Beer tapping: dynamics of bubbles after impact

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Abstract. Beer tapping is a well known prank where a bottle of beer is impacted from the top by a solid object, usually another bottle, leading to a sudden foam overflow. A description of the shock-driven bubble dynamics leading to foaming is presented based on an experimental and numerical study evoking the following physical picture. First, the solid impact produces a sudden downwards acceleration of the bottle creating a strong depression in the liquid bulk. The existing bubbles undergo a strong expansion and a sudden contraction ending in their collapse and fragmentation into a large amount of small bubbles. Second, the bubble clouds present a large surface area to volume ratio, enhancing the CO_2 diffusion from the supersaturated liquid, hence growing rapidly and depleting the CO_2. The clouds of bubbles migrate upwards in the form of plumes pulling the surrounding liquid with them and eventually resulting in the foam overflow. The sudden pressure drop that triggers the bubble dynamics with a collapse and oscillations is modelled by the Rayleigh-Plesset equation. The bubble dynamics from impact to collapse occurs over a time ($t_b \simeq 800$ μs) much larger than the acoustic time scale of the liquid bulk ($t_{ac} = 2H/c \simeq 80$ μs), for the experimental container of height $H = 6$ cm and a speed of sound around $c \simeq 1500$ m/s. This scale separation, together with the comparison of numerical and experimental results, suggests that the pressure drop is controlled by two parameters: the acceleration of the container and the distance from the bubble to the free surface .

1. Introduction

The beer tapping prank, which consists in impacting a bottle of beer at its mouth, involves several physical mechanisms. These multi-physics processes in supersaturated liquids are of interest in physics and chemistry, and are here combined in a simple model experiment, namely strong pressure variations, bubble dynamics, collapse, bubble clouds formation, bubble growth due to gas diffusion and motion of plumes. These processes are relevant to the understanding and description of certain geological phenomena as limnic gas driven eruptions [1] or volcanic eruptions [2], while also relevant, in industry and commercial purposes like in wine and champagne [3]. Simple experimental setups, with daily life products, have proven useful to explain complex phenomena [4, 5]. In this paper, we revisit the setup of [5] exacerbating the initial bubble growth.

Building on the experimental observation of a train of bubbles as illustrated in Fig. 1, the following physical picture appears. First, the solid impact produces a sudden downwards acceleration of the bottle creating a strong depression in the liquid bulk. The existing bubbles undergo a strong expansion and a sudden contraction ending in a collapse and fragmentation in a large amount of small bubbles. Second, because the bubble clouds present a large surface area to volume ratio, the CO_2 diffusion from the supersaturated liquid is enhanced and the clouds grow rapidly, depleting the CO_2. The clouds of bubbles then migrate upwards in the form of plumes pulling the surrounding liquid with them and eventually producing the foam overflow. In this study, we will focus on the first part of the whole process leading to the foaming and overflow.

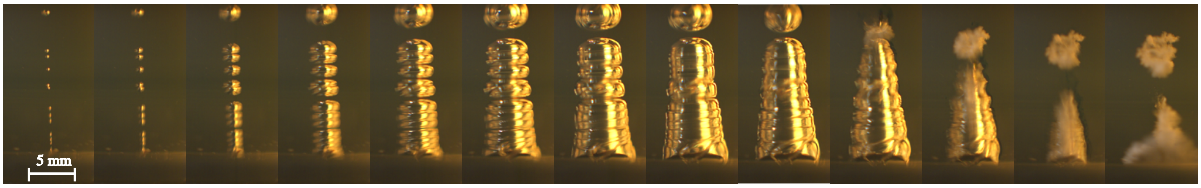

Figure 1. Growth and collapse of a train of ascending bubbles. Note the pyramidal shape of the maximum radii, and a cascade of collapses starting from the top and moving downwards. The collapse leads to bubble fragmentation into a cloud of bubbles that eventually grows and migrates upstream in the form of plumes. The time step between images is $100\mu s$.

2. Experimental setup and numerical model

The experimental setup is sketched in Fig. 2(a) and consists in a 10 cm glass beaker filled with 6 cm of lager beer (150 mL). The beaker is placed on top of a shock absorbing foam layer. The container is then impacted from the top using a piece of wood, released from a chosen height. The experiment is recorded at a frame rate ($\sim 10^4$ fps) with a high-speed camera (Phantom Micro M310).

