LARGE BUBBLE RUPTURE SPARKS FAST LIQUID JET

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Summary This Talk presents the unprecedented experimental observation of long and narrow jets shooting out in disconnecting large elongated bubbles. Following the universal *local* rupture process, the post-pinch-off jet is shown to exhibit a dependence on the *global* height of the bubble, as in any gravity-driven process. We investigate this phenomenon by carrying out experiments with various viscosities, surface tensions and densities. We propose a universal scaling law for the jet velocity, which unexpectedly involves the bubble height to the power 3/2.

OBJECTIVE AND PRINCIPLE OF EXPERIMENT

Irrespective of their initial distortion [1] small bubbles gently relax toward robust equilibrium shapes in the form of spheres or oblate spheroids [2]. In contrast, as regards large bubbles, initial shape matters. Weakly deformed bubbles smoothly evolve either to spherical caps [3] or toroidal bubbles [4], as the ones typically expelled by dolphins [5]. On the other hand, the dynamics of initially strongly deformed bubbles has barely been studied. Such bubbles are yet commonplace in bubbling configurations typically found in geophysics or industry (*e.g.* occuring in glassy melts [6]).
In this Talk, we report an unprecedented violent jet dynamics following large elongated bubble disconnection (Fig. 1). The thin and concentrated jet developing inside the bubble possibly gives rise to liquid projections shooting out way above the free surface.

Figure 1. Time sequence of the jet developing inside a large bubble just after its release from a submerged nozzle. The large bubble pinches off at the first image and the back-to-equilibrium dynamics exhibits an intense and concentrated jet. The time lapse between the snapshots is Δt = 3 ms. The bubble height, right after detachment, is H = 4.22 cm, the bubble front velocity is $V_{\rm front}$ = 0.67 m.s^{-1} and the jet velocity is $V_{\rm jet}$ = 2.69 m.s^{-1}. The liquid viscosity is $\mu = 420$ mPa.s. The gas is injected through an injector of diameter $d = 2$ mm at an airflow rate of $Q = 4.4$ ℓ.min^{-1}. The fluid height is $h = 10$ cm.

Our experiments consist in releasing gas bubbles from a submerged orifice in a viscous liquid contained in a transparent tank. The liquids used include sugar cane syrup (Canadou) of viscosity $\mu = 110$ mPa.s and surface tension $\gamma = 90$ mN.m^{-1} and three water-glycerol mixtures of viscosity $\mu = 140, 280, 420$ mPa.s and surface tension $\gamma = 65$ mN.m^{-1}. The height h of fluid above the injector is typically in the range 5-10 cm. Air is fed through a nozzle of diameter 2 mm. Injection is controlled by a mass flow meter that provides a constant flowrate Q (from 0.01 to 10 ℓ.min^{-1}). The bubble and jet dynamics are analyzed through ultra-fast imagery. To do so, the tank is back lit and images are obtained at 4000 frames per second using a digital high-speed camera (Photron SA-5).

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EXPERIMENTAL RESULTS

Figure 1 illustrates a typical jetting event following the disconnection of a large gas bubble. The entire sequence lasts 18 ms and the bubble height, right after detachment, is $H = 4.22$ cm. Bubble pinch-off occurs on the first image and instantly a narrow, high-speed vertical jet shoots out inside the bubble. Here, the jet is suddenly stopped as it collides with the bubble wall, but in other cases the jet literally perforates the bubble and makes headway in the bulk liquid.
We define here the capillary corrected height $H^\star = H - 2\gamma/\rho g R_{\rm front}$ with H the bubble height right after pinch-off instant, $R_{\rm front}$ the front radius of curvature and g, γ, ρ respectively the gravity, the surface tension and the density of the liquid. By taking the gravito-inertial velocity $\sqrt{gH^\star}$ and the nozzle radius R_o as relevant scales of the problem, we plot the rescaled jet velocity $V_{\rm jet}$ or Froude number Fr = $V_{\rm jet}/\sqrt{gH^\star}$ against the dimensionless height $H^\star/R_o$ in the inset of Fig. 2 for all viscosities and surface tensions. We observe a linear increase of the Froude number with $H^\star/R_o$, identical for all sets of experiments and a shift to lower non-dimensional velocities as the viscosity is increased. This allows us to assume the simple relation $\mathrm{Re} = \alpha\,\mathrm{Ar} - \beta$ with a single identical shift for all viscosities, where we have introduced the jet Reynolds number Re = $\rho V_{\rm jet} R_o/\mu$ and Archimedes number Ar = $\rho\sqrt{gH^\star}H^\star/\mu$.

