

On the Losses of Dissolved CO₂ during Champagne Serving

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Pouring champagne into a glass is far from being consequenceless with regard to its dissolved CO₂ concentration. Measurements of losses of dissolved CO₂ during champagne serving were done from a bottled Champagne wine initially holding $11.4 \pm 0.1 \text{ g L}^{-1}$ of dissolved CO₂. Measurements were done at three champagne temperatures (i.e., 4, 12, and 18 °C) and for two different ways of serving (i.e., a champagne-like and a beer-like way of serving). The beer-like way of serving champagne was found to impact its concentration of dissolved CO₂ significantly less. Moreover, the higher the champagne temperature is, the higher its loss of dissolved CO₂ during the pouring process, which finally constitutes the first analytical proof that low temperatures prolong the drink's chill and helps it to retain its effervescence during the pouring process. The diffusion coefficient of CO₂ molecules in champagne and champagne viscosity (both strongly temperature-dependent) are suspected to be the two main parameters responsible for such differences. Besides, a recently developed dynamic-tracking technique using IR thermography was also used in order to visualize the cloud of gaseous CO₂ which flows down from champagne during the pouring process, thus visually confirming the strong influence of champagne temperature on its loss of dissolved CO₂.

KEYWORDS: Champagne; sparkling wines; carbonated beverages; CO₂; diffusion; infrared thermography

INTRODUCTION

Champagne and sparkling wines elaborated according to the *méthode traditionnelle* typically hold close to 12 g/L of dissolved CO₂ molecules, i.e., about 9 g per each standard 75 cL bottle (1, 2). As soon as a bottle of champagne or sparkling wine is uncorked, the liquid instantaneously becomes supersaturated with dissolved CO₂ molecules (since ambient air contains only traces of gaseous CO₂). To reach a new stable thermodynamic state with regard to CO₂ molecules, champagne must therefore progressively degas. It is worth noting that 9 g of dissolved CO₂ corresponds to approximately 5 L of gaseous CO₂ which must inevitably escape from a standard 75 cL uncorked champagne bottle (i.e., 6 times its own volume!). After uncorking a bottle of champagne or sparkling wine, CO₂ molecules can escape from the supersaturated liquid matrix into the form of bubbles, provided that immersed particles or defects of the glass wall are able to entrap tiny air pockets (larger than a critical size) which may therefore act as bubble nucleation sites (3). It is the so-called effervescence process which enlivens champagne, sparkling wines, ciders, beers, sodas, and fizzy waters. But it is worth noting that CO₂ molecules also inevitably escape by invisible diffusion, through the free air/champagne interface. In a classical flute poured with champagne, experiments were performed a few years ago to indirectly evaluate

the respective losses of CO₂ as time proceeds (into the form of bubbles and by invisible diffusion). It was approximately found that for every one CO₂ molecule which escapes from champagne into the form of bubbles, four others directly escape by invisible diffusion through the free air/champagne interface (4). Invisible diffusion is therefore strongly suspected to be the main pathway as concerns the loss of dissolved CO₂ during champagne and sparkling wine tasting.

In champagne and sparkling wine tasting, the concentration of dissolved CO₂ is a parameter of great importance since it directly impacts the four following sensory properties: (i) the frequency of bubble formation in the glass (1, 2), (ii) the growth rate of rising bubbles (2–4), (iii) the mouth feel, i.e., the mechanical action of collapsing bubbles as well as the chemosensory excitation of nociceptors in the oral cavity (via the conversion of dissolved CO₂ to carbonic acid) (4–7), (iv) and the nose of champagne, i.e., its so-called *bouquet* (8–10). Accurately monitoring the concentration of dissolved CO₂ into a glass, during champagne tasting, is therefore of great interest for both champagne elaborators and glassmakers. Quite recently, glassmakers showed an interest in proposing to consumers a new generation of champagne tasting glasses, especially designed, with a well controlled CO₂ release all along tasting (11). This is the reason why, in recent years, much interest has been devoted to better understand and depict each and every parameter involved in the release of gaseous CO₂ from glasses poured with champagne or sparkling wine. In a recent

