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The gravity-driven migration of bubbles toward a free surface in a high viscous liquid occurs particularly in the glass industry. Indeed in a such process, raw materials are heated in order to react and create a molten glass. The chemical processes lead to a release of large amount of bubbles which further have to be removed to obtain a final product without defects. Since the bubble removal is mainly achieved by the buoyancy effect, the understanding of the bubble interaction with a free surface is an important issue to determine the onset of foaming [8, 5].

In this presentation, we summarize experimental results achieved in molten glasses at high temperature and in oils at room temperature [2]. Experiments have been mainly focused in a thinning rate of liquid film using an interferometry method to determine the dynamics of the liquid film thickness. As a bubble approach a free surface, the interface deformations are driven by a balance between buoyancy and capillary forces meaning that the relevant dimensionless number is the Bond number defined as follows

$$\mathrm{Bo} = \frac{\rho g a^2}{3\gamma}, \tag{1}$$

for which $\rho$ is the liquid density, $g$ the gravity, $a$ the equivalent radius of the bubble and $\gamma$ the surface tension.

The experimental results show that the thickness of the liquid film at the top of the bubble decreases exponentially with time. This important result is the consequence of the mobility of fluid interface. Indeed for shear-free interface, the velocity in the thin liquid film is in first approximation uniform over the film thickness meaning that the flow is purely extensional. In this case, the film thickness is not a relevant parameter to scale the characteristic time given by

$$t = \frac{6\mu}{\rho g a} \tag{2}$$

corresponding to a balance between gravity and viscosity forces. The quantity $\mu$ is the dynamic viscosity.

Whatever the fluid employed in the experiments, we establish a strong influence of the interface deformation measured by the Bond number. The smaller the Bond number is, the larger the thinning rate is. In other words, the film rupture occurs earlier when the Bond number is small (small bubble compared to the capillary length).

We develop also a numerical method to simulate this problem established in the framework of Stokes flow since the typical Reynolds number in this particular problem is obviously much lesser than one. The problem has been solved using a boundary-integral formulation in two dimensions axisymmetric configuration [4]. When the bubble is stuck close to the free surface, its shape is compared to the static form established previously by Princen [6]. The exponential decrease is also found numerically and the thinning rate obeys the same behavior observed experimentally.

In this presentation, we also present the recent results obtained with the boundary element method for a bubble and a free surface having uniform but unequal surface tensions [1]. This situation is motivated by the fact that in application the surface tension can vary as a function of the gas nature [3]. Here, the problem is driven by two parameters: the Bond number $\mathrm{Bo}_1$ based on the surface tension of the bubble interface $\gamma_1$ and the ratio of the two surface tensions $\hat{\gamma} = \gamma_0/\gamma_1$ for which $\gamma_0$ is the surface tension of the free surface interface.

The numerical results show that the deformation of interfaces is more important when the Bond number is large and when the surface tension ratio is smaller than one. The bubble shape obtained at long times is compared to the static form established by Princen and Mason [7]. The deformation of interfaces are strongly correlated to the thinning rate which is more and more important when the surface tension ratio is larger than one.

Assuming a pure extensional flow in the liquid film when the bubble is stuck at the free surface, we point out that the thinning rate is inversely proportional to the area of the spherical cap created at the top of bubble. Using an asymptotic result provided by Princen and Mason [7], we find that the thinning rate is controlled by a unique parameter given

$$\chi = \frac{(1+\hat{\gamma})\,\mathrm{Bo}_1}{2\hat{\gamma}}, \tag{3}$$

corresponding to the harmonic average of the two Bond numbers based on the two surface tensions of interfaces.

Finally, we show that the thinning rate behaves following two asymptotic regimes: at small $\chi$, the thinning rate is inversely proportional to $\chi$ meaning that the film drainage is driven by the surface tension and the viscosity and at large $\chi$, the thinning rate reaches an asymptotic value for which the drainage is driven by the gravity and the viscosity.

The thinning rate can be used to estimate the characteristic time scale of the liquid film drainage which is proportional to the bubble size for tiny bubbles and inversely proportional to the bubble size for a large bubble. The consequent is that the time scale of drainage is a non-monotone function of the bubble size for which the maximum is observed for a size close to the capillary length.

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