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Understanding the tasting of champagne and other sparkling wines from a scientific perspective

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ABSTRACT

From uncorking the bottle to the bursting of bubbles in the glass, the science behind the tasting of champagne and other sparkling wine is both traditional and at the forefront of modern developments. The strong interaction between the various parameters at play in a bottle and in a glass of sparkling wine has been the subject of study for around two decades. Indeed, sparkling wine tasting is often seen as the pinnacle of glamor and frivolity for most people, but it should also be considered as a fantastic playground for chemists and physicists to explore the subtle science behind this centuries-old drink, whose prestige today goes well beyond the borders of Champagne and France. This article offers an overview of the physicochemical processes that mark a tasting of champagne or sparkling wine in the broad sense, from the cork popping out of the bottleneck to the formation and bursting of bubbles in your glass, including the choice of the glass and how to serve and drink the wine correctly.

1. Introduction

According to a definition from the Organization of Vine and Wine (OIV): “Sparkling wines are characterized on uncorking by the production of a more or less persistent effervescence resulting from the release of CO₂ (the excess pressure of this gas in the bottle is at least 3.5 bars at 20  C) of exclusively endogenous origin” (OIV, 2020). Over the previous two decades, and driven by a strong global demand, the production of sparkling wines has climbed by 57 % to reach nearly 2.5 billion bottles per year in 2018 (Alexandre, 2024), with Italy being the leading producer, followed by France and Germany (OIV, 2020). In 2023, the global production of sparkling wines therefore accounted for almost 8 % by volume of the world’s total wine production of nearly 32 billion bottles (OIV, 2024).

After uncorking and serving a bottle of sparkling wine in a glass, the consumer can experience a multisensory tasting experience. Indeed, it turns out that all the taster’s senses are stimulated, from the visual appeal of bubbles and foam in the glass to the olfactory and taste perception of carbonation. Furthermore, the individual’s sensory perception and acceptance of a wine is influenced as much by the design of the glassware as by wine-related parameters (such as the wine temperature or the level of alcohol for example), as discussed in the overviews by Spence & Wan (2015) and Campo et al. (2021). There has also

recently been a growing interest in how wine consumers are influenced by the consumption context as well as their past experience (Parr, 2019; Picket & Dando, 2019; Shepherd, Parr, Monaco, & Rodrigues, 2023). Moreover, the recent study by Shepherd et al. (2023) showed that some specific intrinsic descriptors of sparkling wines, such as “bubbles”, “champagne”, and “mousse”, were associated with the perception of elegance of sparkling wines by both wine experts and novice consumers.

Demystifying wine tasting involves a scientific approach that we have undertaken for around twenty years in the case of champagne and sparkling wines in the broad sense (Liger-Belair, 2005). From the physicochemical angle, champagne and other sparkling wines can be viewed as multicomponent hydroalcoholic solutions, with a surface tension $\gamma \approx 46 - 48 \text{ mN m}^{-1}$ (i.e., reduced by about a third compared to that of pure water, mainly due to $\approx 12-13 \%$ ethanol by volume), a viscosity close to 1.5 mPa s at 20  C ($\approx 50 \%$ more than that of pure water, also mainly because of ethanol), and a density close to unity (Liger-Belair, 2012). Moreover, whatever their method of elaboration, sparkling wines are saturated with dissolved carbon dioxide (CO₂), whether during a second in-bottle fermentation process called *prise de mousse* for premium sparkling wines elaborated according to the *m thode traditionnelle* (Liger-Belair & Cilindre, 2021), or through simple exogenous gas-phase CO₂ injection for some cheaper sparkling wines (Gonzales Viejo et al., 2019). For premium sparkling wines such as

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champagne, the *prise de mousse* is launched by adding selected yeasts and a certain amount of saccharose (classically about 22–24 g/L) inside bottles filled with a base wine and sealed with a crown cap or with a cork stopper (Liger-Belair et al., 2023). During this second alcoholic fermentation which occurs in cool cellars, the bottles are sealed, so that yeast-fermented gas-phase CO₂ cannot escape and progressively dissolves into the wine. The *prise de mousse* is generally completed within two months, at the end of which the pressure of CO₂ in the bottle reaches about 6 bar (at 12 °C) (Liger-Belair & Cilindre, 2021).

Under a partial pressure of CO₂ close to 6 bar, it turns out that the wine can dissolve up to 11–12 g/L of CO₂ (Liger-Belair & Cilindre, 2021). However, when it comes to sparkling wine tasting, dissolved CO₂ is the key compound responsible for their ability to produce bubbles and foam (i.e., the very much sought-after effervescence in glasses). Dissolved CO₂ is indeed responsible for CO₂ bubble nucleation and growth in the glass (Liger-Belair, 2012), as well as for the very characteristic tingling sensation in mouth (Chandrashekar et al., 2009; Dessirier, Simons, Carstens, O'Mahony, & Carstens, 2000; Dunkel & Hofmann, 2010). Moreover, the myriads of ascending and bursting bubbles release both gas-phase CO₂ and volatile compounds in the headspace above glasses, thus continuously modifying the chemical space perceived by the consumer throughout the tasting (Alfonso et al., 2024; Cilindre, Conreux, & Liger-Belair, 2011; Lecasse et al., 2022; Liger-Belair, Bourget, Pron, Polidori, & Cilindre, 2012; Mulier et al., 2009; Moriaux et al., 2021). Bubbling is in fact the hallmark of all sparkling wines, which are characterized by the presence of very characteristic columns of bubbles (also called bubble trains), which run along the glass wall during tasting. By the naked eye, on the macroscopic scale, bubbles seem to continuously nucleate from several specific spots on the glass wall. But why, how, and where do all these bubbles really form, and, beyond aesthetic concerns, what is their role when tasting sparkling wines?

This review focuses on the chronology of the successive stages which mark the tasting of a sparkling wines, from the cork popping out of the bottleneck, involving visually appealing condensation phenomena, to the formation and bursting of bubbles in your glass, including the choice of the glass and how to serve and drink sparkling wines correctly. The authors specifically focused on the physicochemical processes at work, observed and analyzed under standard sparkling wine tasting conditions. This bibliographical synthesis is intended to be as exhaustive as possible, bringing together the articles published on this subject since the first work dating from the early 2000s to the most recent ones. In addition, the science behind sparkling wine tasting being inherently multidisciplinary, this review also builds on more fundamental and pioneering work on sensory analysis, CO₂, and bubble dynamics, so that readers can have access to more fundamental knowledge on the subject if they wish.

2. The cork popping revisited through high-speed imaging

In a sealed bottle of sparkling wine, gas-phase CO₂ and dissolved CO₂ undergo thermodynamic equilibrium according to the so-called Henry's law. The concentration c_L of dissolved CO₂ in the wine is indeed proportional to the partial pressure of gas-phase CO₂, according to the formula $c_L = k_H P_{CO_2}$, with k_H being the strongly temperature-dependent Henry's constant of gas-phase CO₂ in wine (Liger-Belair, 2005), and P_{CO_2} being the partial pressure of gas-phase CO₂ in the sealed bottle. As a result, the temperature dependence of the Henry's constant leads to a strong temperature dependence of the pressure prevailing in the bottle hermetically sealed with a cork, as was modeled by Liger-Belair et al. (2017). It ranges from around 4.5 bar at 5 °C to more than 10 bar at 30 °C.

During the cork popping process, concomitantly with the cork stopper being expelled from the bottleneck under the action of CO₂ pressure, a gas mixture mainly composed of CO₂ (with traces of water and ethanol vapors) freely expands out of the bottleneck through the ambient air and then experiences adiabatic cooling (Batt, 1971; Liger-

Belair, Bourget, Cilindre, Pron, & Polidori, 2013; Vollmer & Möllmann, 2012). For a bottle stored in the fridge (at a temperature close to 5 °C, and with a pressure close to 4.5 bar), a corresponding drop of temperature of order of several tens of degrees during adiabatic expansion causes the immediate condensation of water vapour in ambient air into the form of a cloud of tiny droplets of water. It is the scattering of ambient light by these droplets of liquid water (which is almost isotropic in space and is observed for all wavelengths of the visible spectrum) that gives the condensation trail a whitish tint, as seen in Fig. 1. This mode of light scattering, when the size of the objects that diffuse it is comparable to or greater than the wavelengths of ambient light (which vary from 0.4 μm for blue to 0.8 μm for red), is known as Mie scattering.

Nevertheless, the temperature of a bottle (and therefore its inner pressure) was found to be a key parameter concerning the condensation processes that can occur just above, and inside the bottleneck. Most interestingly, for bottles stored at 20 °C (under a pressure close to 7.5 bar), the characteristic grey-white cloud of fog classically observed above the bottlenecks of bottles stored at lower temperatures was replaced by a more evanescent plume, surprisingly blue, starting from inside the bottleneck, as exemplified in Fig. 2. Under such a pressure close to 8 bar in a corked bottle, adiabatic expansion allowed the temperature of the escaping gas to plummet to a glacial temperature of minus 90 °C. Because this frigid temperature lies much below the freezing point for carbon dioxide (i.e., minus 78.5 °C), it was emphasized that blue haze is the signature of a partial and transient heterogeneous freezing of gas-phase CO₂ on ice water clusters homogeneously nucleated in the bottleneck (Liger-Belair et al., 2017). Blue haze is indeed typical of the Rayleigh scattering of light by clusters much smaller than the wavelengths of ambient light ranging from 0.4 μm to 0.8 μm. This blue flash is finally caused by the same process that colors the sky with its blue hues.

Moreover, for bottles stored at 20 °C and beyond, the initial bottle-to-ambient-pressure ratio (above 7.5 bar) was found to much exceed the critical ratio needed for the CO₂/H₂O gas mixture to reach Mach 1 (i.e., the sound velocity in ambient air) (Liger-Belair et al., 2019). Under such circumstances, under-expanded supersonic gaseous jets got expelled from the throat of the bottlenecks, with the formation of an evanescent normal shock wave in the plumes, made visible through high-speed imaging during the very first millisecond following the cork popping process (Liger-Belair et al., 2019). Such a shock pattern (also called Mach disc or shock diamond) is pointed by a white arrow in the high-speed time-sequence displayed in Fig. 2. From a phenomenological perspective, a parallel between the CO₂/H₂O gas mixture freely expanding from a champagne bottleneck while cork popping and the phenomena arising in a rocket plume exhaust was even done (Liger-Belair et al., 2017, 2019).