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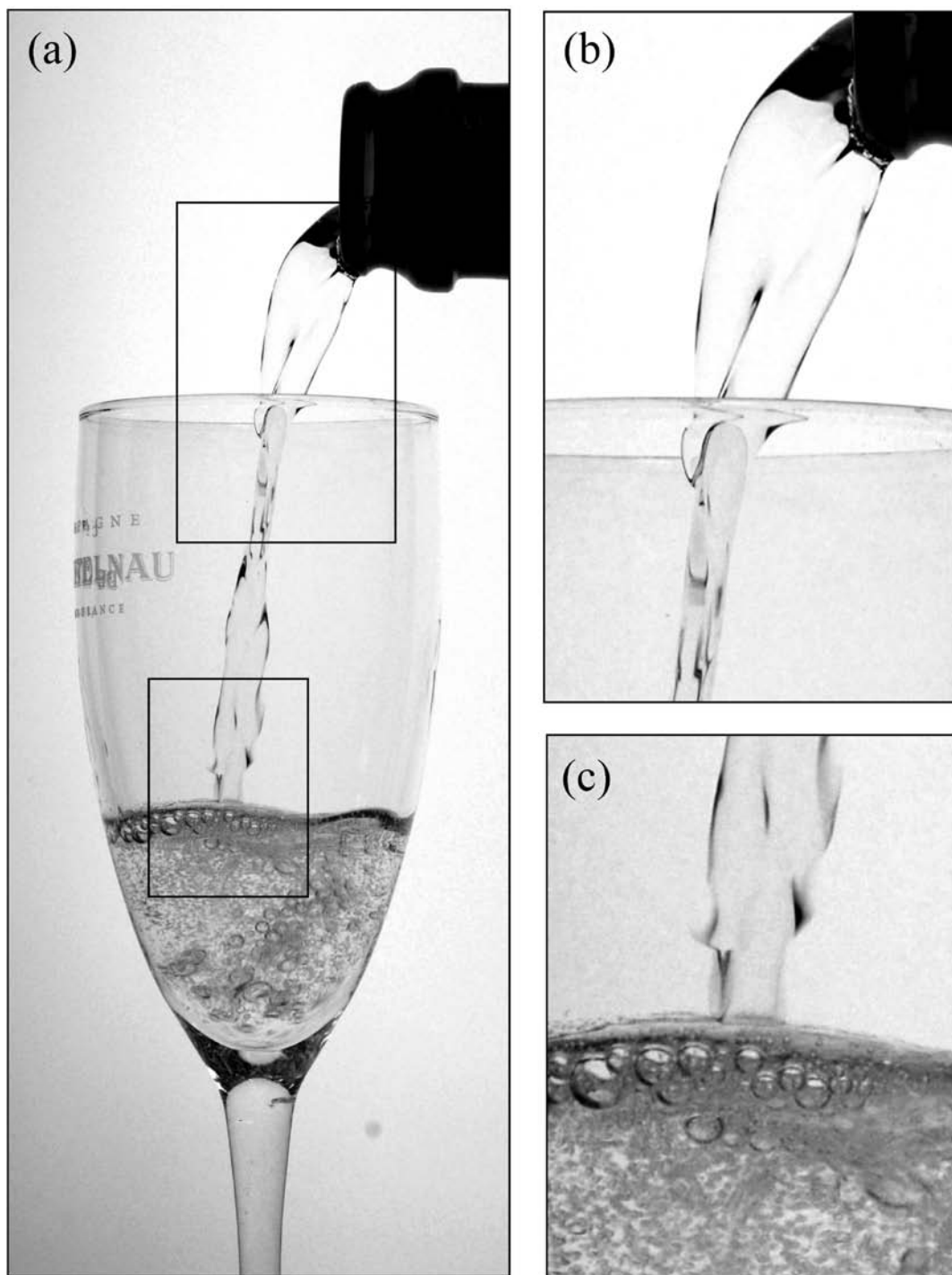


