Numerical simulation of bubble interactions

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Introduction

Single bubble dynamics has been intensively investigated theoretically, experimentally and numerically during the last century [1]. Analysis of the interactions between bubbles in a cavitating flow or the interactions among an individual bubble pair has risen from the demand of a more comprehensive understanding of bubble dynamics.

When a bubble is induced near an interface by a laser beam, it collapses in an asymmetric way. If the interface is a rigid surface, a liquid jet of velocity in the order of 100 m/s is induced and hits onto this rigid surface. This is a source of cavitation erosion but not the most promising method for an active control of jet formation. If the bubbles are arranged into a pair, their dynamics is governed by three parameters: the phase difference, the initial energy and the distance between them. Through adjusting these parameters, both the jetting direction and the jetting intensity can be controlled. This is of particular interest for cell transfection, i.e. the introduction of nucleic acids into living cells [2, 3].

In order to investigate the roles of these three parameters in the jetting formation, numerical simulations are performed in this paper and compared with previous experimental results [4]. The insight gained from the numerical simulations will be helpful in guiding further experimental investigations.

Numerical scheme

The numerical investigations for the influence from the phase difference on the dynamics of the bubble pair are performed through Level-set method of COMSOL based on FEM. Three typical phase differences are calculated: in-phase (symmetric), out-phase (the second bubble is induced before the first bubble reaches its maximum radius) and anti-phase (the second bubble is induced when the first bubble reaches its maximum radius). The model geometries for the symmetric bubble pair (in-phase) and the asymmetric bubble pairs (out-phase and anti-phase) are shown in Fig. 1. Simulation results for the in-phase, out-phase and anti-phase bubble pairs are shown in Fig. 2, Fig. 3 and Fig. 4, respectively. Experimental results for bubbles with $R_{max} < 10$ µm are supplied by Laila Paulsen [2]. OpenFOAM, an open-source CFD software programmed in C++ based on FVM, is selected to perform the numerical calculations for the optimization of the inception distance. The Volume of Fluid (VOF) method and quadrangle/hexahedron meshing are used. Simulation results for different inception distances of an anti-phase bubble pair are shown in Fig. 5, Fig. 6, Fig. 7 and Fig. 8, respectively, with experimental results from [5]. Both of the two numerical methods from COMSOL and OpenFOAM are focused on tracking and locating the fluid-fluid interface and belong to the class of Eulerian methods.

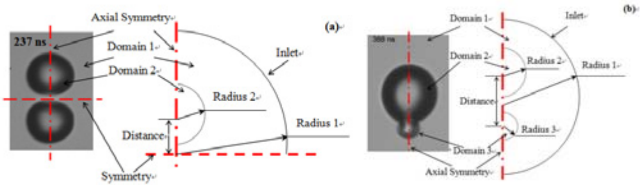

Fig. 1: Model geometry for the (a) symmetric and (b) asymmetric bubble pairs.

Results and discussions

Influence from the phase difference of a bubble pair in the bulk on the jetting formation

Fig. 2 shows that two symmetric jets moving toward each other are induced by the interaction of a symmetric bubble pair. The dynamic behavior of either one in the bubble pair is similar to that of a single bubble induced near a rigid surface. If the interaction in the bubble pair starts when there is a moderate phase difference between the bubbles and a small distance in between, as shown in Fig. 3, a jet will be induced from the phase-lagged bubble pointing into the phase-ahead bubble. However, the intensity of the jet is not high enough to sustain a penetration of the phase-ahead bubble. The phase-ahead bubble is the upside one in Fig. 3. If enlarging the phase difference between the bubbles, a jet will be induced from the phase-ahead bubble pointing into the phase-lagged bubble, as shown in Fig. 4, where the phase-ahead bubble is the downside one. Here the jet direction is opposite to that shown in Fig. 3, and the intensity of the jet is obviously enhanced because of the "catapult effect"[6], as shown at $t_{sim,0}$+0.28 µs in Fig. 4, so that the penetration of the phase-lagged bubble is finally achieved. Because of the "catapult effect", we call the phase-lagged bubble the "shooting bubble", and the phase-ahead bubble the "pulling bubble".