Most interestingly, behind the iconic “pop!” accompanying the uncorking of a champagne bottle clearly hides a gas flow with surprisingly complex shock structures. Recently, Computational Fluid Dynamics (CFD) simulations were developed to still more deeply decipher the complex fluid dynamics of the gas mixture expelled from the bottleneck during champagne cork popping (Benidar et al., 2022), as seen in the time-sequence displayed in Fig. 3. CFD revealed that, before the formation of the normal shock wave seen in Fig. 3b, indeed previously observed through high-speed imaging by Liger-Belair et al. (2017, 2019), a first “crown-shaped” shock wave pattern develops radially around the bottleneck (as seen in Fig. 3a), and which has not been observed to date through high-speed imaging in the visible light spectrum. More recently, other computational simulations of the uncorking of a champagne bottle have been reported by Wagner et al. (2023), who even predicted the formation and dissipation of two Mach discs between the bottleneck and the expelled cork stopper. Even more recently, by using high-speed and high sensitivity schlieren imaging, Fréreau et al. (2024) finally revealed diamond shock cells expanding radially around the bottleneck, as well as the formation and dissipation of two Mach

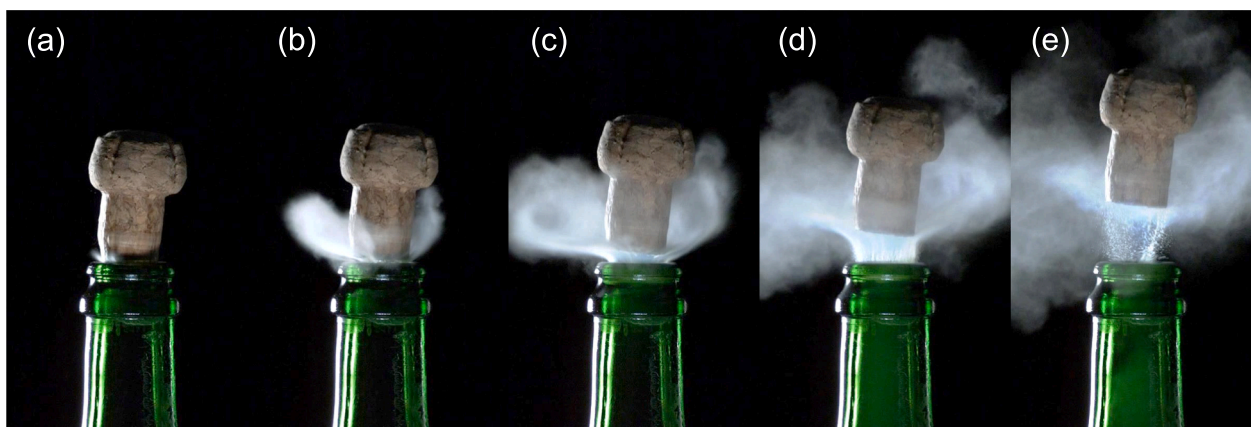


Fig. 1. Time-sequence of the cork popping process as seen through high-speed imaging for a champagne bottle stored at 5 °C; The time interval between the successive frames is 400 μ s. (Université de Reims Champagne-Ardenne).

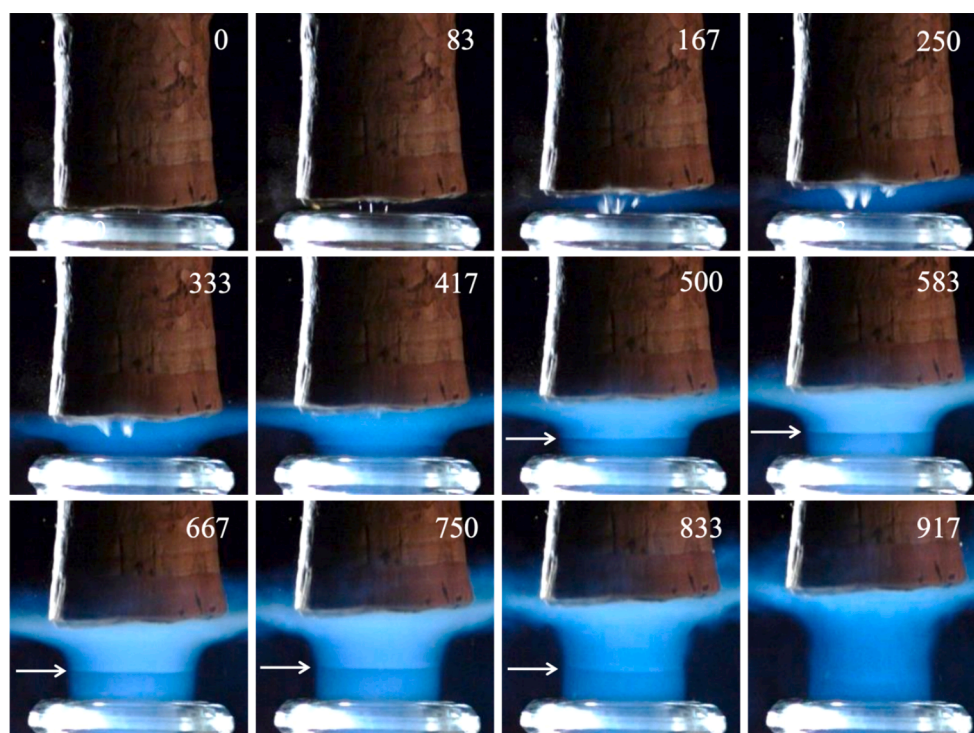


Fig. 2. Close-up time-sequence of the cork popping process as seen through high-speed imaging for a champagne bottle stored at 20 °C; The time elapsed since uncorking is displayed on each image (in μ s); The formation and evolution of the Mach disc is pointed by a white arrow. (Université de Reims Champagne-Ardenne).

discs during the first two milliseconds following the cork popping, as predicted by Wagner et al. (2023).

3. The action of pouring in a glass: A key step for dissolved CO₂

Immediately after uncorking a bottle of sparkling wine, the thermodynamic equilibrium between gas-phase and dissolved CO₂ is broken. Under the low abundance of CO₂ in ambient air (≈ 400 ppm), and subsequent low CO₂ partial pressure ($\approx 4 \times 10^{-4}$ bar), the liquid phase becomes supersaturated with CO₂. To recover a new stable thermodynamic state, dissolved CO₂ must therefore progressively desorb from the liquid phase. Inevitably, once the bottle has been uncorked, the liquid phase (i.e., the wine) progressively loses its initial level of dissolved CO₂.

The concentration of dissolved CO₂ in champagne and other sparkling wines is indeed the real key to the production of bubbles. The

higher the level of dissolved CO₂, the higher the reservoir of CO₂ bubbles, and therefore the longer the precious effervescence during tasting. But the act of pouring the sparkling wine into a glass is far from inconsequential, in terms of its effect on the level of dissolved CO₂ remaining in the glass. As firstly observed by Liger-Belair et al. (2010), massive losses of dissolved CO₂ were indeed experienced by a standard commercial Champagne wine during the turbulences of the pouring step. Immediately after serving the champagne in a glass, the dissolved CO₂ concentration had fallen to a level around 6–9 g/L, depending on several parameters such as the champagne temperature (Liger-Belair et al., 2010), the bottle type (Liger-Belair et al., 2012), or the glass shape (Liger-Belair, Bourget, Pron, Polidori, & Cilindre, 2012; Liger-Belair, Conreux, Villaume, & Cilindre, 2013). It is worth noting that this range of dissolved CO₂ concentration of 6–9 g/L is nevertheless well beyond the minimum level of dissolved CO₂ close to 3 g/L needed to trigger heterogeneous bubble nucleation under standard tasting

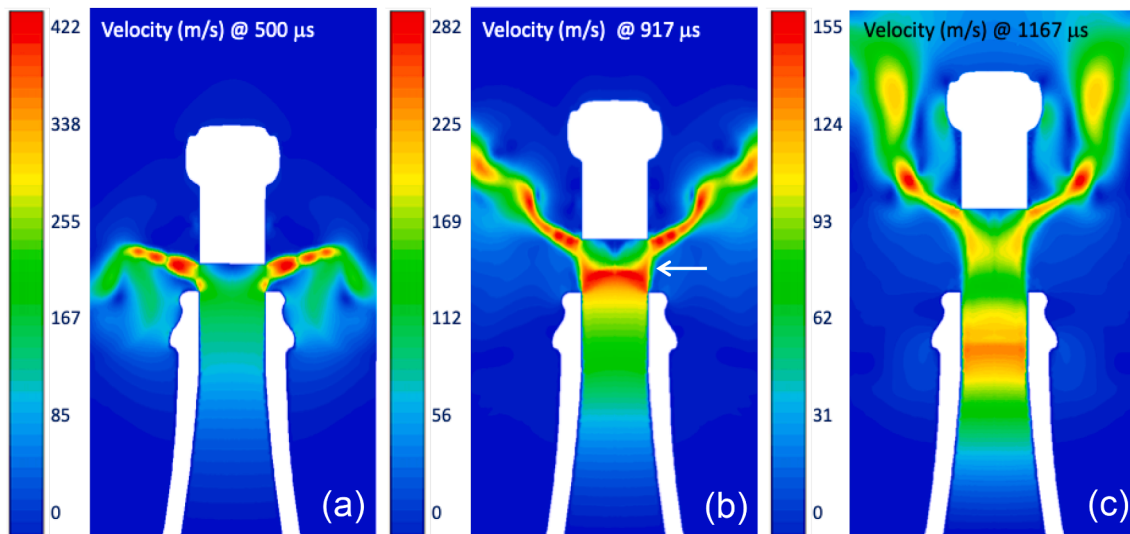


Fig. 3. CFD simulations of the velocity field of pure CO₂ freely expanding in ambient air (under 1 bar, and at 20 °C), at 500 μs (a), 917 μs (b), and 1167 μs (c) after uncorking a bottle of champagne with an inner pressure of 7.5 bar (kept at 20 °C); In (b), the Mach disc is pointed by a white arrow. Readapted from Benidar et al. (2022). (Université de Rennes 1).

conditions (Liger-Belair et al., 2018).

But have you ever wondered how best to pour a sparkling wine in a flute to better preserve the precious fizz? We investigated the effect of two different pouring methods (Liger-Belair et al., 2010). One method involved pouring a Champagne wine straight down the middle of a vertically oriented flute. The other one involved pouring champagne down the side of a tilted flute. Tilting the flute was found to have significantly less impact on the concentration of dissolved CO₂ than the former method because the “beer-like” way of serving is gentler. Pouring a sparkling wine straight down the middle of a vertically oriented glass produces turbulence and traps air bubbles in the liquid, both of which force dissolved CO₂ to escape more rapidly from the wine. These findings were corroborated through infrared imaging which made it possible to visualize the cloud of gaseous CO₂ escaping during service, as shown in Fig. 4 (Liger-Belair et al., 2010). To better preserve the dissolved CO₂ reservoir and the resulting fizz when tasting, we should therefore treat champagne and other sparkling wines a little more like beer – at least when serving them.

4. An energy barrier to overcome for CO₂ bubble nucleation in glasses

4.1. A little bit of nucleation theory

According to the classical nucleation theory (CNT), the nucleation energy barrier ΔG^* to overcome, the corresponding critical radius r^* needed for a cluster of gaseous CO₂ to spontaneously grow *ex nihilo* in a liquid phase supersaturated with dissolved CO₂, and the nucleation rate for homogeneous nucleation J_{hom} (defined as the number of clusters that grow past the critical radius r^* per unit volume and per unit time), express as follows (Blander & Katz, 1975; Wilt, 1986):

$$\left\{ \begin{array}{l} \Delta G^* = \frac{16\pi\gamma^3}{3(\Delta g_v)^2} \\ r^* = \frac{2\gamma}{\Delta g_v} \\ J_{\text{hom}} \approx N \left(\frac{2\gamma}{\pi m} \right)^{1/2} \exp\left(-\frac{\Delta G^*}{k_B T} \right) \end{array} \right. \quad (1)$$

with γ being the surface tension of the gas/liquid interface, Δg_v being the

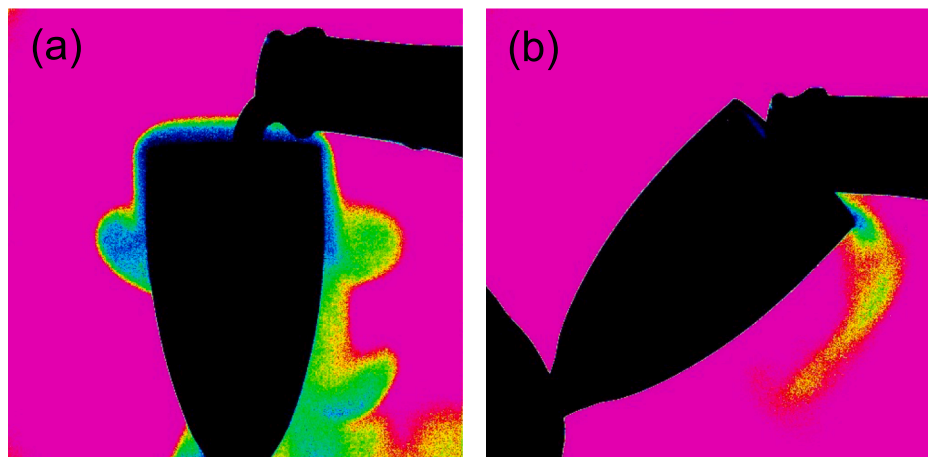


Fig. 4. Snapshots performed through infrared imaging showing the massive losses of dissolved CO₂ during the pouring of champagne in a vertically oriented flute (a), and in a tilted flute (b). (Université de Reims Champagne-Ardenne).

so-called Gibbs free energy per unit volume between the phase that nucleates (i.e., gaseous CO₂) and the thermodynamic phase nucleation is occurring in (i.e., liquid phase supersaturated with dissolved CO₂), N being the molecular concentration of dissolved CO₂ in the liquid phase, m being the mass of a single CO₂ molecule, T being the absolute temperature (in K), and k_B being the Boltzmann constant.