Figure 1. Closeup of the pouring step (a), which is characterized by a champagne “tongue” flowing from the bottle’s neck (b), and by turbulence and air bubble entrapment as champagne impacts the bottom of the flute (c). (Photography by Gérard Liger-Belair.)

paper for example, the role of temperature on the kinetics of CO_2 fluxes outgassing from a champagne flute was investigated (12). Very recently also, kinetics of CO_2 fluxes outgassing from champagne were compared when champagne was served in a flute or in a coupe (13). Even more recently, the impact of champagne aging was examined (14). Nevertheless and to the best of our knowledge, the impact of the pouring step on the loss of dissolved CO_2 from champagne and sparkling wine was rather neglected up to now. During the pouring step, the free air/champagne interface indeed considerably increases. Actually, champagne flows from the bottle to the glass in the form of a liquid tongue which presents a very large interface with regard to its own volume, as illustrated

in **Figure 1**. Moreover, the pouring step is a hugely turbulent phase, with possible entrapment of air pockets inside the champagne, which also contribute to the diffusion of dissolved CO_2 from the champagne to the ambient air. Besides, champagne is strongly mixed during the pouring step, with the formation of eddies of various sizes in the liquid matrix, which also undoubtedly contribute to a significant loss of dissolved CO_2 . Suffice to say that pouring champagne into a glass is strongly suspected to be far from being consequenceless with regard to its concentration of dissolved CO_2 after pouring.

In this article, the impact of the pouring step on the loss of dissolved CO_2 from champagne was examined, depending on the

