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Strong interaction between a gas bubble and a free surface in a Hele-Shaw cell at low pressure

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Résumé : *L'interaction d'une bulle d'air immergée dans de l'eau liquide avec une surface libre est étudiée en considérant des écoulements bidimensionnels, représentatifs d'une situation en canal plan. Le fluide est à basse pression induisant un rapport de masse volumique élevé entre les phases liquide et gazeuse. Des simulations numériques sont conduites à l'aide d'un code dédié, capable de représenter des écoulements diphasiques sous l'hypothèse faible Mach. L'impact de la surpression intiale de la bulle est étudié en considérant comme autres paramètres les valeurs initiales du rayon et de la position de la bulle sous la surface libre. Une analyse dimensionnelle est réalisée permettant la mise en évidence des groupements pertinents pour ce type d'étude.*

Abstract : *The interaction of an air bubble immersed in liquid water and a free surface is investigated. Two-dimensional flows, representative of a flat channel situation, are considered. The fluid is at low pressure inducing a large density ratio between liquid and gaseous phases. Numerical simulations are conducted with an in-house code, allowing for the description of two-phase flows under the low Mach approximation. The impact of the initial excess pressure in the bubble is investigated considering as additional parameters, initial values of the radius and of the position. A dimensional analysis is performed highlighting some relevant numbers for this kind of study.*

Mots clefs : Ecoulements diphasiques, bulle, surface libre, faible Mach

1 Introduction

The interaction of bubbles with a free surface has been the object of ongoing research since the pioneering work of Blake et al. [1]. Various studies have been reported in the literature, most of them having underwater explosions for application purpose. Results are derived from experiments and/or numerical simulations.

Most studies deal with an axisymmetric gas (air) bubble immersed in liquid water, in close proximity of the free surface. Bubble expansion, generally initiated by an excess pressure, is investigated. Bubble interaction with the free surface depends on initial conditions. Large and complex deformations of the interfaces are observed and sometimes bursting (see for instance [2]). Some works focus on the opposite situation where bubble expansion is followed by collapse.

As concerned geometry, numerical investigations first examined bubble growth in an infinite medium

(e.g. [3]) while more recent works addressed bubble expansion in a confined fluid domain [4] .
Whatever the scenario, the rapid expansion of a gas bubble immersed in a liquid medium nearby a free surface is an intricate phenomenon. Complexity arises in particular due to highly non linear deformations of both interfaces (gas inclusion and liquid free surface) combined to very short time scales.
To our knowledge, no study was conducted considering a thin rectangular channel a few millimeters in hydraulic diameter. No results are either available for a fluid at low pressure whereas specific features are expected to happen with a high density ratio $\rho_l/\rho_v \sim 10^4$. Both aforementioned effects are simultaneously encountered in compact heat exchangers making use of water at low pressure as the working fluid [5]: a thin channel is half filled with liquid water (~ 1000 Pa). A vapour bubble is created (by heat transfer from the secondary hot fluid) under the free surface. The small vapor density makes the bubble size to rapidly increase up to 15 centimeters. A strong non-linear interaction is observed between the vapor inclusion and the free surface. It results in the creation of multiple small droplets whose rapid evaporation leads to highly efficient heat transfer between both primary and secondary fluids.
The present communication investigates the non linear interaction of an air bubble with a free surface (water) in a thin rectangular channel and at low pressure. Numerical simulations are realised with a compressible approach in the Low-Mach approximation. Phase change is not considered in the present work. The physical model is first detailed, then a short description of the numerical methods is given. Results will next be presented and discussed.

2 Physical Model

The geometry of interest is a rectangular channel $H \times W \times e = 0.5 \times 0.2 \times 0.006\ \mathrm{m}^3$. It is partially filled with liquid water ($H_{fs} = 0.243\,\mathrm{m}$), initially at rest. The upper part of the channel contains air at low pressure ($P_\infty = 980\,\mathrm{Pa}$). This pressure is controlled by an opening of the top boundary of the channel). A circular bubble, R_0 in radius, is initially located in the vertical mid plane at a distance h below the free surface ($z_b = H_{fs} - h - R_0$). An excess pressure ($\Delta P = P_0 - P_\infty = \epsilon P_\infty$) is supplied to the bubble which starts to expand.