Thermodynamically speaking, and following the CNT, spontaneous CO₂ bubble formation and growth (*ex nihilo*) in a supersaturated liquid phase, such as a sparkling wine after uncorking, is therefore limited by an energy barrier to overcome (Lubetkin & Blackwell, 1988; Lubetkin, 2003). More than two decades ago, Jones et al. (1999) made a classification of the broad range of the various nucleation types of bubble nucleation in liquids supersaturated with dissolved gas. Following their nomenclature, classical homogeneous bubble nucleation within the liquid bulk, and heterogeneous bubble nucleation on perfectly smooth surfaces (i.e., both nucleation types without the help of any pre-existing gas cavity) are referred to as type I and II nucleation, respectively. Pseudo-classical heterogeneous bubble nucleation – referred to as bubble nucleation from a pre-existing gas pocket with a radius of curvature smaller than the critical radius classically (defined earlier as $r^* = 2\gamma/\Delta g_v$) is called type III bubble nucleation. Finally, following their nomenclature, non-classical heterogeneous bubble nucleation from pre-existing gas cavities with radii larger than the critical radius, is referred to as type IV bubble nucleation.

4.2. Preexisting gas cavities are required for bubbling in sparkling wines

In champagne and other sparkling wines, despite dissolved CO₂ concentrations rising to almost 11–12 g/L, it turns out that CO₂ bubbles cannot be born *ex nihilo* after uncorking the bottle. Type I and II bubble nucleation are thus thermodynamically forbidden, because they both require much higher levels of dissolved CO₂ than the standard concentrations close to 11–12 g/L. Even type III bubble nucleation is very unlikely to occur unless pre-existing gas cavities show radii very close to the critical radius. This is the reason why, in weakly supersaturated liquids such as sparkling wines and carbonated beverages in general, bubble formation and growing require pre-existing gas cavities immersed in the liquid phase, with radii of curvature large enough to overcome the nucleation energy barrier and grow freely (i.e., type IV bubble nucleation) (Jones et al., 1999; Lubetkin, 2003). The critical radius (denoted r^*) required to trigger type IV bubble nucleation was accessed by using simple arguments based on classical diffusion principles (Liger-Belair et al., 2002b). r^* obeys the following relationship, with every parameter being expressed in the international system of units (SI):

$$r^* \approx \frac{2\gamma k_H}{(c_L - k_H P_0)} \quad (2)$$

with γ being the wine surface tension (≈ 46 – 48 mN m⁻¹ in wines with 12–13 % ethanol by volume), with k_H being Henry's constant of CO₂ in champagne (indeed strongly temperature dependent), as described in detail in the overview by Liger-Belair (2017), with P_0 being the ambient pressure ($\approx 10^5$ N m⁻², if not too far from seal level), and with c_L being the concentration of dissolved CO₂ found in wine (expressed in mol m⁻³).

Consider a standard Champagne wine (at 12 °C) with a concentration of dissolved CO₂ in the order of 8 g/L (i.e., $c_L \approx 180$ mol m⁻³) just after serving in a standard flute, as reported by Liger-Belair et al. (2010). By retrieving equation (2), and by replacing each parameter by its numerical value, yields a critical radius r^* required to enable bubble nucleation in the order of 0.3 μm. In sparkling wine glasses, bubbling therefore requires pre-existing gas cavities immersed in the liquid phase, with radii of curvature greater than this critical radius. Such gas cavities can have two distinct origins, referred to as “natural” or “artificial”, as described in the following section.

5. Natural versus artificial effervescence

5.1. Natural effervescence

Natural effervescence is related to the bubbling process from a glass which has not experienced any specific surface treatment. Closer inspection of such glasses poured with champagne, sparkling wines, beers, or any other sparkling beverage was conducted through a high-speed video camera fitted with a microscope objective (Lee, McKechnie, & Devereux, 2011; Liger-Belair, Marchal, & Jeandet, 2002; Liger-Belair, Parmentier, & Jeandet, 2006; Liger-Belair, Topgaard, Voisin, & Jeandet, 2004; Liger-Belair, Voisin, & Jeandet, 2005; Liger-Belair, Vignes-Adler, Voisin, Robillard, & Jeandet, 2002; Uzel, Chappell, & Payne, 2006). It revealed that most of the bubble nucleation sites were found to be located on pre-existing gas cavities trapped inside hollow and roughly cylindrical cellulose-fibre-made structures in the order of 100 μm long with a cavity mouth of several micrometres. Such fibres, naturally present in the surrounding air, probably adhere on the glass wall due to electrostatic forces. Additional cellulose fibres will also naturally detach from a towel and adhere to the glass wall if the glass is wiped by a towel. The hollow cavity within the fibre where a gas pocket is trapped is called the *lumen* (like a tiny channel within the fibre). It can be clearly noticed in Fig. 5 that the radii of curvature of gas pockets trapped within the fibres' lumens are much higher than the critical radius r^* required for type IV bubble nucleation.

More information and a discussion about the physical conditions which favour the entrapment of tiny air pockets in the lumen of cellulose fibres during the service of sparkling wine can be found in an overview of bubble dynamics in champagne and other sparkling wines (Liger-Belair, 2017). In sparkling wine glasses, natural bubble nucleation may also arise from tartrate crystals precipitated on the glass wall and resulting from the evaporation process after rinsing the glass with tap water. Therefore, there is a substantial variation concerning the “natural” effervescence between several glasses depending on how a glass was cleaned and wiped, and how and where it was stored before serving.

5.2. Artificial effervescence from laser-etched glasses

Unlike natural effervescence, the term “artificial” was related to the formation of bubbles nucleated from imperfections done intentionally by the glassmaker on the glass wall to trigger effervescence. Indeed, we have known for decades that bubbling in sparkling beverages may arise from micro-scratches done in the surface of the glass (Ronteltap et al., 1991; Lynch & Bamforth, 2002). This is the reason why, years ago, glassmakers proposed to champagne and other sparkling wine tasters a new generation of glasses designed with standardized conditions of effervescence (Liger-Belair et al., 2007, 2008; Polidori et al., 2009; Liger-Belair, 2016; Beaumont et al., 2024). To trigger CO₂ bubble nucleation, such glasses were simply etched on their bottom, with a ring-shaped structure done with adjoining laser beam impacts (as seen in Fig. 6). The local melting of the glass surface caused by a laser impact followed by its sudden cooling generates a network of micrometric crevices in the glass surface, as seen in the micrographs of adjoining laser beam impacts displayed in Fig. 6. When a sparkling wine is served in such a laser-etched glass, the network of tiny crevices at the bottom of the glass surface allows for the trapping of tiny pockets of ambient air. In addition to certain geometrical considerations such as both the depth and width of these crevices, unfavourable wetting conditions increase the probability of trapping air-filled sites in the crevices (Liger-Belair, 2016).

In the same way as for the natural bubble nucleation process, because the radii of curvature of these tiny air pockets are larger than the critical radius r^* reported in equation (2), favourable conditions for non-classical heterogeneous bubble nucleation process are met. Glasses with adjoining laser beam impacts are thus able to initiate repetitive bubble nucleation in the form of a very characteristic central column of ascending bubbles, as seen in Fig. 6. Note that the bubbling process

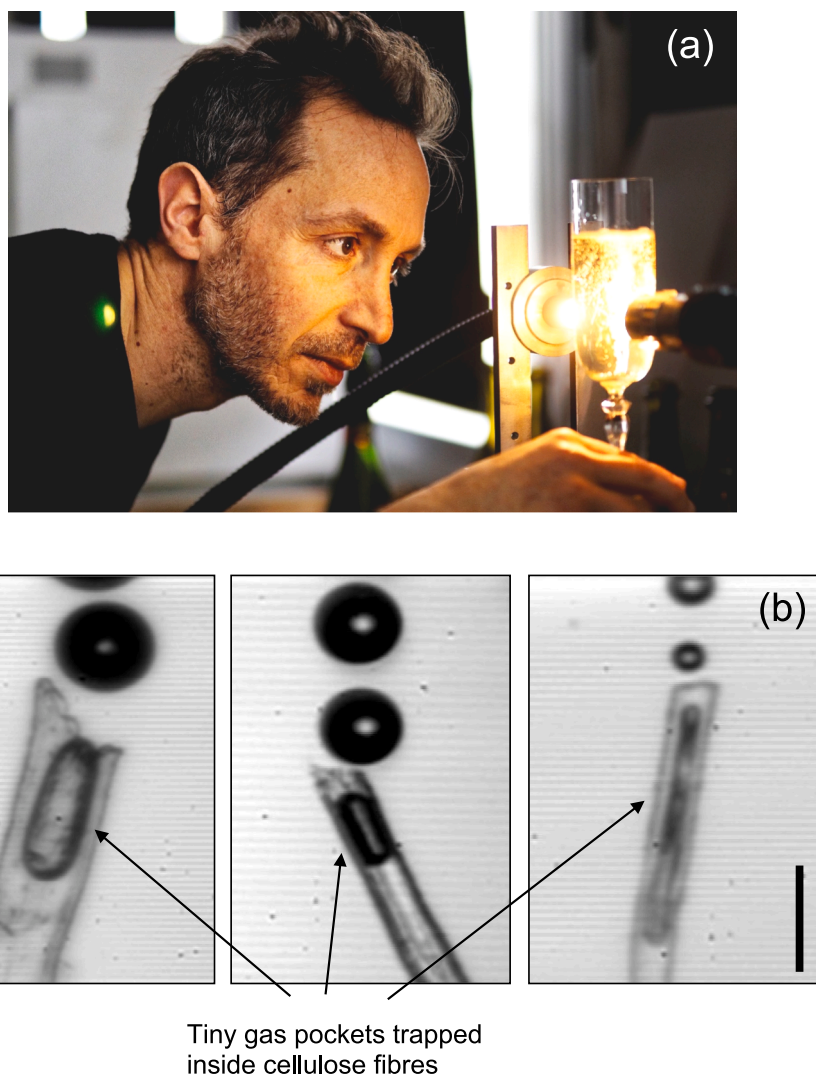


Fig. 5. Optical workbench used to visualize the nucleation of bubbles in champagne glasses through high-speed video imaging (a); Three micrographs showing the non-classical type IV natural bubble nucleation process from tiny gas pockets (pointed with a black arrow) trapped within tiny cellulose fibres stuck on the wall of a glass poured with champagne (scale bar = 50 μm). (Emmanuel Goulet/G rard Liger-Belair).

arising from laser-etched glasses is generally much more vigorous than the bubbling process driven by isolated cellulose fibres far apart (Polidori et al., 2009).

Besides, effervescence in a glass, whether natural or artificial, would go far beyond the sole aesthetic (and rather subjective) point of view. Indeed, strong differences were found concerning the kinetics of gaseous CO_2 release in the headspace above champagne glasses depending on the number of artificial bubble nucleation sites (Liger-Belair, Conreux, Villaume, & Cilindre, 2013; Moriaux et al., 2018), as well as in beers glasses showing different laser etchings (Beaumont et al., 2024). Furthermore, since differences in the flow of gaseous CO_2 escaping from the wine exist depending on the intensity of the effervescence, it has also been proposed that concomitant differences might exist concerning the release kinetics of the aromas throughout the tasting of a sparkling wine (Liger-Belair et al., 2007, 2008; Polidori et al., 2009).