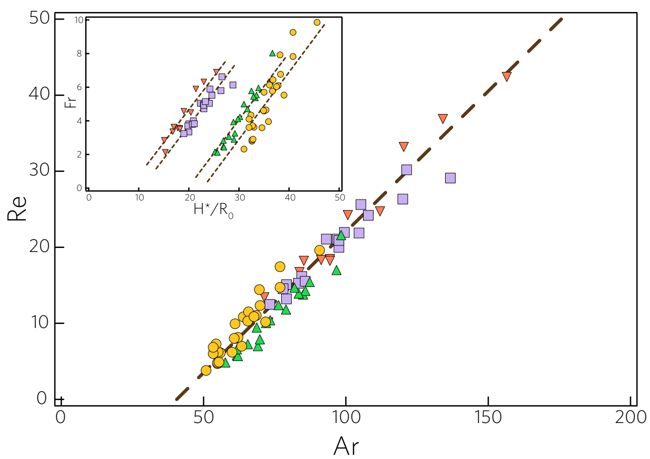

Figure 2. Jet Reynolds number Re = $\rho V_{\rm jet} R_o/\mu$ versus Archimedes number Ar = $\rho\sqrt{gH^\star}H^\star/\mu$ for for four different viscosities μ : 110 mPa.s (▼), 140 mPa.s (■), 280 mPa.s (▲), 420 mPa.s (●). The surface tension and density are $\gamma = 65$ mN.m^{-1} and $\rho = 1250$ kg.m^{-3} except for the lowest viscosity (▼) for which $\gamma = 90$ mN.m^{-1} and $\rho = 1350$ kg.m^{-3}. The equation of the oblique dashed line is Re = α Ar - β, with $\alpha = 0.37$ and $\beta = 15$. The inset shows the Froude number Fr = $V_{\rm jet}/\sqrt{gH^\star}$ versus the nondimensional height $H^\star/R_o$. The lines act as eye guides and present the same slope α. The injector diameter is $d = 2$mm and the fluid height is $h = 10$cm.

Figure 2 represents this relation for all the conducted experiments. The collapse of the four series of experiments corresponding to four different viscosities and two surface tensions and densities is excellent.

CONCLUSIONS

In conclusion, the present experimental work reports the first observation of intense and narrow jets inside detaching large bubbles. These jets follow the singular pinch-off of the bubble, described by a universal self-similar *local* process independent of gravity. Strikingly the features of the post-pinch-off jet bear a dependence on the *global* scale $H^\star$ of the bubble, as any simple gravity-driven process. Yet an intriguing consequence of this scaling law is the dependence of the jet velocity $V_{\rm jet}$ with $H^{\star 3/2}$ instead of the expected $H^{\star 1/2}$ law, as is typical in systems exhibiting a balance between buoyancy and inertia.

References

[1] B. Yang, A. Prosperetti, and S. Takagi. The transient rise of a bubble subject to shape or volume changes. *Phys. Fluids*, 15(9):2640–2648, 2003.
[2] J. Magnaudet and I. Eames. The motion of high-reynolds-number bubbles in inhomogeneous flows. *Annu. Rev. Fluid Mech.*, 32(1):659 (2000).
[3] R. M. Davies and Geoffrey Taylor. The mechanics of large bubbles rising through extended liquids and through liquids in tubes. *Proc. R. Soc. London A*, 200(1062):375–390, 1950.
[4] J. K. Walters and J. F. Davidson. The initial motion of a gas bubble formed in an inviscid liquid. *J. Fluid Mech.*, 17(03):321–336, 1963.
[5] K. Marten, K. Shariff, S. Psarakos, and D. J. White. Ring bubbles of dolphins. *Sci. Am.*, 275(2):82–87, 1996.
[6] James E. Shelby. *Introduction to Glass Science and Technology*. The Royal Society of Chemistry, 2nd ed. edition, 2005.