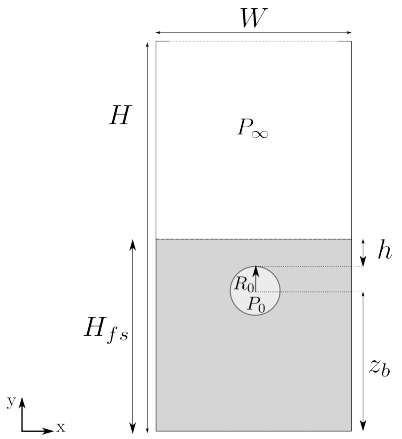


Figure 1: 2D-sketch of the domain.

Fluids have following properties: liquid density $\rho_l = 1000\,\mathrm{kg\,m^{-3}}$, liquid dynamic viscosity $\mu_l = 1.4\ 10^{-3}\,\mathrm{Pa\,s}$, gas density $\rho_g = 0.0076\,\mathrm{kg\,m^{-3}}$ and gas viscosity $\mu_g = 9\ 10^{-6}\,\mathrm{Pa\,s}$. The surface tension coefficient is $\sigma = 0.0748$ N/m. The gravity acceleration equals $g = 9.81\,\mathrm{m^2\,s^{-1}}$.

2.1 Validation of the 2D approach

Numerical simulations developed in the present work consider 2D flows. This approach is consistent with the situation of interest provided that ([6]) :

$$Re\left(\frac{e}{D}\right)^2 >> 1 \tag{1}$$

where D is the bubble diameter. Considering water at room temperature, the Reynolds number is estimated to $Re \sim \sqrt{\frac{p_\infty}{\rho}}\frac{D}{\nu} \sim 10^6 D$ and Eq.(1) becomes $10^6 e^2/D >> 1$. Considering the $6\,\mathrm{mm}$ thickness e of the channel, this condition corresponds to $D << 36\,\mathrm{m}$. As the bubble size is, in the present study, limited to $0.15\,\mathrm{m}$, this condition is enforced.

The governing equations for the two-phase flows and their numerical treatment are available in [7] and will not be detailed here. In the present work will be only discussed the momentum equation with gravity, viscous and surface tension effects (this latter is modeled with a regularization approach thanks to δ_s Dirac function concentrated on interface):

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla(\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla p - \rho \mathbf{g} + \nabla \cdot (\mu(\nabla \mathbf{v} + {}^t\nabla \mathbf{v})) + \sigma \kappa \delta_s \mathbf{n} \tag{2}$$

Under initial conditions, the fluid is motionless and the bubble is submitted to an excess pressure. Due to the presence of the lateral walls one expects the difference between the pressure inside the bubble and that on the free surface, i.e. $P_0 - P_\infty$, to be the governing effect. Considering the early stages of the bubble expansion process, the vertical projection of the momentum equation in the liquid domain includes the vertical component of the pressure gradient.

$$\rho\left[\frac{\partial v}{\partial t} + \mathbf{v}\nabla \cdot v\right] = -\frac{\partial p}{\partial y} - \rho g + \mu \Delta v + \sigma \kappa \delta_s \tag{3}$$

In order to estimate the relative importance of the various contributions, a non dimensional approach is developed using reference quantities defined as $p_{ref} = p_\infty$ and $v_{ref} = (p_\infty/\rho)^{0.5}$. The reference length L_{ref} equals R_0 except in the pressure gradient $\partial p/\partial y$ where the liquid thickness h appears to be relevant. The momentum equation then reads (non dimensional quantities are noted with a star) :

$$\left[\frac{\partial v^*}{\partial t^*} + \mathbf{v}^* \nabla \cdot v^*\right] = -\epsilon \frac{R_0}{h}\frac{\partial p^*}{\partial y^*} - \frac{\rho g R_0}{p_\infty} + \frac{\nu}{v_{ref} R_0}\Delta v^* + \frac{\sigma}{p_\infty R_0} \tag{4}$$

One recognizes the classical Reynolds, Froude and Weber numbers $Re = \dfrac{v_{ref} R_0}{\nu}$, $Fr = \dfrac{p_\infty}{\rho g R_0}$ and $We = \dfrac{p_\infty R_0}{\sigma}$.