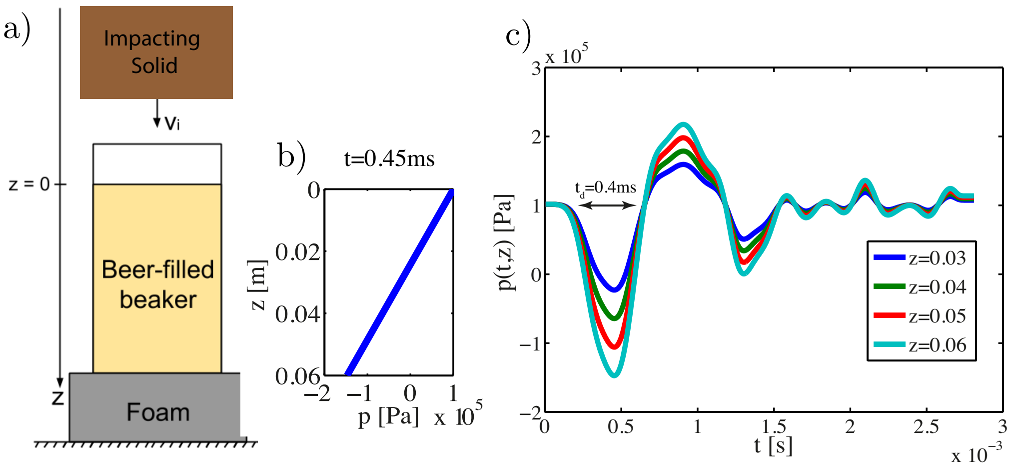

Figure 2. (a) Sketch of the experimental configuration. (b) Shown is the instantaneous pressure as function of depth $p(z)$ for the maximum pressure drop at $t = 0.45 \cdot 10^{-3}s$. (c) Pressure variation with time t calculated from the measured beaker displacement during the vertical impact (see (1)) for several depth z.

The bubble dynamics is assumed to be driven by the surrounding pressure variations over time. The pressure in the liquid was derived from own measurements of the acceleration of the liquid bulk using Navier-Stokes equations for the liquid phase solely. Assuming that the fluid moves as a whole, the convective terms and viscosity effects can be neglected [6], yielding

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} = -\nabla p + \rho \mathbf{g} \;\Rightarrow\; p(z,t) = p_{atm} - \rho \frac{\partial u_z}{\partial t} z + \rho g z, \tag{1}$$

where ρ is the liquid density, $\mathbf{g}$ is the acceleration from gravity and $\boldsymbol{u}$ is the velocity field. For an unidirectional velocity u_z, the pressure $p(t,z)$ can simply be extracted as function of time t and height z. The amplitude of the pressure drop is linearly related to the depth (z) (see Fig. 2(b,c)) as well as to the acceleration of the liquid (1). The acceleration of the liquid bulk is obtained from the beaker displacement, which is measured experimentally from the recorded images and then derivated twice numerically. A verification of the methodology was performed based on momentum conservation as well as its reproducibility. Subsequently, knowing the pressure in time at any point of the liquid $p(t,z)$, the Rayleigh-Plesset equation is used to model the bubble dynamics as standard in literature [7, 8].

3. Discussion

The numerical integration of Rayleigh-Plesset equation was performed using Runge-Kutta method with an initial radius $R_0 = 2.8e^{-4}$ m based on recorded images and the pressure evolution from Fig. 2(c). It provided the bubble time evolution at different depths z as plotted in Fig. 3(a). Furthermore, the comparison with the experimental results shows an excellent agreement. An increase in the depth of the bubble entails a stronger pressure drop (Fig. 1(c)) yielding longer collapse times (Fig. 3(b)) and larger maximum radii (Fig. 3(c)). Notice that the bubble dynamics from growth to collapse occurs over a time $t_b \simeq 300 - 800\ \mu s$ (Fig. 3), which depends on the depth through the pressure drop, despite a constant duration of the pressure oscillation $t_d = 400\ \mu s$, as defined in Fig. 2(c).