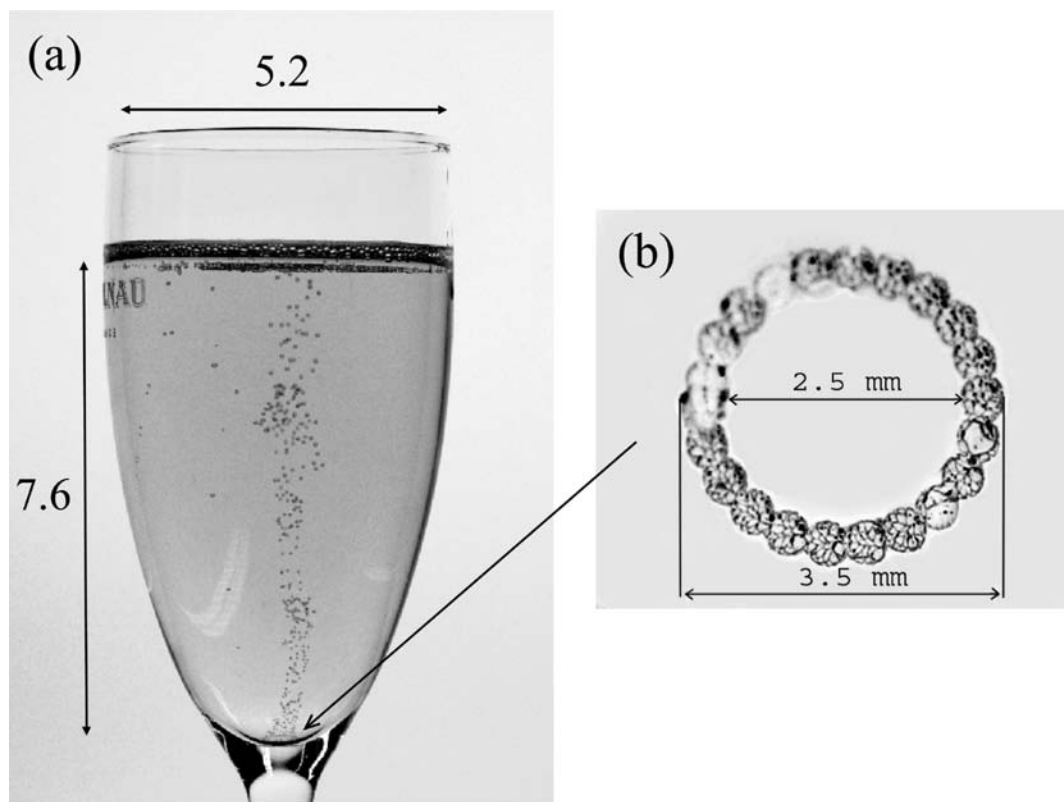


Figure 2. Radius of aperture and liquid level in the flute, once it is poured with 100 mL of champagne (characteristic dimensions are indicated in cm) (a); at the bottom of this flute, on its axis of symmetry, the glassmaker has engraved a small ring (done with adjoining laser beam impacts) to promote artificial and standardized effervescence (b).

way champagne is poured into the flute. Two ways of serving champagne were examined, i.e., (i) a standard champagne-like way (ii) and a standard beer-like way of serving. Impacts on the losses of dissolved CO_2 of three champagne service temperatures were also examined (i.e., 4 °C, 12 °C, and 18 °C, respectively). Moreover, a recently developed dynamic tracking technique using infrared thermography was also used in order to visualize the cloud of gaseous CO_2 which escapes during champagne serving (15).

MATERIALS AND METHODS

Some Physicochemical Parameters of Champagne. A standard commercial Champagne wine, recently elaborated with a blend of 100% chardonnay base wines (vintage 2008, Cooperative Nogent l'Abbesse, Marne, France), was used for this set of experiments. Since their elaboration, bottles were stored in a cool cellar, at 12 °C. Some classical physicochemical parameters of champagne samples were already determined at 20 °C, with samples of champagne first degassed (1). Its static surface tension, γ , was found to be of the order of 50 mN m^{-1} , and its density ρ was found to be very close to that of water, i.e., 10^3 kg m^{-3} .

In the range of usual champagne tasting temperature (varying from approximately 5 to 15 °C), both surface tension and the density of champagne are known to be very slightly temperature-dependent (1), contrary to its viscosity which is known to be strongly temperature-dependent. The temperature dependence of champagne, measured with a thermostatted Ubbelohde capillary viscosimeter (with a sample of champagne first degassed), was found to classically obey the following Arrhenius-like equation (16):

$$\eta(T) \approx 1.08 \times 10^{-4} \exp(2806/T) \quad (1)$$

where the dynamic viscosity η is expressed in mPa s, and the temperature T is expressed in K.

Flute and Its Washing Protocol. A classical flute, namely, a long-stemmed glass with a deep tapered bowl and a narrow aperture, was used

for this set of experiments. In order to avoid the randomly located bubbling environment inevitably provided in glasses showing natural effervescence, we decided to use a single standard flute engraved at its bottom (thus providing a standardized and artificial effervescence). Champagne was thus poured into a standard commercial flute engraved at its bottom with a characteristic ring-shaped structure, done with 22 laser impacts, such as the one used in recent papers (see Figure 2) (12–14, 17). Between the successive pouring and data recordings, the flute was systematically thoroughly washed in a dilute aqueous formic acid solution, rinsed using distilled water, and then compressed and air-dried. This drastic treatment forbids the formation of calcium carbonate crystals on the flute wall as well as the adsorption of any dust particle acting as natural bubble nucleation sites so that bubble nucleation is strictly restricted to ring-shaped engraving, thus providing a standardized effervescence. By pouring champagne into such glasses (standardized with regard to their bubbling behavior), differences in losses of dissolved CO_2 during champagne serving are therefore attributed only to the differences between both ways of serving champagne and between the various champagne temperatures. Before pouring champagne, glasses were stored at room temperature ($\approx 20 \pm 1$ °C).