The factor associated to the vertical component of the pressure gradient is :

$$N_\epsilon = \frac{\epsilon}{\gamma} \tag{5}$$

where γ is the classical parameter (e.g. [4]) defined as $\gamma = h/R_0$ comparing the initial thickness of the liquid film separating the bubble and the free surface to the initial radius of the bubble.

The momentum equation (4) then reads

$$\left[\frac{\partial v^*}{\partial t^*} + \mathbf{v}^* \nabla \cdot v^*\right] = -N_\epsilon \frac{\partial p^*}{\partial y^*} - \frac{1}{Fr} + \frac{1}{Re}\Delta v^* + \frac{1}{We} \tag{6}$$

The relative magnitude of the different terms will be discussed in the next section.
Yet, the present study concerns water at low pressure. Bubbles are expected to be of large dimension and the lateral confinement of the present configuration cannot be disregarded. A large value of the ratio $\gamma_w = W/(2R_0)$ should contribute to promote the growth of spherical bubbles. Oppositely, a small $W/(2R_0)$ should foster the formation of elongated bubbles in the vertical direction since their growth is hindered by the lateral walls.

3 Results

The numerical set-up corresponds to the physical model (section 2) with some specificity. The pressure in the top section of the channel is controlled by an opening of 90% of the top boundary, where a pressure outlet boundary condition is applied. Both fluid are modelled with a barotropic equation of state [7]: pressure variations are only linked to density variations, which is a reasonable assumption due to slow dynamics of bubbles. Thus following speed of sound have been used ($c_l = 1433\,\mathrm{m/s}$, $c_g = 414\,\mathrm{m/s}$), which corresponds to thermodynamic properties of water at such P_∞ pressure. With fluid velocities of order of magnitude around one meter per second, the Low Mach hypothesis is fulfilled in the liquid while allowing full compressible effects in the gas.
Three parameters have been investigated, $R_0 \in [0.0048, 0.02]\,\mathrm{m}$, $h \in [0.003, 0.0276]\,\mathrm{m}$ and $\epsilon \in [4, 60]$. The main dimensional groups have following magnitude : $Re \sim O(10^3)$, $Fr \sim O(10^2)$, $We \sim O(10)$. The other control parameters vary as $\gamma \in [0.15, 3.73]$ and $\gamma_w \in [5, 21]$ while the ratio N_ϵ ranges between 2 and 116 and covers two decades. At early stages, the inertial term in the l.h.s. of Eq. (6) is mainly balanced by the pressure gradient and the control parameter is the non dimensional group N_ϵ.
Two situations have then to be considered :
1- N_ϵ small : This case corresponds to a small value of the initial excess pressure in the bubble combined to a large value of the initial immersion depth. One expects a limited growth of the bubble as pressure effects will not balance inertia of the liquid.
2- N_ϵ large : This case oppositely corresponds to a large value of the initial excess pressure combined to a small value of the initial immersion depth. One expects a rapid growth of the bubble possibly combined with the fusion between both interfaces (bubble and free surface).

3.1 Bubble growth with small N_ϵ

We first consider a small value of $N_\epsilon \sim 10$. Bubble growth is presented in Fig. 2.

One observes a rapid expansion of the bubble resulting from the initial overpressure ϵp_∞ ($\epsilon = 14$). In the present study, air density is small and a large bubble, a few centimeters in size, is observed. Its shape becomes rapidly elongated due to the lateral walls and induces in turn a large deformation of the free surface. A slight elevation of the liquid level can be noticed on the lateral walls due to volume conservation imposed by incompressibility of the liquid. A thin liquid film can be seen separating the bubble and the free surface due to lateral drainage. This film gets thinner but does not break. The two gaseous