Influence from the initial energy and the inception distance of a bubble pair in the bulk on the jetting formation

The numerical results from COMSOL show that the jet arising from the "catapult effect" of out-phase bubbles is the most interesting jet form. Likely, the most efficient energy usage scheme would employ anti-phase bubbles having the same oscillating period, in other words, the same initial energy. With this assumption, the only parameter left to be optimized is the initial distance of the anti-phase bubble pair. The simulation results of the anti-phase bubble pairs with different initial distances d in the bulk are shown in Fig. 5 to Fig. 8, where phase fields (blue is air and red is water) with velocity vectors (the arrows) are presented. The number below each picture is time, unit s. Every tick of the scale on the left side of each picture represents 5µm. The interaction between the bubbles is weak in Fig. 5 and the jet is not able to penetrate the other side of the shooting bubble. The interaction between the bubbles is enhanced by shortening the distance between them, and finally jet penetration is achieved as shown in Fig. 6. With even smaller distance as shown in Fig. 7, the jetting reaches a higher intensity. However, it is disadvantageous to produce the bubbles in too short a distance, as proved in Fig. 8, where the two bubbles merge during the early expanding stage of the shooting bubble [7]. Here, a jet flowing from the pulling bubble pointing into the shooting bubble is still observed, but can hardly penetrate the entire shooting bubble.

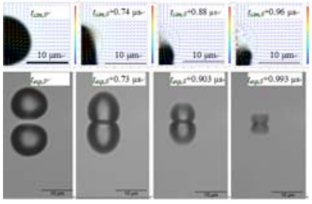

Fig. 2: Simulation (COMSOL) and experimental results of an in-phase bubble pair in the bulk [4].

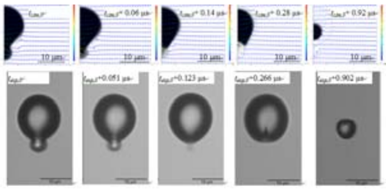

Fig. 3: Simulation (COMSOL) and experimental results of an out-of phase bubble pair in the bulk [4].

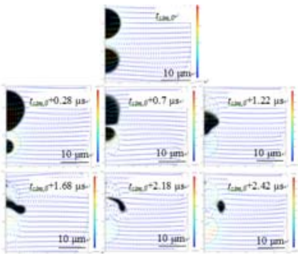

Fig. 4: Simulation results (COMSOL) of an anti-phase bubble pair in the bulk.

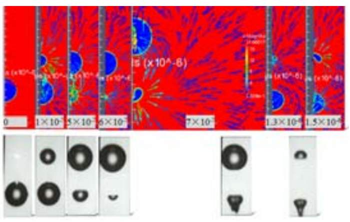

Fig. 5: OpenFOAM simulation for d=2.5$R_{p\text{-}max}$ and experimental results from [5].

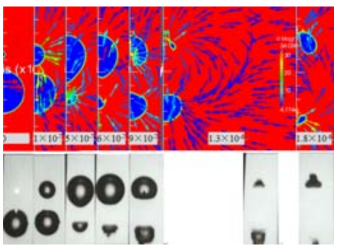

Fig. 6: OpenFOAM simulation for d=1.75$R_{p\text{-}max}$ and experimental results from [5].

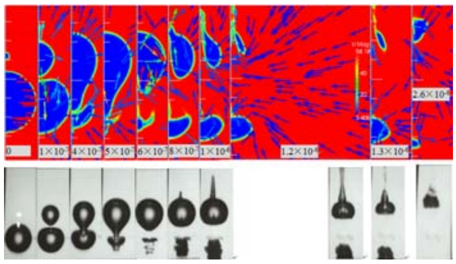

Fig. 7: OpenFOAM simulation for d=1.5$R_{p\text{-}max}$ and experimental results from [5].

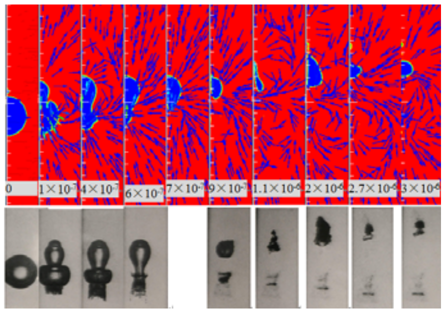

Fig. 8: OpenFOAM simulation for d=1.25$R_{p\text{-}max}$ and experimental results from [7].

Conclusions

Most pronounced jet formation occurs with bubble pairs for which the ‘shooting bubble’ is produced when the ‘pulling bubble’ just reaches its maximum radius, both of them having the same initial energy. In this case, the liquid jet will be directed from the pulling bubble into the shooting bubble and penetrate this bubble. For maximizing the jet intensity, the initial inception distance of the anti-phase bubble pair must be optimized according to the flow parameters.

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