6. Ascending bubble dynamics and bubble size

After being periodically released from tiny gas pockets immersed in the glass (through non-classical heterogeneous nucleation), the CO_2 bubbles rise in-line in the form of very characteristic bubble trains. During their journey to the wine surface, driven by their buoyancy, bubbles continuously grow by progressively absorbing dissolved CO_2

through molecular diffusion. As a result, growing bubbles continuously accelerate during their course, as it can be easily guessed by observing the ever increasing spacing between the successive bubbles released with clockwork regularity from their respective nucleation sites (Fig. 7).

Bubbling is indeed the hallmark of sparkling beverages in general. Champagne and other sparkling wines enthusiasts often claim that the smaller the bubbles, the better the wine. This is the reason why much attention was paid to progressively decipher each, and every parameter involved in the size of ascending bubbles. To the best of our knowledge, the first observations about bubbles ascending in sparkling drinks were conducted in beer glasses in the early 1990s, by Shafer and Zare (1991). They reported that bubbles' diameter linearly increases with time as they rise toward the liquid surface. A decade after the pioneering work by Shafer and Zare (1991), high-speed photography and strobe lighting were applied to decipher the dynamics of bubbles ascending in champagne glasses (Liger-Belair et al., 2000; Liger-Belair, 2002; Liger-Belair & Jeandet, 2003). Under standard tasting conditions, collections of various bubble trains were systematically observed. Both the velocity and the growth of bubbles rising in-line were monitored. More details about the methodology used to monitor ascending bubbles in champagne glasses can be found in the article by Liger-Belair et al. (2000). By combining fundamental developments in bubble dynamics rising at small and intermediate Reynolds numbers with mass transfer equations,

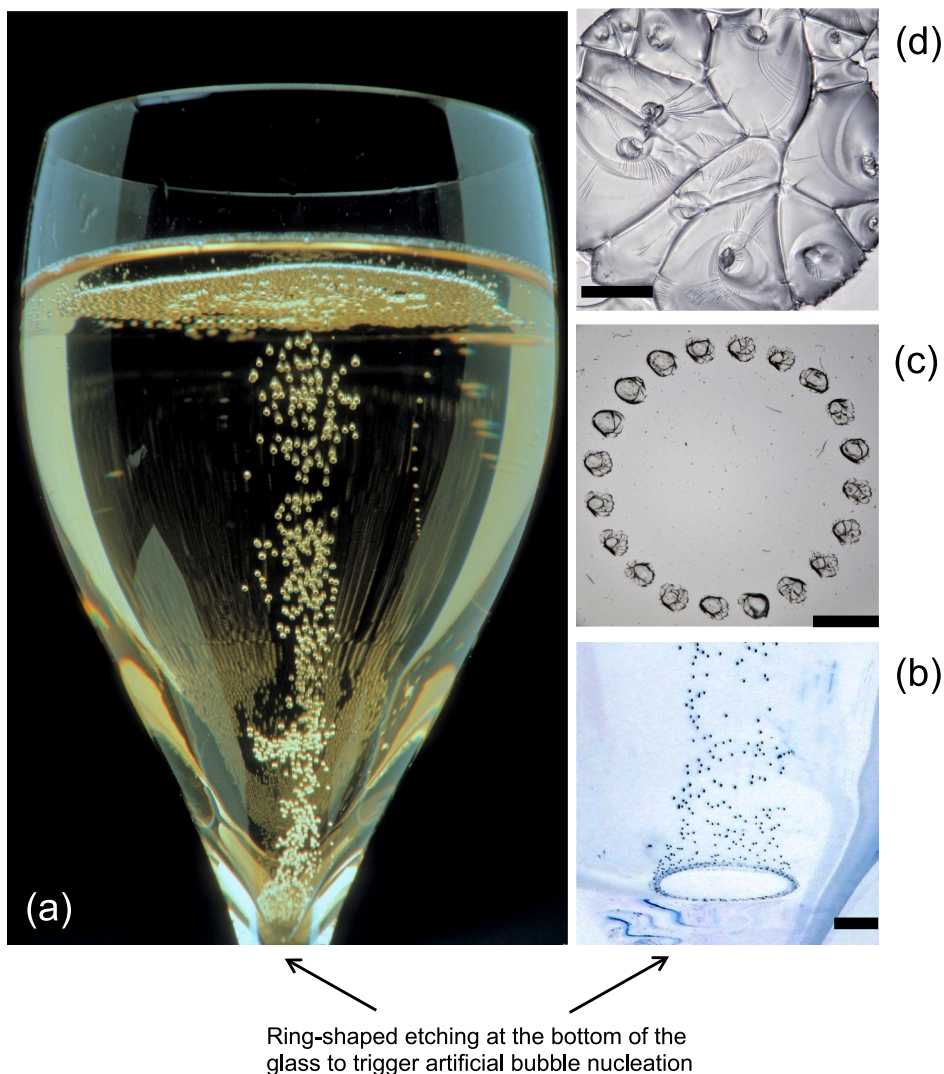


Fig. 6. To trigger artificial bubble nucleation in a glass (a), adjoining laser beam impacts can be made on its bottom, with a ring-shaped structure for example (b and c) (scale bar = 1 mm); Detail of a single beam showing the network of crevices responsible for non-classical heterogeneous bubble nucleation (d) (scale bar = 50 μm). (Collection CIVC/Université de Reims Champagne-Ardenne).

the following relationship was derived (in the SI units), which links the diameter d of a single CO_2 bubble rising in the wine bulk supersaturated with dissolved CO_2 , with several parameters of both the liquid phase and the glass itself (Liger-Belair, 2005):

$$d \approx 5.4 \times 10^{-3} T^{5/9} \left(\frac{1}{\rho g} \right)^{2/9} \left(\frac{c_L - k_H P_0}{P_0} \right)^{1/3} h^{1/3} \quad (3)$$

with T being the wine temperature (in K), ρ being the wine density ($\approx 10^3 \text{ kg m}^{-3}$), g being the gravity acceleration ($\approx 9.8 \text{ m s}^{-2}$), and h being the distance traveled by a bubble from its nucleation site to the wine surface (in m).

We will discuss, and emphasize the influence of the following parameters on the bubble size: (i) the travelled distance h , (ii) the liquid temperature T , (iii) the gravity acceleration g , (iv) the ambient pressure P_0 , and (v) the dissolved CO_2 content c_L .

(i) The longer the travelled distance h , the larger the bubble size. This dependence of the bubble size with its travelled distance through the liquid means that, during champagne tasting, the average bubble size at the champagne surface varies from on glass to another. In a narrow flute, for example, the level of champagne poured is about three times higher than that in a typical coupe (with a shallower bowl and a much wider

aperture). Therefore, the average bubbles' diameters in the flute will be larger than those in the coupe by a factor of about $R_{\text{flute}}/R_{\text{coupe}} \approx 3^{1/3} \approx 1.45$ (i.e., bubbles about three times larger in volume!), as seen in the photograph displayed in Fig. 8, which compares the average size of bubbles after pouring, whether champagne is served into a flute or into a coupe (Liger-Belair et al., 2009).

(ii) In equation (3), the temperature appears directly as $T^{5/9}$, but we should not forget that the Henry's law constant k_H is also strongly temperature-dependent, and conveniently expressed by a Van't Hoff like equation (Liger-Belair, 2005). Increasing the liquid temperature by 10 K (let's say from 278 to 288 K, which roughly corresponds to the temperature range for tasting sparkling wine) makes bubbles grow from about only 5–6 % in diameter.

(iii) The gravity acceleration which is the driving force behind the bubble rise (through buoyancy) plays also a quite important role in the final bubble size. This could indeed be evidenced during a parabolic flight where the acceleration changes from micro-gravity (close to zero-g) to macro-gravity (up to 1.8 g). On the Moon for example, where the gravity is about 1/6 the gravity on Earth, the average bubbles' size would increase by a factor of about $g_{\text{Moon}}/g_{\text{Earth}} \approx 6^{2/9} \approx 1.49$ (i.e., bubbles almost 50 % larger in diameter and therefore more than 3 times larger in volume).

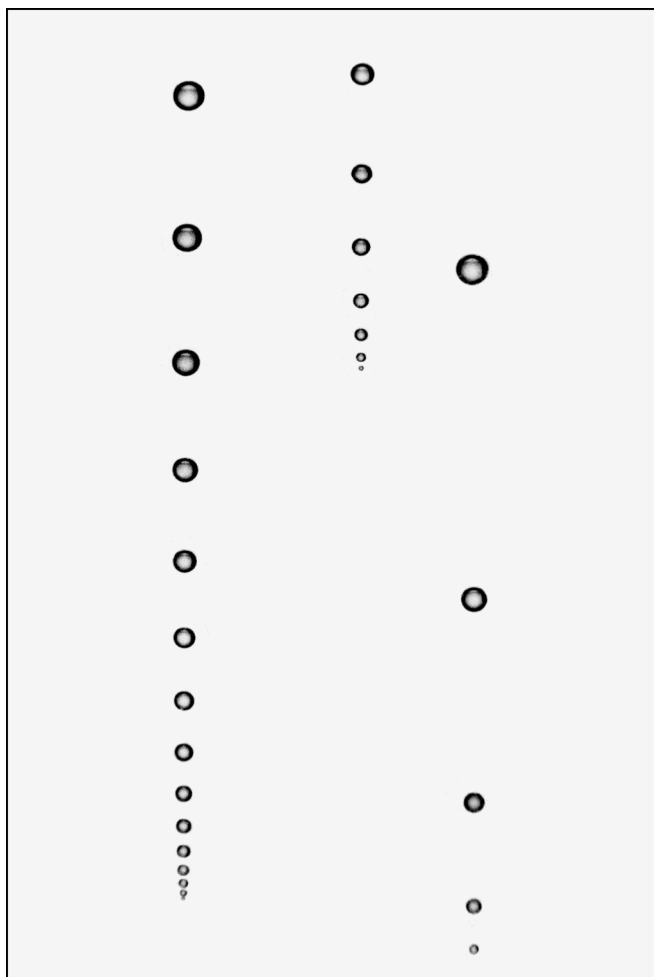


Fig. 7. High-speed photograph showing several trains of growing and accelerating bubbles resulting from non-classical heterogeneous bubble nucleation in a champagne glass. (G rard Liger-Belair).

(iv) The pressure in rising bubble is very close to the ambient pressure P_0 . At the sea level, this pressure is equivalent to 1 bar (or 10^5 N m^{-2}). Reducing the atmospheric pressure to only 0,3 bar (on the top of Mount Everest, for example) would increase the average bubble diameter by about 55 % (and therefore by a factor of almost 4 in volume).

(v) Because dissolved CO_2 progressively escapes from the liquid phase after pouring a sparkling wine in a glass (through bubbling and diffusion across the free surface), the dissolved CO_2 concentration c_L continuously decreases as time proceeds (Liger-Belair, 2016). Therefore, both the growth rate and the resulting velocity of ascending bubbles progressively decrease throughout tasting (Liger-Belair, 2002, 2005). Moreover, because older sparkling wines show lower levels of dissolved CO_2 (due to losses of gaseous CO_2 through the caps or cork stoppers during prolonged aging on lees), they also therefore naturally show smaller bubbles than young sparkling wines do. Beyond the complexity of their aromas (Tominaga et al., 2003), old champagne vintages are thus also easily recognizable through the fineness of their bubbles (Liger-Belair, 2017).