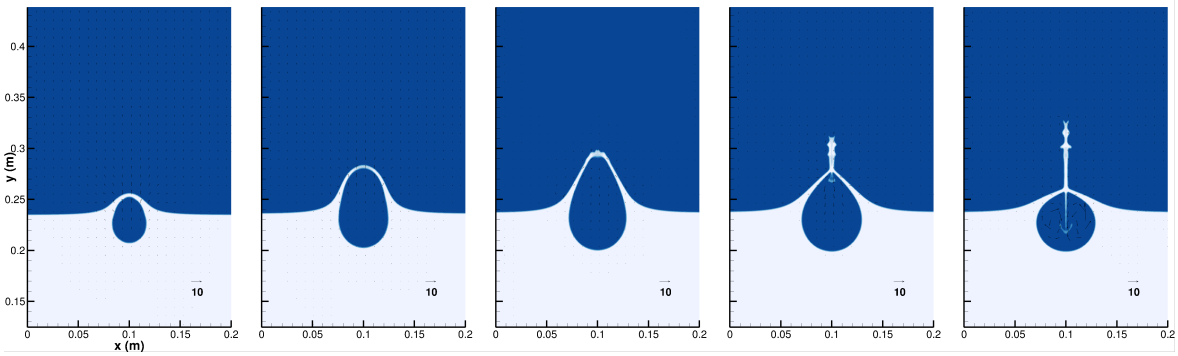


Figure 2: Bubble growth for $R_0 = 0.0052\,\mathrm{m}$, $z_b = 0.22\,\mathrm{m}$, $\epsilon = 14$ which corresponds to $N_\epsilon = 8.3$ and $\gamma\gamma_w = 32.5$. Volume fraction field at different instants (7 ms, 14 ms, 21 ms, 28 ms and 35 ms) with velocity vector field.

media, air entrapped in the bubble and air in the upper part of the canal remain separated. It is worth noticing that the bubble bottom keeps roughly at the same level during the whole growing process. As pressure in the bubble decreases while it expands, inertial effects which are responsible for the upward pushing are getting reduced. A maximum volume is then observed next followed by compression of air inside the bubble. A vertical liquid jet is emitted at the bubble top.

3.2 Bubble growth with large N_ϵ

We now consider a large value of $N_\epsilon \sim 40$. Bubble growth is presented in Fig. 3.

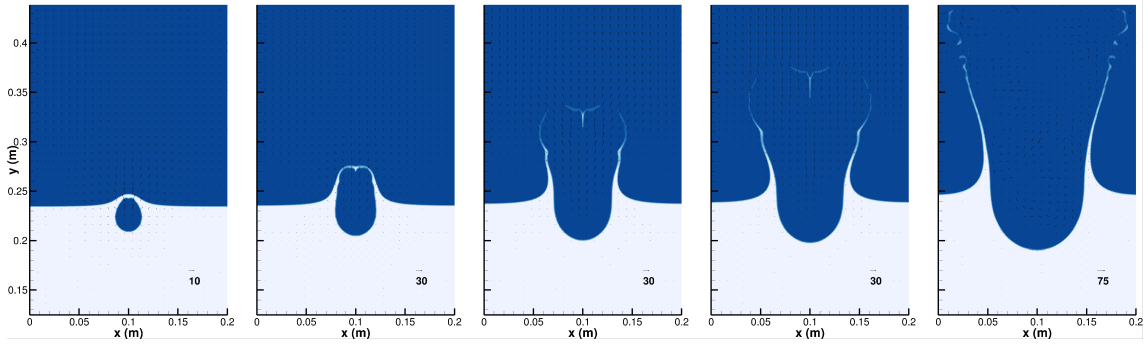


Figure 3: Bubble growth for $R_0 = 0.0075\,\mathrm{m}$, $z_b = 0.22\,\mathrm{m}$, $\epsilon = 44$, which corresponds to $N_\epsilon = 38.6$ and $\gamma\gamma_w = 11.55$. Volume fraction field at different instants (2 ms, 4 ms, 7 ms, 9 ms and 19 ms) with velocity vector field.

