respectively, which are defined as signed distances from the interfaces, as depicted in Fig. 1. It is assumed that the flow is axisymmetric and laminar; the vapor phase is compressible whereas the liquid phases are incompressible; all fluid properties except vapor density are constant in each phase; the vapor phase is at the saturation temperature while phase change occurs.

### 2.1. Governing equations

The conservation equations of mass, momentum and energy for each phase are written as

$$\frac{\partial \rho_f}{\partial t} + \nabla\cdot\mathbf{u}_f\rho_f = 0 \tag{1}$$

$$\frac{\partial \rho_f \mathbf{u}_f}{\partial t} + \nabla\cdot\mathbf{u}_f\rho_f\mathbf{u}_f = -\nabla p_f + \nabla\cdot\boldsymbol{\tau}_f \tag{2}$$

$$\frac{\partial \rho_f c_f T_f}{\partial t} + \nabla\cdot\mathbf{u}_f\rho_f c_f T_f = -p_f\nabla\cdot\mathbf{u}_f + \nabla\cdot\lambda_f\nabla T_f + \boldsymbol{\tau}_f\colon\nabla\mathbf{u}_f \tag{3}$$

where the viscous stress $\boldsymbol{\tau}_f$ is expressed as

$$\boldsymbol{\tau}_f = \mu_f\left[\nabla,\mathbf{u},+,\nabla,\mathbf{u}^T,-,\frac{2}{3},,(,\nabla,\cdot,\mathbf{u},),,\mathbf{I}\right]_f. \tag{4}$$

The subscript $f$ denotes the bubble phase ($b$) for $\phi_b \le 0$, the droplet phase ($d$) for $\phi_b > 0$ and $\phi_d > 0$, and the water phase ($w$) for $\phi_b > 0$ and $\phi_d \le 0$ (refer to Fig. 1).

The conservation equations for each phase are coupled through the matching conditions at the interfaces ($\phi_b = 0$ or $\phi_d = 0$). At $\phi_b = 0$:

$$\mathbf{u}_d - \mathbf{u}_b = \beta\dot{m}\mathbf{n}_b \tag{5}$$

$$\mathbf{n}_b\cdot[(p_b - p_d)\mathbf{I} + \boldsymbol{\tau}_d - \boldsymbol{\tau}_b] = (\sigma_{bd}\kappa_b - \beta\dot{m}^2)\mathbf{n}_b \tag{6}$$

$$T_d = T_b = T_{sat}(p_{bI}) \tag{7}$$

At $\phi_d = 0$:

$$\mathbf{u}_w - \mathbf{u}_d = 0 \tag{8}$$

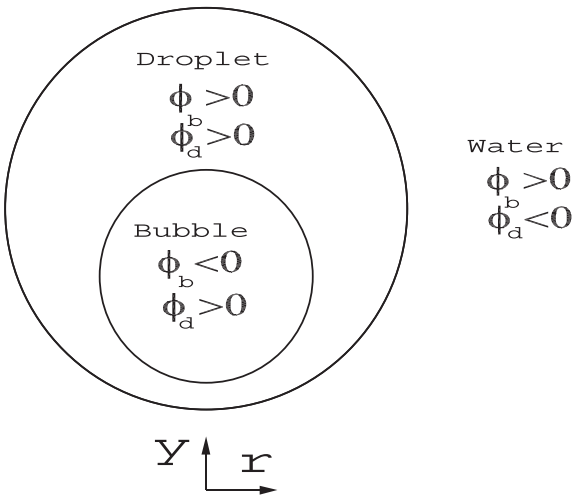


**Fig. 1.** Configuration of bubble, droplet and water phases in computation of ADV.