7. Is there an ideal glass to best appreciate the tasting of sparkling wines?

In still wine tasting, glass shape was clearly found to influence the perception of aromas (Delwiche & Pelchat, 2002; Hummel et al., 2003; Bai et al., 2023). More recently and more broadly, the reviews by Spence & Wan (2015) and Spence & Van Doorne (2017) highlighted how much

the drinking receptacle influence the taste/flavor perception of a beverage (including its shape, color, and material properties, for example). But, when it comes to tasting sparkling wines, dissolved and gaseous CO_2 become key parameters throughout the tasting. When one tastes a sparkling wine from a glass, gaseous CO_2 and volatile aromatic compounds progressively invade the “headspace” above the glass, thus modifying the taster’s global perception of aromas. Nevertheless, Humans can sense gaseous CO_2 , which produces a stinging sensation, as noted more than 100 years ago by the Scottish philosopher Alexander Bain (Cain & Murphy, 1980). It turns out that CO_2 activates the same pain receptors in the deep brain that are activated by tasting spicy food (Wang et al., 2010). Indeed, inhaling a gas space with a concentration of gaseous CO_2 close to 20 % and higher triggers a very unpleasant pungent sensation, the so-called “carbonic bite” (Cain & Murphy, 1980; Wise et al., 2003), which might completely disrupt the perception of the wine’s bouquet. Moreover, the link between carbonation and the release of some aroma compounds has also been highlighted in other carbonated beverages. By using a proton transfer reaction–mass spectrometric technique (PTR-MS), Pozo-Bayon et al. (2009) unveiled a higher release of aroma compounds above carbonated waters than above still waters, under both static and dynamic conditions (when the the headspace is diluted by air at a constant rate).

7.1. Flute versus coupe

To enhance the sparkling wine tasting experience and finally try to identify the best glass shapes, monitoring gas-phase CO_2 in the headspace of various glasses dispensed with champagne and other sparkling wines has become a topic of interest over the last dozen years. Since decades, advantages, and disadvantages of the two iconic glass shapes for champagne tasting (i.e., the tall and narrow flute versus the broader coupe) have long been debated in bars, clubs, restaurants, and wine magazines. But until very recently, no analytical data have ever been brought to bear on the age-old dilemma, regarding the effect of each type of drinking vessel on champagne tasting. To study the effect of the glass on the perception of gaseous CO_2 and aromas, we first measured the levels of gaseous CO_2 via gas chromatography (Cilindre, Conreux, & Liger-Belair, 2011; Liger-Belair, Bourget, Pron, Polidori, & Cilindre, 2012). Gaseous CO_2 was found in nearly twice the concentration above the flute as above the coupe. Our results therefore clearly suggest that the narrow flute funnels the gaseous CO_2 , and therefore certainly to a larger extent the aromas, more effectively, whereas the broader coupe “dilutes” them. Our results are thus consistent with sensory analyses of Champagne wines conducted by human tasters. It is indeed generally accepted that the smell of champagne, and especially its “first nose”, is more irritating when champagne is served in a narrow flute than when it is served in a much broader coupe. We also used infrared imaging to visualize gaseous CO_2 escaping from both types of glass (see Fig. 9) and confirmed the tendency of the narrow flute to generate, in its headspace, concentrations of gas-phase CO_2 much higher than the broader coupe (Liger-Belair et al., 2012).

7.2. Mapping gas-phase CO_2 in the headspace of glasses through infrared laser absorption spectroscopy

Based on the Tunable Diode Laser Absorption Spectroscopy (TDLAS), a CO_2 -Diode Laser Sensor (called the CO_2 -DLS) for high-frequency gaseous CO_2 measurements was developed around fifteen years ago (Mulier et al., 2009). By including two distributed feedback (DFB) diode lasers emitting at 4985.93 cm^{-1} and 3728.41 cm^{-1} , respectively, the CO_2 -DLS allows the precise measurement of gas-phase CO_2 over the entire range of possible concentrations (i.e., from 0 to 100 % (v/v)). Since then, this instrument has been continuously upgraded and improved to finally perform the simultaneous spatial monitoring of CO_2 along a multipoint network in the headspace of champagne glasses (Moriaux et al., 2020; Moriaux, Vallon, Cilindre, et al., 2018; Moriaux,

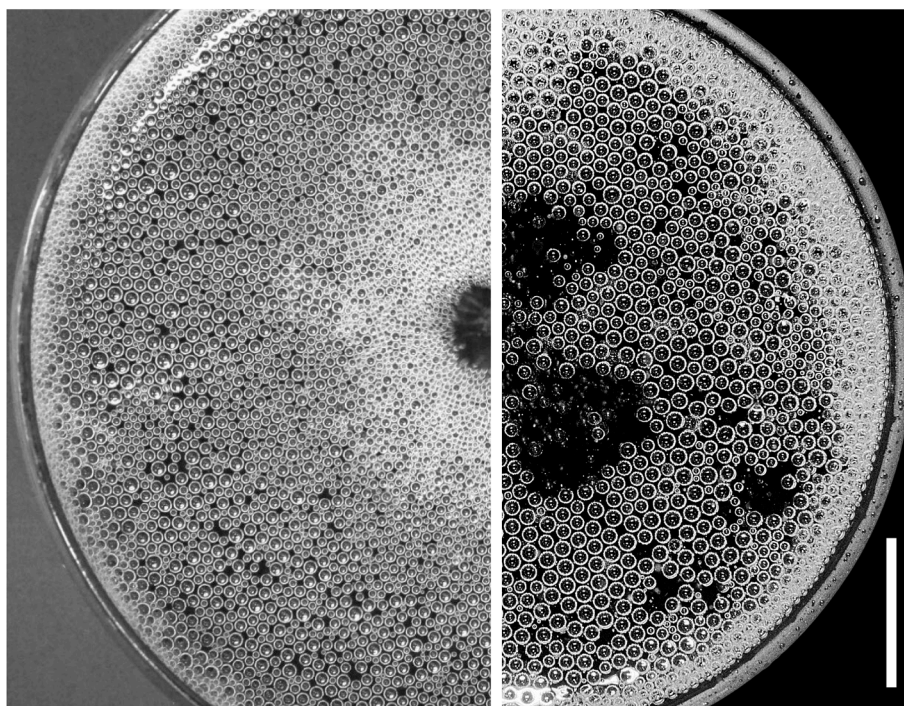


Fig. 8. Distribution of the size of the bubbles floating on the surface of a Champagne wine, 30 s after the service, depending on whether champagne was served in a coupe (left), or in a flute (right) (scale bar = 1 cm). (G rard Liger-Belair).

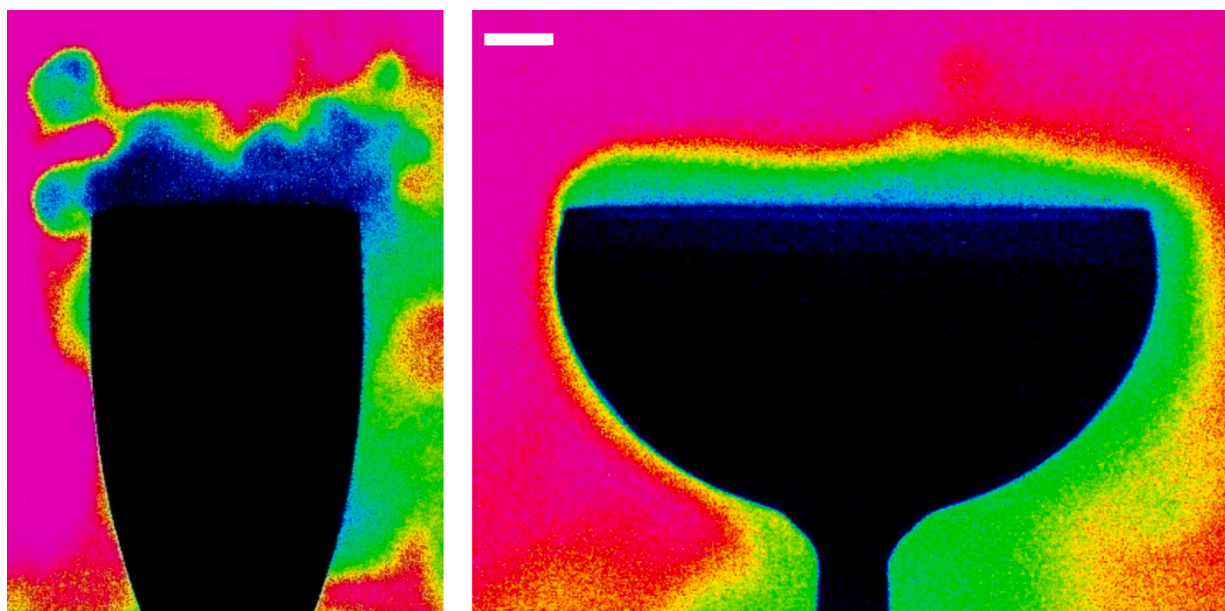


Fig. 9. Gaseous CO₂ escaping from a flute (left) or from a coupe (right), revealed by infrared imaging, around ten seconds after the two glasses were served with 100 mL of champagne; The gas mixture above glasses is all the darker as it is concentrated with gaseous CO₂ (scale bar = 1 cm). (Universit  de Reims Champagne-Ardenne).

Vallon, Parvitte, et al., 2018; Moriaux et al., 2021). The optical setup of the CO₂-DLS aimed at mapping gas-phase CO₂ in the headspace of glasses is displayed in Fig. 10. Now, the CO₂-DLS allows real-time monitoring of gas-phase CO₂ in the headspace of sparkling wine glasses, and carbonated drinks in general, under multivariate tasting conditions, and with a very high time resolution.

With the CO₂-DLS, the mapping of gas-phase CO₂ was thus performed in the headspace of various champagne glasses showing distinct shapes and volume capacities (Moriaux et al., 2021). From the start of

the pouring stage and during the several minutes following, a kind of space- and time-dependent CO₂ footprint was revealed in the headspace of glasses, which was discussed based on the glass geometry and headspace volume. More recently, the space- and time-dependent CO₂ footprint found in the standard 21cL INAO glass was compared with that found in the brand-new 45cL (EnoXpert® glass, designed by the Union of French Oenologists as a universal glass for the tasting of still and sparkling wines (Alfonso et al., 2024). For 100 mL of champagne dispensed at 12  C in both the INAO and (EnoXpert® glasses, the resulting time

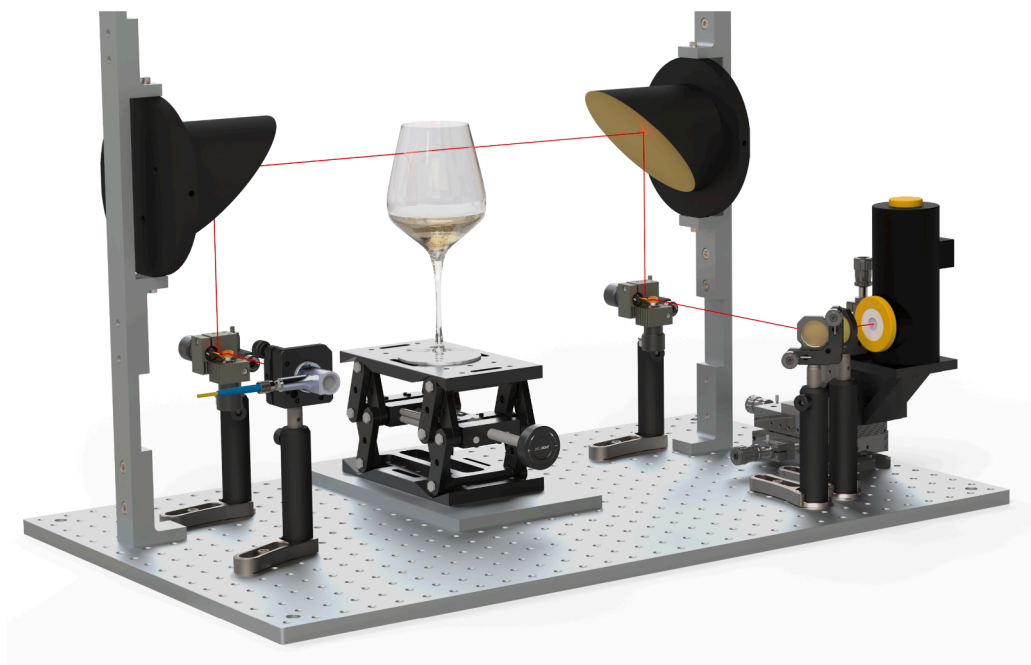


Fig. 10. Digital sketch of the optical part of the CO₂-DLS dedicated to scanning horizontally and vertically the glass headspace, with the two pairs of galvanometric mirrors both located at the focal point of an off-axis parabolic mirror positioned on either side of the glass headspace. (Université de Reims Champagne-Ardenne).