These parameters lead to a very fast expansion of the bubble combined with a strong deformation of the free surface. The liquid level on the lateral walls is almost unchanged. The time scales are so short that liquid motion is mainly upwards. The strong drainage makes the liquid film thinner and thinner until breakup happens. The 2D situation produces two symmetric filaments. These jets are pushed towards the walls due to the intense velocity of air which was contained in the bubble before breakup. An extension of the free surface persists after breakup due to inertial effects. Bubble reformation is never observed.

3.3 Bubble growth with intermediate N_ϵ

We now consider an intermediate value of $N_\epsilon \sim 21.75$. Bubble growth is presented in Fig. 4. One observes bubble expansion leading to a large elongated shape. The liquid film separating the bubble top and the free surface becomes very thin and starts to disrupt. Tiny droplets are observed at time 18 ms. However, the next pictures show that the two lateral jets re-close leading to the recovering of the bubble. A similar process is reported by Tian et al [2] for underwater explosions at atmospheric pressure.

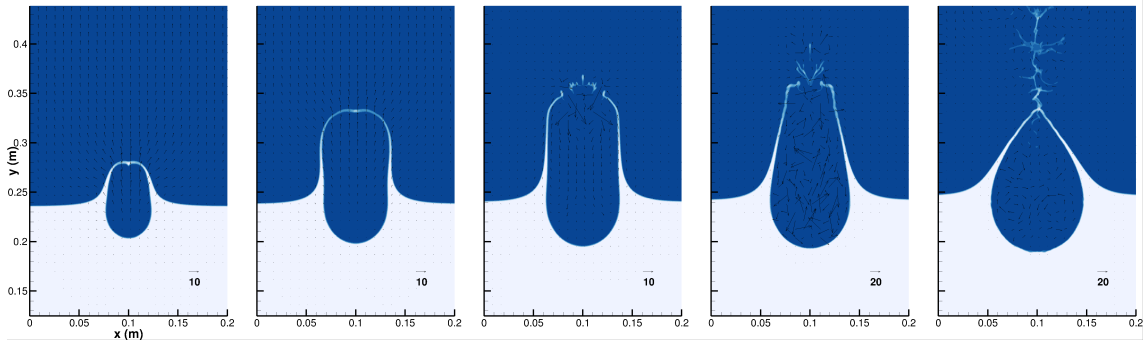


Figure 4: Bubble growth for $R_0 = 0.006\,\mathrm{m}$, $z_b = 0.22\,\mathrm{m}$, $\epsilon = 29$, which corresponds to $N_\epsilon = 21.75$ and $\gamma\gamma_w = 22.2$. Volume fraction field at different instants (7 ms, 14 ms, 18 ms, 23 ms and 38 ms) with velocity vector field.

3.4 Bubble growth map

Several numerical simulations have been conducted covering a large range of the three quantities h, R_0, ϵ. An attempt to classify them is to consider as a major criterion the possible fusion of the two interfaces followed by the breakup of the thin liquid film.

This phenomenon is more likely to happen when the initial bubble presents a small $\gamma = h/R_0$ ratio combined with a large excess pressure ϵ. However, regarding the small density of air in the present study, very large bubbles are observed. The lateral confinement is therefore an essential effect, not taken into account by the two quantities γ and ϵ. The ratio $\gamma_w = W/(2R_0)$ ranges between 5 and 21 in the present study. A small γ_w value will contribute to promote bubble elongation in the vertical direction and therefore fusion of bubble interface with the free surface. We propose to plot the scenario type (fusion of both interfaces -large N_ϵ- or not fusion -small N_ϵ-) obtained from the various numerical simulations in a graphical representation $\gamma\gamma_w$ vs ϵ. The result is presented in Fig. 5. One observes two distinct regions: one characterized by a small ϵ value combined with a large $\gamma\gamma_w$ ratio where no fusion is observed. Conversely a large ϵ value combined with a small $\gamma\gamma_w$ ratio leads to a fusion process. Interestingly, the bisector constitutes a clear separation between these two scenarii making possible to define a criterion in the form of the non dimensional group $\epsilon/(\gamma\gamma_w) = \epsilon 2R_0^2/(Wh)$. Thus, the fusion or the absence of fusion can be straightforwardly predicted from the three initial parameters R_0, h, ϵ (the other quantities being unchanged in the present study).