Two Ways of Serving Champagne. After uncorking a bottle, two ways of serving 100 mL of champagne into the flute were examined with regard to their respective impacts on the losses of dissolved CO_2 : (i) a standard champagne-like and (ii) a standard beer-like way of serving.

- (i) During the standard champagne-like way of serving, champagne vertically falls and hits the bottom of the flute (thus usually providing a thick head of foam, which quickly vertically extends and then progressively collapses during serving). This way is the traditional way of serving champagne and sparkling wines in bars, clubs, and restaurants.
- (ii) During the beer-like way of serving, champagne flows along the inclined flute wall and progressively fills the flute. The axis of symmetry of the flute inevitably and progressively recovers its vertical position during serving. This beer-like way of serving champagne is less turbulent, with usually much less foam generation.

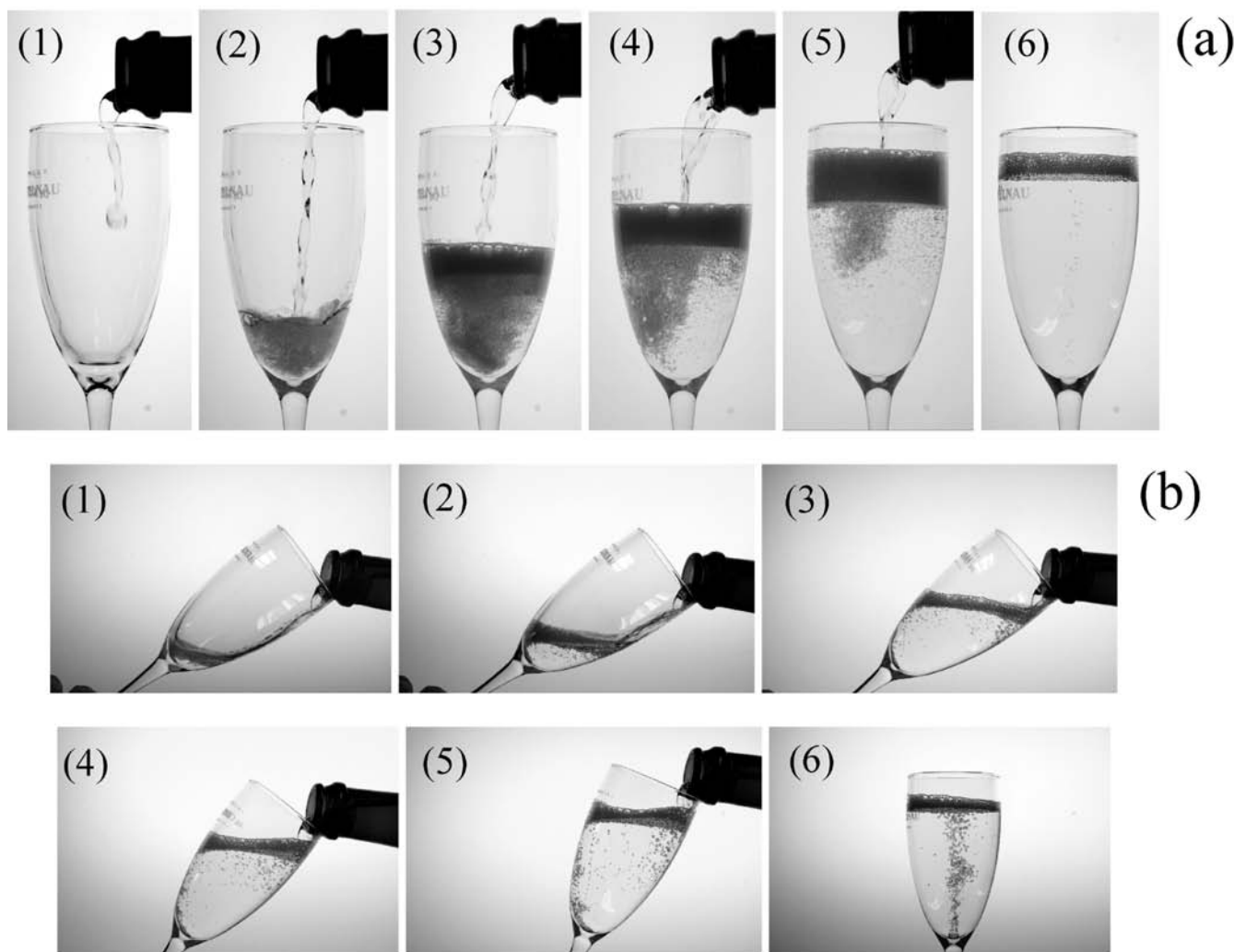


Figure 3. Time-sequences illustrating both ways of serving 100 mL of champagne into the flute: the champagne-like way of serving (this way is the traditional way of serving champagne and sparkling wines in bars, clubs, and restaurants) (a) and the beer-like way of serving, traditionally reserved for serving beer (to prevent an excessive formation of foam) (b). (Photography by Gérard Liger-Belair.)

Photographs displayed in **Figure 3** illustrate both ways of serving champagne into the flute. Impacts on the losses of dissolved CO_2 in champagne were investigated for three sets of champagne temperatures, i.e., 4 °C, 12 °C, and 18 °C, and for both ways of serving champagne. A volume of 100 ± 4 mL of champagne was carefully poured into the flute. It is worth noting that because the heat capacity of the glass ($\approx 0.8 \text{ kJ kg}^{-1} \text{ K}^{-1}$) is much lower than that of champagne ($\approx 4.2 \text{ kJ kg}^{-1} \text{ K}^{-1}$), the temperature of the champagne remains almost constant during the few seconds of the pouring process (18).