dependence of the vertical distribution of gas-phase CO₂ is displayed in Fig. 11 (in the headspace, along the vertical axis, within the next five minutes following the beginning of the pouring stage). After the sharp increase in CO₂ concentration corresponding to the few seconds of the serving stage, a vertical stratification of CO₂ was revealed, with CO₂ concentrations decreasing as one gets closer to the rim of the glass and as time passes. For an identical volume of champagne dispensed in both glasses, the headspace of the EnoXpert® glass was found to retain gaseous CO₂ much more efficiently over time than the INAO glass does. Therefore, and extrapolating to aromatic compounds, it is reasonable to assume that the chemical space of the EnoXpert® glass should be better preserved throughout the tasting than that of the INAO glass. Nowadays, it seems indeed generally accepted that tulip-shaped wine glasses (a bit shorter than a traditional flute, with a much larger headspace, and

curved slightly inwards at the top, such as the EnoXpert® glass) would be the best compromise and would provide the taster a better overall sensory experience than either the tall flute or the shallow coupe (Liger-Belair et al., 2021).

A much more in-depth discussion about the influence of the glass geometry on the space- and time-dependent CO₂ footprint found in the headspace of glasses can be found in the articles by Moriaux et al. (2021) and Alfonso et al. (2024). These two articles are considered as being first steps toward a more global approach, combining real-time monitoring of gaseous CO₂ (and volatile organic compounds, such as ethanol) in the headspace of various glasses, computational fluid dynamics simulations, and sensory analysis, with the aim of ultimately better understanding the crucial role of glass shape on the overall perception of sparkling wines' bouquet.

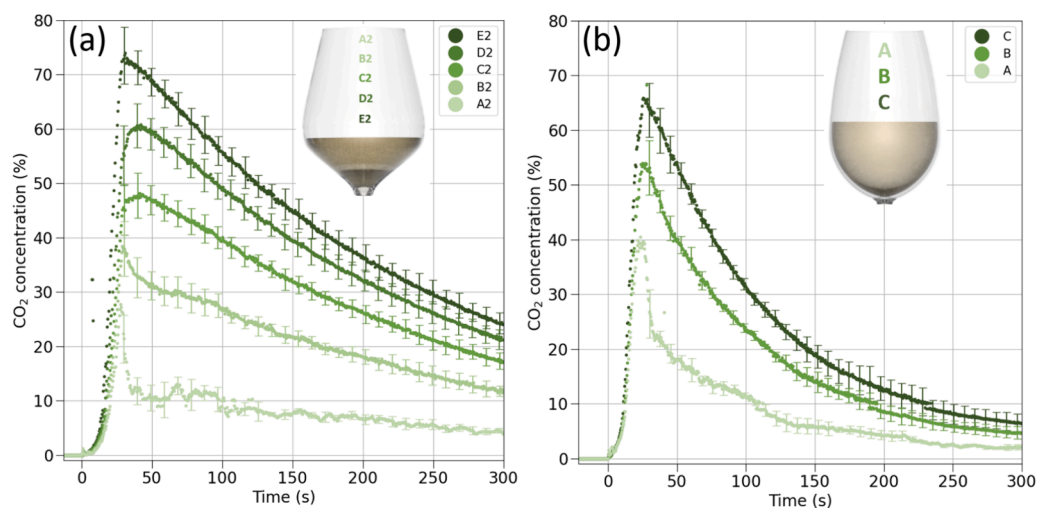


Fig. 11. Real-time monitoring of gaseous CO₂ along five vertically aligned points on the central axis in the headspace of the EnoXpert® glass (a), compared with real-time monitoring of CO₂ along three vertically aligned points in the headspace of the INAO glass (b); At $t = 0$, both glasses were carefully filled with 100 mL of a standard commercial Champagne wine (at 12 ± 1 °C); The CO₂ time series records resulting from three successive pourings were averaged, with their respective standard deviations displayed every 20 measurement points.

8. Unveiling ascending bubble-driven flow patterns in champagne glasses

In sparkling wine tasting, as we gradually understood, the effervescence in your glass goes well beyond the sole aesthetic point view. Indeed, fluid mechanics told us that gas bubbles ascending in a liquid phase drag along fluid particles in their wakes, which in turn disturbs the neighbouring fluid layers. In sparkling wine glasses, ascending bubbles are no exception to this rule.

8.1. Laser tomography and PIV experiments

In glasses poured with champagne, laser tomography and Particle Image Velocimetry (PIV) techniques were used to reveal the complex and visually appealing flow patterns driven by ascending bubbles (Beaumont, Liger-Belair, & Polidori, 2015; Liger-Belair et al., 2007, 2008; Polidori, Jeandet, & Liger-Belair, 2009). As an example, laser tomography unveiled the beauty of the large circulation flows that develop in two laser-etched champagne glasses (see Fig. 12). In such laser-etched glasses, tomography and PIV proved that the wine bulk is subjected to a very efficient stirring process resulting from the continuous central bubbly flow (Beaumont, Liger-Belair, Bailly, & Polidori, 2016; Beaumont, Liger-Belair, & Polidori, 2015). Homogeneous stirring of sparkling wines under the action of rising bubbles confers an advantage (compared with a situation where the liquid phase would be at rest) by continuously renewing the subsurface layers with wine from the bulk. Indeed, rising bubbles and their resulting recirculation flows were found to enhance the release of CO₂ in the headspace above glasses, as well as the evaporation of ethanol, the main volatile organic compound (VOC) of wines, as experimentally observed through gas chromatography by Cilindre et al. (2011). Conversely, non-effervescent flat wines, at rest in your glass, progressively become odorless (unless you swirl your glass to replenish the subsurface layers with wine from the bulk). Therefore, by enhancing the diffusion of gaseous CO₂ and VOCs above glasses, the vertical recirculation naturally driven by ascending bubbles should be considered as a wonderful gift to sparkling wine lovers (despite a glaring lack of experimental data linking the sensory evaluation of taster panels to the presence of rising bubbles in

sparkling wine glasses). In addition, by examining the photographs displayed in Fig. 12, no doubt that different glasses show different circulation flow patterns, depending on their volume, shape, and conditions of effervescence, as described in minute details in previous articles (Beaumont, Liger-Belair, Bailly, & Polidori, 2016; Beaumont, Liger-Belair, & Polidori, 2015, 2019b). Depending on the choice of glass, the release of aromas and gaseous CO₂ will not occur at the same rate, thus offering a different overall sensation to the taster. This might explain why some consumers get different aromas from a critic whose note they have read: they were maybe using different glasses and therefore experienced different aromas.

Moreover, a collection of several two-dimensional vortices, which formed at the air/champagne interface, were captured through long-exposure photography (Beaumont et al., 2016). Depending on the intensity of the ascending bubbly flow, and therefore on the time elapsed since champagne was poured, various regimes were evidenced. Early after pouring, the situation is highly unstable, with many rather small but rapidly counter-rotating cells changing, from a very unstable 8-cells regime (see Fig. 13a) to a usually more stable 6-cells regime (see Fig. 13b). Shortly afterward, the system reorganizes itself in a long-lasting and stable regime, with four large counter-rotating cells (see Fig. 13c). These vortices are the result of the fine interplay between ascending bubbles, which continuously drive some fluid across the champagne surface and the circular glass edge, which confines the fluid circulation around its interior boundary. It is worth noting that floating bubbles on the surface of champagne freely follow the two-dimensional movement of the flat air/champagne interface and help us to track the trajectories of champagne surface currents (exactly as drifting buoys allow us to track sea surface currents). This phenomenological parallel between the champagne vortices and the sea surface currents can be evidenced on the fantastic satellite image displayed in Fig. 13d.

8.2. Computational fluid dynamics (CFD) simulations

In complete accordance with the various experimental observations conducted through laser tomography and PIV techniques in laser-etched glasses, CFD simulations revealed a very complex flow composed of surface eddies interacting with a toroidal flow that develops around the



Fig. 12. Large circulation flows that develop in the liquid bulk, whether champagne is served in a tall and narrow flute (left) or in a broader coupe with a shallow bowl (right); Both glasses are laser-etched with a ring-shaped etching at their bottom, with a resulting central bubbly flow ascending along their axis of symmetry. (Université de Reims Champagne-Ardenne).

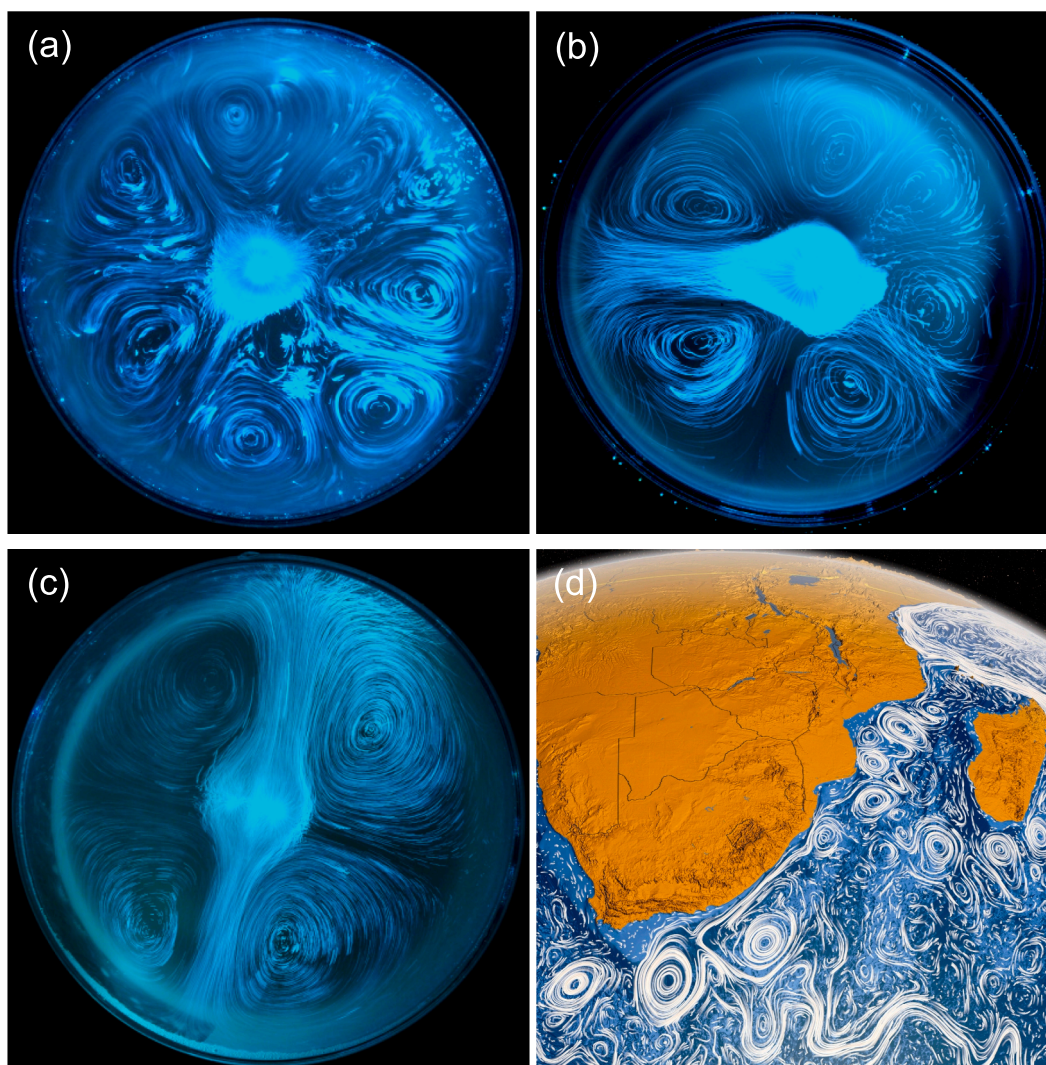


Fig. 13. Laser tomography combined with long exposure time photography showing the self-organized 2D convection cells at the free surface of a coupe poured with 100 mL of champagne (a-c) (Université de Reims Champagne-Ardenne); A highly unstable 8-cells regime is often first evidenced, early after pouring champagne (a), usually followed by a poorly stable 6-cells regime (b), and by a highly stable and long lasting 4-cells regime, several minutes after pouring champagne (c); In panel (d), 2D sea surface currents in the southern Indian Ocean, near the east coast of South Africa, as evidenced through satellite imagery (NASA).