4 Conclusion

The interaction between a free surface and a gas bubble submitted to an initial excess pressure is investigated considering two specific conditions: a fluid at low pressure and 2D flows. Numerical simulations show that this phenomenon, associated with a rich and complex dynamics can be classified in two main

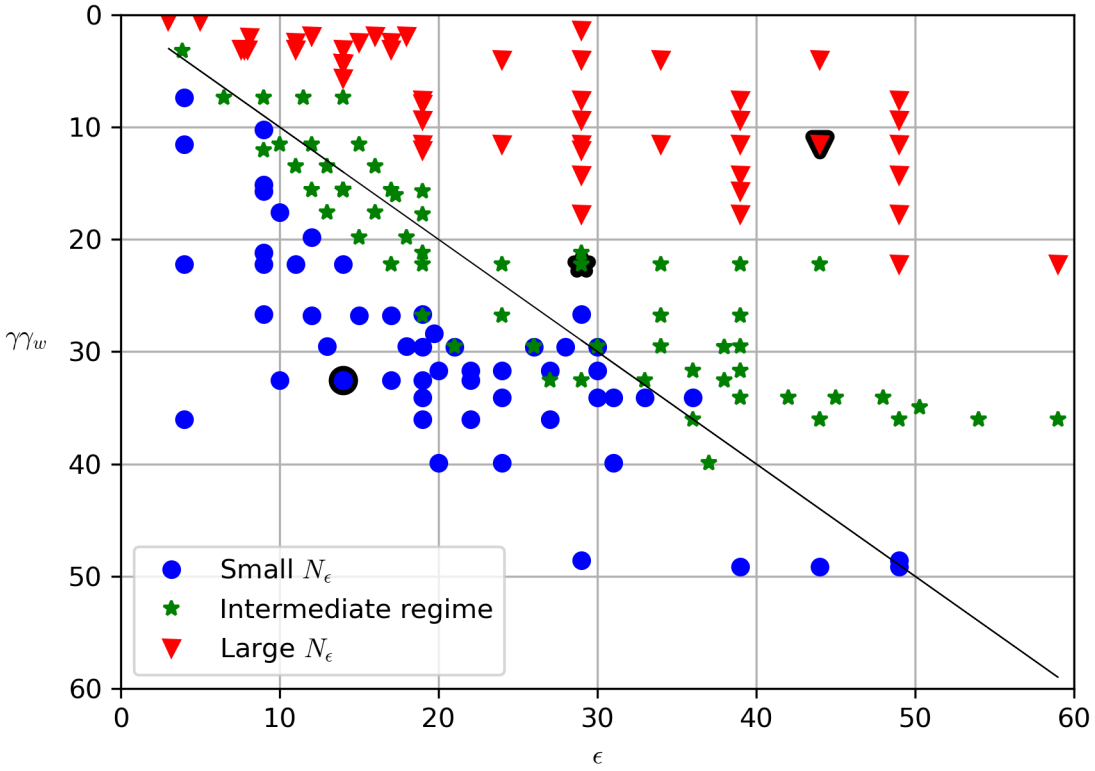


Figure 5: Map for bubble growth: $\gamma\gamma_w = Wh/(2R_0^2)$
as a function of initial overpressure ϵ for different ranges of N_ϵ. Symbols with black line contour correspond to parameters of figures 2, 4 and 3.

categories. In the first case, the rupture of the interface is observed along with the simultaneous formation of two lateral jets. In the other, the bubble and the free surface, even though closely located, remain separated by a thin liquid film and no rupture happens. An intermediate scenario also exists where the interface is temporarily disrupted before recovering of the bubble.
A non dimensional analysis of the momentum equation allows to predict which kind of scenario will happen. Two relevant groups are highlighted which fully rely on the initial conditions. This is a major difference with other studies of the literature. All of them make use of the maximum diameter of the bubble as a reference length. A major drawback is that this quantity is a priori unknown.
Future work will focus on time analysis of bubble growth in the various scenarii. A parametric study will also be conducted in order to precise the effect of pressure.

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