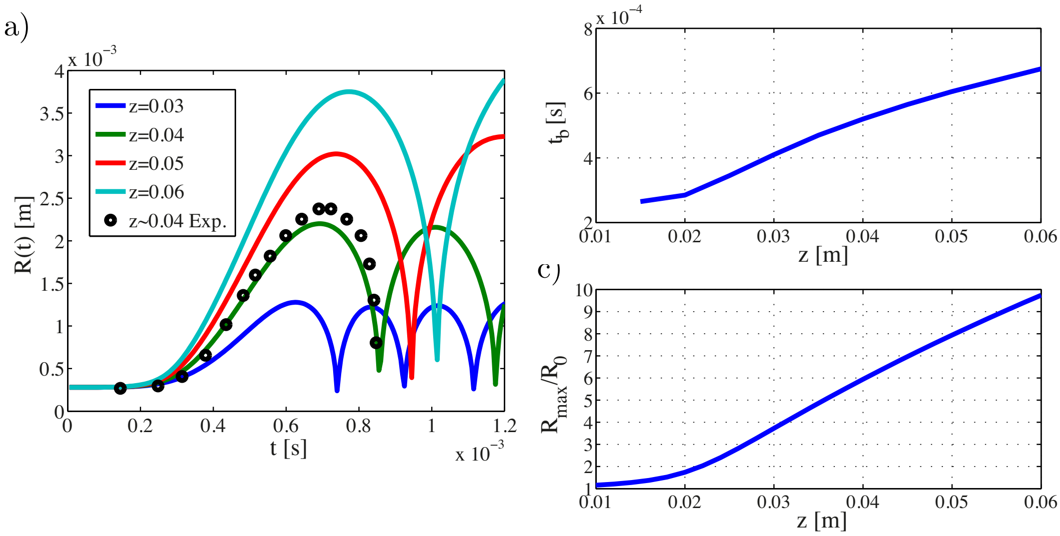

Figure 3. (a) Variation of the bubble radius with time for various depths compared to experiments denoted with black circles. (b) Variation of the impact to collapse time t_b with the depth z and (c) variation of the maximum radius $R_{\max}/R_0$ with the depth z. All results are integrated from the Rayleigh-Plesset equation using the pressure drop from Fig. 2 (c).

The experimental observations illustrated in Fig. 1 are in line with the numerical integration of the Rayleigh-Plesset equation (Fig. 3), showing the anticipated influence of the depth (z) in the bubble dynamics. The larger z the larger is the maximum radius and longer collapse time. The distance from the surface is key and it influences the pressure drop and the maximum radius controlling the strength of the oscillation. If the bubble oscillation is not strong enough, collapse will not occur. This was observed for bubbles very close to the free surface. The linear vertical pressure distribution rationalises the cascade of bubble collapses (Fig. 1).

The bubble dynamics from impact to collapse occurs in a time scale $t_b \simeq 800\ \mu s$ much larger than the acoustic time of the liquid bulk, $t_{ac} = 2H/c \simeq 80\ \mu s$ (own container of height H =6 cm and a speed of sound around $c \simeq 1500$ m/s), so that a train of bubbles such as the one in Fig. 1 grows in apparent synchrony. These results and observations are consistent with the idea that the acceleration of the container drives the bubble dynamics. This contrasts with the travelling acoustic waves interpretation mentioned in [5] (no time scale separation was reported).

Our development highlights the importance of using a rigid container to produce high accelerations. Soft and elastic materials damp the impact acceleration reducing the pressure drop. In contrast, the supporting material should allow the displacement of the container, to ensure a soft absorption of the downwards acceleration. Materials such as synthetic foam are well suited for this purpose. Holding the beer would lead to the same result. We have verified that a similar experiment performed on top of a rigid support does not lead to foam overflow. The impact is absorbed in the walls of the container. The container cannot move and there is no acceleration downwards entailing the required pressure drop for the growth and collapse of bubbles.

As a final remark, note that this simple experimental setup brings together a rich physical insight and accounts for complex phenomena such as jetting during bubble collapse. In the present case, the jetting is observed downwards towards the bottom of the container, which is in opposite direction to a gravity-induced jetting as illustrated in Fig. 4. This difference can be interpreted by the inverse pressure gradient created by the container acceleration, opposite to the pressure gradient induced by gravity (Fig. 2(a)).

Figure 4. (a) Gravity-induced jetting, directed upwards, from [9]. (b) Downwards jetting observed during the collapse of a beer bubble under the reverse acceleration due to the vertical impact. The time step between images is 24 μs.

4. Conclusions

A thorough description of the physics involved in the beer tapping process is presented based on numerical and experimental investigations. Two key parameters have been identified to maximise the beer overflow: the acceleration of the container due to the impact, and the distance of the bubble from the free surface.

References

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