ascending bubble column (Beaumont et al., 2019a, 2020). Fig. 14 shows the column of ascending bubbles found in a laser-etched glass poured with 100 mL of champagne (Fig. 14a), the subsequent self-organized recirculation flow patterns determined through a three-dimensional (3D) CFD model (Fig. 14b), and the corresponding velocity field showing the highest flow velocities along the axis of symmetry of the glass where the central bubbly flow operates (Fig. 14c). CFD therefore also revealed a highly complex network of various convective cells driven by the central bubbly flow (in the champagne bulk and at the air/champagne interface), thus confirming the close interplay between the 2D flow patterns at the air/champagne interface and the 3D recirculation flow patterns found in the subsurface fluid layers. Ultimately, for a glassmaker, the goal of the CFD approach could be to quickly, and cost-effectively, analyze the influence of both glass shape and bubbling on the subsequent ascending bubble-driven flow patterns (which strongly influences the overall organoleptic perception of the wine by modulating the escape kinetics of CO₂ and VOCs in the headspace of glasses).

All these observations finally allowed us to understand how crucial the choice of glass is when tasting a sparkling wine, probably even more than for a still wine. The lesson from all these measurements and observations is that the tasters should not smell the champagne immediately after it is poured, because too many vortices will release too much

carbon dioxide likely to irritate the tasters' nostrils. The best way to do is probably to wait a little bit, so that the more stable 6-cells and 4-cells regimes have taken over, to get a better, fuller, truer sense of the wine's aromas. The fundamental knowledge of the bubbling process and its resulting self-organized networks of various recirculation flows can help design specific glass shapes to bring out the best characteristics of champagne and other sparkling wines. For a few years now, some glass manufacturing companies have already been doing just that, bringing together physicists, engineers, sommeliers, and wine connoisseurs (Liger-Belair et al., 2021; Mathijssen, Lisicki, Prakash, & Mossige, 2023).

9. Bursting bubbles provide an aromatic boost to champagne

Bursting bubbles are ubiquitous in industrial and environmental processes (in physics, chemical and mechanical engineering, marine science, geophysics, medicine, and even food science). For detailed information about the complex processes generated by bursting bubbles in a wide range of scientific fields, see for example the articles and reviews by Ghabache et al. (2014), Lohse (2018), Nikolov & Wasan (2019), Deike (2022), Villermaux et al. (2022), and Xiang et al. (2023). Most interestingly in the context of this review, bubbly drinks (Zenit and Rodríguez-Rodríguez, 2018) and especially Champagne wines (Liger-

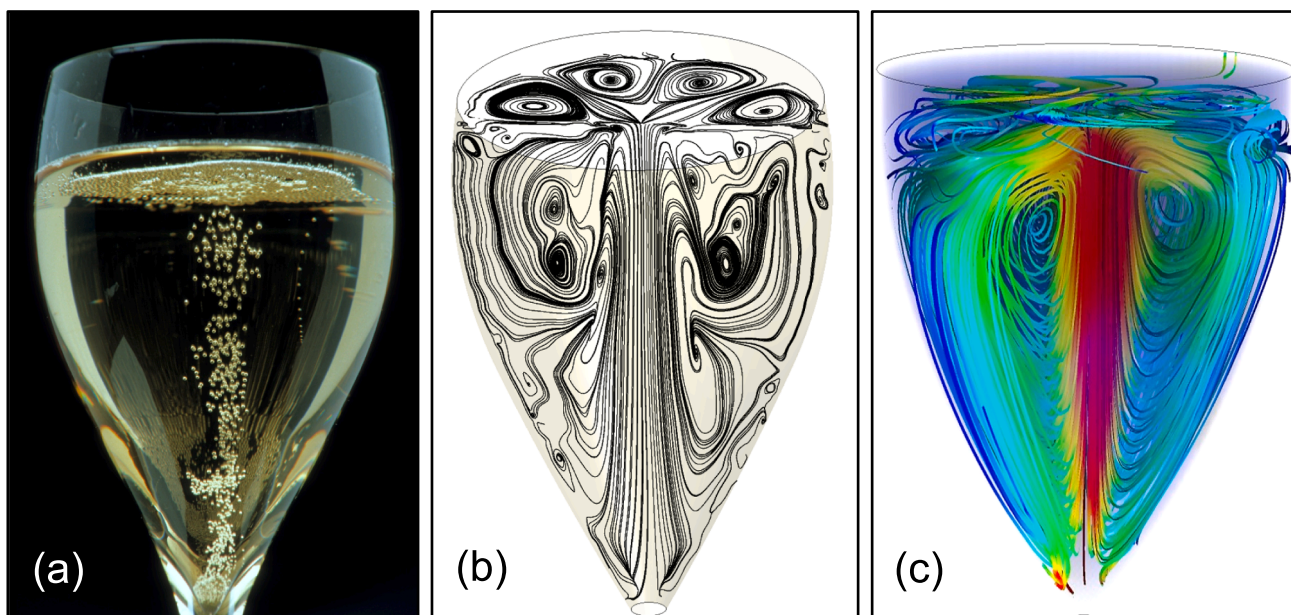


Fig. 14. Central bubbly flow ascending in a laser-etched glass poured with 100 mL of champagne (a), resulting network of various convective cells revealed through 3D CFD modeling (in the plane of symmetry of the glass and at the air/champagne interface) (b), and corresponding velocity field in the champagne bulk showing the highest flow velocities along the axis of symmetry of the glass (c). (Collection CIVC/Université de Reims Champagne-Ardenne).

Belair et al., 2012) also proved to be fantastic playgrounds to explore the complex and sometimes counter-intuitive physics behind bursting bubbles.

9.1. The subtle mechanics of bursting bubbles

As it reaches a liquid surface, and before it bursts, a gas bubble floats for a while, separated from the open atmosphere by a thin liquid film (the bubble-cap). Immediately after the disintegration of their emerging bubble-caps, floating bubbles release their gaseous content above the liquid surface, as nicely captured using high-speed stereophotogrammetry with around 400 μm to 4 cm diameter smoke-filled bubbles bursting at an air–water interface (Dasouqi et al., 2021, 2022). Recently also, Singh & Das (2021) presented numerical simulations aimed at deciphering the dynamics of evacuating inner gas of a bubble bursting at an air/liquid interface.

A sparkling wine bubble that has typically traveled around ten centimeters between its nucleation site lying at the bottom of a glass and the free surface of the wine sees its diameter increase from a few tens of micrometers to around one millimeter (Liger-Belair, 2005). Because the radius of a bubble remains smaller than the so-called capillary length $\kappa^{-1} = \sqrt{\gamma/\rho g} \approx 2\text{mm}$, gravity (and therefore buoyancy) is thus largely dominated by capillarity, which prevents the bubble from emerging above the air/liquid interface. Floating bubbles in sparkling wine glasses

are finally like tiny spherical icebergs, with most of their gaseous volume remaining below the free surface (Séon & Liger-Belair, 2017). In sparkling wine glasses, immediately after the disintegration of their respective bubble-caps, bursting bubbles release their content in gaseous CO_2 and VOCs above the wine surface. In tasting, the foam which progressively collapses after the pouring step and the hundreds of bubbles that burst every second are therefore responsible for the “bouquet” felt by the taster inhaling the headspace of the glass. A remarkable time-sequence done through infrared imaging is displayed in Fig. 15, where the release of gaseous CO_2 is revealed as the head of foam rapidly collapses immediately after pouring champagne in a glass (Bourget et al, 2013).

Moreover, after the disintegration of the emerged bubble-cap of a floating bubble, concomitantly with the evacuating inner gas, a very complex hydrodynamic process ensues causing the rapid collapse of the submerged spherical part of the bubble (Deike et al., 2018). In the case of a champagne bubble, the very first reconstructed time-sequence of this collapsing process is displayed in Fig. 16. It was captured about two decades ago *in situ* (i.e., on the top of a glass poured with champagne) through high-speed macrophotography (Liger-Belair et al., 2001). Fig. 16 shows how a single bursting bubble triggers the production of a tiny upward jet, which quickly breaks-up into several tiny droplets of wine under the effect of the so-called Rayleigh-Plateau instability (Eggers & Villermaux, 2008).

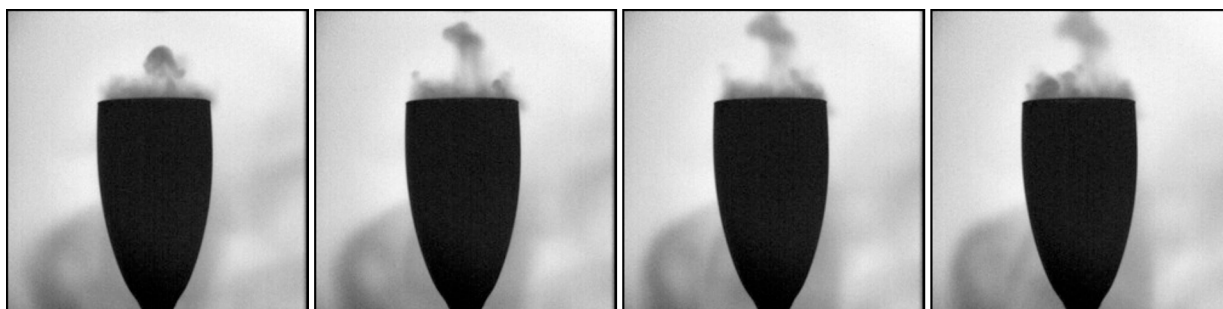


Fig. 15. A plume of gaseous CO_2 expelled above the glass is revealed, through infrared imaging, as the head of foam rapidly collapses immediately after pouring champagne in a flute; The time interval between successive frames is 100 ms. (Université de Reims Champagne-Ardenne).

