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# On bubble cloud growth in shock-droplet interaction

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## Abstract

Investigations of shock-induced cavitation is highly challenged by the multiphase nature of the mechanisms involved. Thermodynamically well-posed multiphase numerical models accounting for phase compression and expansion however allow to elucidate the underlying physics. A description of the bubble cloud growth and its effects on the early droplet dynamics is proposed, as well as a critical discussion on the analytical predictions of the cavitation event previously reported.

## Introduction

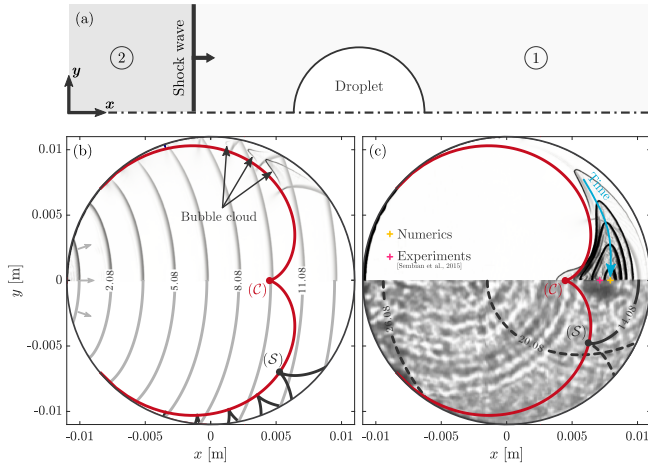
Shock-induced droplet aerobreakup occurs in a rich variety of technical applications such as rain erosion damage, bulk dissemination of liquid agents or liquid jet atomization. Over the last decades, the aerobreakup phenomenology has been extensively addressed assuming that the incident shock does not affect the fragmentation processes. However, research efforts have recently shown that internal shock reflections inside the droplet might result in cavitation bubbles. Previous attempts to explicit the conditions for the bubble to grow, and possible consequences on the droplet dynamics, failed because of inappropriate methods. Recently, Kyriazis et al. (2018) demonstrated that thermodynamically well-posed models incorporating phase change (although not primary) are suitable for simulating the growth of bubbles, thus standing out as a promising method to elucidate the physics of shock-induced cavitation inside a water droplet. Based on numerical simulations and ray theory, we herein address the bubble cloud growth and its effect on the early stage of the droplet dynamics.

## Numerical modelling and wave analysis

A thermodynamically well-posed, pressure-non-equilibrium, multi-component flow model (Saurel et al. 2009) that conserves mass, momentum and total energy is used. The effects of viscosity and surface tension are insignificant on the observation time scale. The model requires pressure relaxation to recover a unique equilibrium pressure, achieved by an infinite-relaxation procedure. A second-order-accurate scheme (MUSCL) is used to solve the model and is combined with an adaptive mesh refinement technique to resolve

the wide range of spatial and temporal scales of shock fronts and interfaces. This modelling is implemented in ECOGEN (Schmidmayer et al. 2020), which has been validated for several gas bubble dynamics problems, including free-space and near-wall bubble collapses, and other multi-component problems such as liquid–gas shock tubes and water column and droplet breakup due to high-speed flow (see Dorschner et al. (2020) and references herein). The computational setup is shown in Fig. 1(a). The shock wave travels at Mach 2.4 in air at atmospheric conditions, and interacts with a two-dimensional water column. The initial air volume fraction in water is  $10^{-6}$ . This corresponds to the preexisting nuclei in non-purified water. Considering the difference in the acoustic impedance between both phases, the modelling enables to simulate each phase response, within the mixture, to compression and expansion effects, i.e. cavitation without phase change.

Numerical simulations are complemented with the analytical analysis of the wavefronts propagating within the droplet. These fronts are shaped by the internal reflections, which can be interpreted by applying the classical ray-tracing method to geometrical acoustics. The incident shock is modelled as an incoming parallel bundle of rays, which is transmitted to the droplet before experiencing internal reflections that obeys the fundamental law of refraction. Within the context of shock-droplet interaction and in the absence of bubble growth, the parametric equations for the transmitted wavefront and its  $n$ -reflections have been derived by Biasiori-Poulanges & El-Rabii (2020), and thoroughly validated against ECOGEN. Mainly based on direct comparisons of the numerical schlieren and the theoretical wavefronts, the present work illuminates the effect of bubble growth on the early stages of the shock-droplet interaction.



**Figure 1:** (a) Computational setup. Domains 1 and 2 refer to post-shock and pre-shock states, respectively. (b) Comparison of (top) numerical results with (bottom) theory and (c) experiments of Sembian et al. (2016). Times on the wavefronts are indicated in  $\mu\text{s}$ . Time steps are (b)  $1.5 \mu\text{s}$  and (c)  $6.0 \mu\text{s}$ . Note that only the transmitted and the once-reflected wavefronts are plotted.

## Results and Discussion

Figure 1(b) shows the comparison between numerical schlieren (top) and the wavefronts predicted by the ray tracing approach (bottom). The light gray lines corresponds to the transmitted wavefront  $\mathcal{F}_1$ . When meeting the droplet boundary,  $\mathcal{F}_1$  experiences a first internal reflection resulting in the development of the singly-reflected wavefront  $\mathcal{F}_2$  (dark lines).  $\mathcal{F}_2$  consists of two segments and exhibits a singular point  $\mathcal{S}$ . The reflection of  $\mathcal{F}_1$  is completed when it reaches the downstream droplet surface [see dark lines on Fig. 1(c)]. As time proceeds,  $\mathcal{S}$  traces out a surface, the so-called *caustic*, shown in red on Figs. 1(b)-(c). The caustic has a cusp singularity at  $\mathcal{C}$ , where  $\mathcal{S}$  vanishes. Figure 1(b) reports a very good agreement between theory and numerics up to the growth of the bubble cloud that annihilates the downstream segment of  $\mathcal{F}_2$ , as clearly seen from  $t = 9.58 \mu\text{s}$ .

Not considering phase change or wave interplay, previous works on shock-induced cavitation inside confined fluid volume suggests that the location of strongest shock-induced cavitation is at  $\mathcal{C}$  (Obreschkow et al. 2011). In this context, it is instructive to compare the numerical results with experimental observations, under the same initial conditions [Fig. 1(c)]. The upper-half image plots the numerical time history of the bubble cloud collapse, which occurs at the yellow cross. The lower-half shows the shadowgraph of the bubble cloud from Sembian et al. (2016) experiments. The origin of the cloud and the collapse location on the  $x$ -axis is estimated to be at the pink cross. The solid lines are in good agreement with the numerics, while the dashed lines do not agree with the numerical schlieren.

Figure 1(c) illuminates the significant error between the experiments and the predicted cloud location at  $\mathcal{C}$ , while a significantly better match is reported with the numerics. In addition, it demonstrates that not accounting for the wave in-

terplay and the bubble cloud cavitation leads to unfortunate descriptions of the wave system and its role in the shock-induced cavitation event.

## Conclusion

This work illuminates the effect of the bubble cloud growth on the early stages of the shock-droplet interaction. Our numerical results reveals that the cloud modifies, and ultimately annihilates, the wave development as predicted by geometrical acoustics. It also shows that the analytical prediction of the cavitation location is incorrect, while our simulations are in good agreement with the experimental observations. However, these results are limited by the infinite relaxation rate, i.e. instantaneous phase equilibrium, which results in the sudden growth of the cloud. Consequently, its size is overestimated and much larger than the experimental observations. Future research will address this limit by assuming a finite relaxation rate, calibrated against experiments.

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