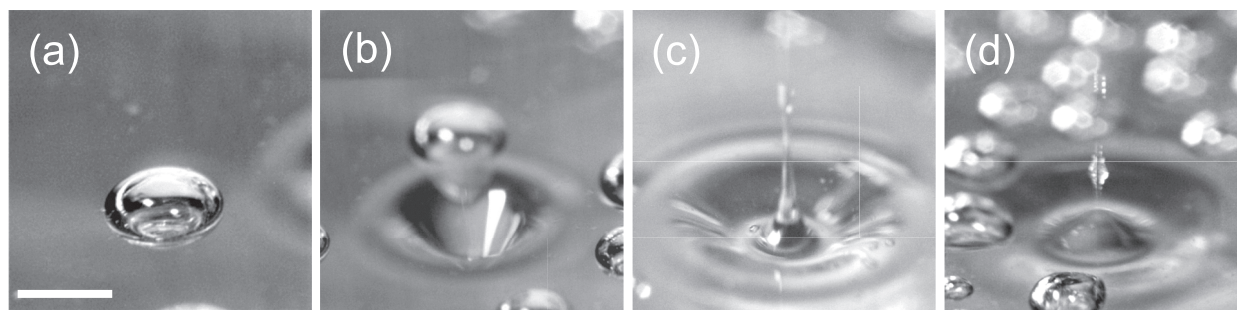


Fig. 16. First reconstructed time sequence, done through high-speed macrophotography, showing the hydrodynamical process immediately following the bursting of a millimetric bubble floating at the champagne surface (a); After the rupture of the emerged bubble-cap, the submerged spherical-cap of the floating bubble (b) collapses and triggers the formation of a tiny upward champagne jet (c), which quickly breaks-up into several droplets (d). (scale bar = 1 mm). (Gérard Liger-Belair).

More recently, rigorous approaches that combine high-speed video imaging and numerical modeling were conducted to better understand the role of the various parameters at play on the formation and break-up of this upward jet of champagne (Ghabache, 2015; Ghabache et al, 2016; Séon & Liger-Belair, 2017; Deike et al., 2018). The typical high-speed video sequence displayed in Fig. 17a shows how the submerged spherical cavity left by a millimetric bursting bubble quickly collapses at the millisecond time scale, before it projects the high-speed liquid jet which breaks-up into tiny droplets on a time scale of milliseconds (Fig. 17b). The velocity, number and size of champagne droplets produced per bursting bubble mainly depend on the diameter of the bursting bubble and on the combined action of surface tension and viscosity of the liquid phase (Berny et al., 2020). During champagne and other sparkling wine tasting, the myriads of ascending bubbles collapse and therefore radiate a multitude of tiny droplets above the free surface, in the form of

refreshing aerosols, as shown in the two photographs displayed in Fig. 18.

9.2. An aerosol overconcentrated with VOCs

Years ago, a phenomenological analogy between the fizz of the ocean and the fizz in sparkling wines was done (Liger-Belair et al., 2001). It was hypothesized that aerosols projected in the headspace above sparkling wine glasses could considerably enhance the fragrance release of champagne by bringing chemical compounds, showing both surface activity and organoleptic interest, to the taster's nostrils. Indeed, Champagne and other sparkling wines are multicomponent hydroalcoholic solutions holding hundreds of surface-active compounds, some of them showing organoleptic interest. However, in surfactant solutions, preferential adsorption of surfactants at the air-solution

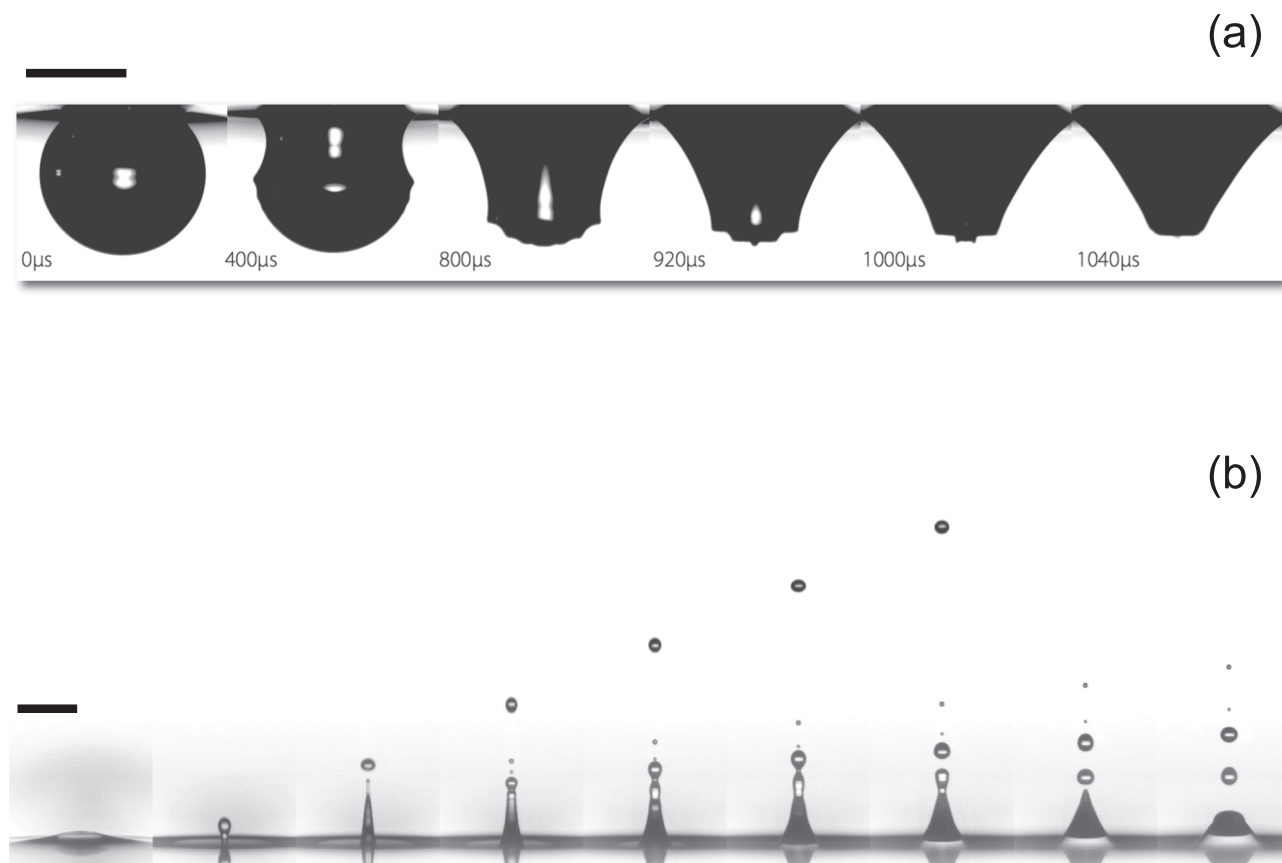


Fig. 17. Time-sequences showing how the submerged spherical cavity left by a millimetric bursting bubble quickly collapses at the millisecond time scale (a), before it projects a high-speed tiny liquid jet upward above the air/champagne interface (b). (scale bars = 1 mm). (Elisabeth Ghabache).

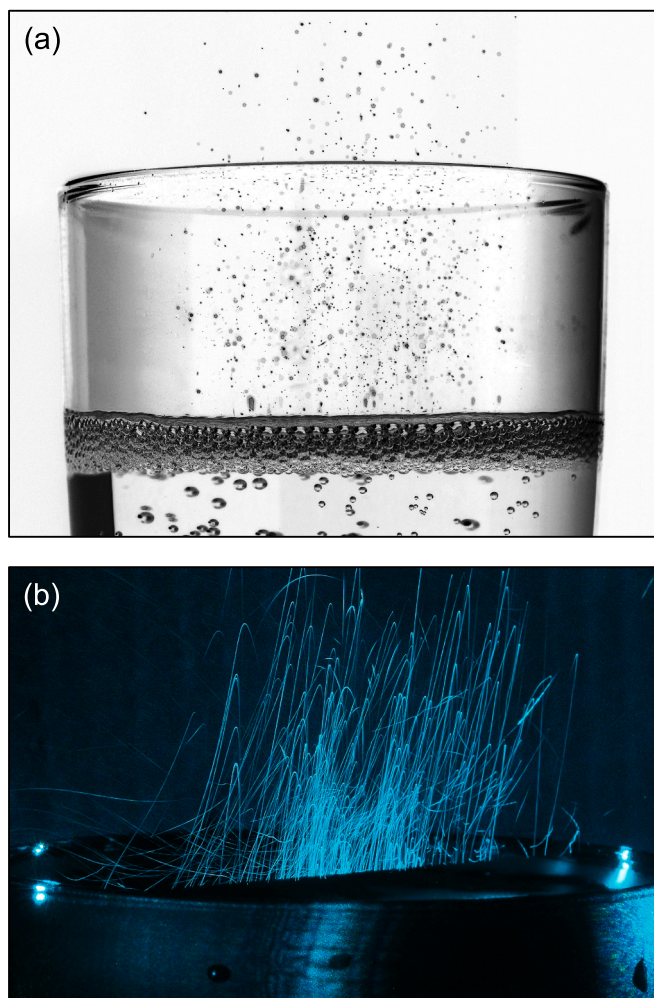


Fig. 18. Photographs showing the aerosol of tiny droplets propelled by bursting bubbles above the champagne surface (a) and the trajectories of droplets as revealed by blue streaks of light through laser tomography (b). (Alain Cornu/Université de Reims Champagne-Ardenne). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

interface occurs because of the amphiphilic properties of surfactants, with the water-soluble moiety plunging into the solution and the hydrophobic component in contact with the air. In surfactant solutions, a fundamental aspect of ascending bubble dynamics is therefore the subsequent substantial enrichment of surface-active organic matter in the bursting bubble aerosol relative to the bulk solution (Chingin et al., 2018). Across the oceans, it is estimated that between 10^{18} and 10^{20} bubbles burst every second to form the so-called sea spray aerosol, enriched in surfactant materials by several orders of magnitude relative to the bulk sea water (O'Dowd et al., 2004; O'Dowd & De Leeuw, 2007; Schmitt-Kopplin, et al. 2012). At a smaller scale, the situation found in glasses poured with champagne or sparkling wine is quite like that described above. Indeed, directly in a flute poured with champagne, it has been demonstrated by use of ultrahigh resolution mass spectrometry (Fourier Transform – Ion Cyclotron Resonance – Mass Spectrometer; FT-ICR-MS), that bursting bubbles radiate a cloud of tiny droplets overconcentrated with tens of VOCs showing organoleptic interest or being precursors of aromas (Liger-Belair et al., 2009).

Moreover, the numerical modeling proposed by Ghabache et al. (2016) revealed that, in the context of sparkling wine with a standard bubbling/bursting rate close to 400 bubbles per second, the aerosol of droplets produced by the bursting of bubbles allows evaporation of the

wine approximately 10 times more efficient than the evaporation from the free surface of the wine only (as for a still wine, for example). Indeed, it turns out that this very characteristic aerosol made up of hundreds of tiny droplets expelled at high speed several centimeters above the wine surface by the myriads of bursting of bubbles partly evaporate during their journey, thus considerably enhancing the release of VOCs when tasting sparkling wines compared to still wines.

10. Conclusion and prospects

The strong interplay between the various parameters at play in a bottle and in a glass of sparkling wine has been the subject of study for about two decades. Indeed, we have been making and tasting sparkling wines for more than three centuries, but the pursuit of this art can still benefit from the latest scientific advances today. This review offered a complete overview of the physicochemical processes that mark a sparkling wine tasting, from the cork popping to the bursting of bubbles in your glass, including the choice of the glass and how to serve it correctly. Sure, sparkling wine tasting is often seen as the pinnacle of glamor and frivolity, but it should also be considered as a fantastic playground for chemists and physicists to explore the subtle science behind this centuries-old drink, whose prestige today goes well beyond the borders of Champagne and France.

The impact of swirling the wine into the glass (as tasters usually do before inhaling the wine) on the spatial and temporal distribution of CO_2 and VOCs within the headspace of glasses, is the subject of work in progress. In the near future, we also plan to combine sensory analysis with CFD and real-time monitoring of gaseous CO_2 and VOCs in the headspace of various glasses, with the aim of ultimately better understanding the role of glass shape on the overall perception of sparkling wines' bouquet.

CRediT authorship contribution statement

G rard Liger-Belair: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Clara Cilindre:** Methodology, Formal analysis, Data curation, Conceptualization. **Fabien Beaumont:** Visualization, Software, Formal analysis, Data curation. **Guillaume Polidori:** Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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