To enable a statistical treatment, four successive pouring and dissolved CO_2 measurements were done for both ways of serving champagne and for each champagne temperature. An arithmetic average of the four data provided by the four successive pourings were done to finally produce one single average dissolved CO_2 concentration corresponding to a given way of serving champagne at a given temperature (with standard deviations corresponding to the root-mean-square deviations of the values provided by the four successive pourings).

Measuring Concentrations of Dissolved CO_2 in Champagne Samples. Concentrations of dissolved CO_2 in champagne samples were determined using carbonic anhydrase (labeled C2522 Carbonic Anhydrase Isozyme II from bovine erythrocytes and provided by Sigma-Aldrich, USA). This is the official method recommended by the OIV (namely, the International Office of Vine and Wine) for measuring the dissolved CO_2 concentration in champagne and sparkling wines (19). This method is thoroughly detailed in a recent paper by Liger-Belair et al. (12). The initial concentration of dissolved CO_2 in bottles was carried out immediately after uncorking the bottle (to prevent a loss of dissolved CO_2 due to the

progressive and ineluctable diffusion once a bottle is uncorked). Exactly for the same reason, the concentration of dissolved CO_2 was also carried out immediately after having poured the 100 mL of champagne inside the flute.

Infrared Thermography Technique Used to Visualize the Gaseous Flow of CO_2 Escaping during Champagne Serving. A visualization technique based on the Infrared (IR) thermography principle has been used to film the gaseous CO_2 fluxes outgassing from champagne (invisible in the visible light spectrum) (20). The CO_2 absorptions observable by the IR camera are quite weak because this gas molecule has only a strong absorption peak in the detector bandwidth at $4.245 \mu\text{m}$. Consequently, the best way to visualize the flow of gaseous CO_2 desorbing from champagne is to fit the camera with a band-pass filter (centered on the CO_2 emission peak), as shown in a recent article (15). The experimental device consists of a CEDIP middlewaves Titanium HD560M IR video camera, coupled with a CO_2 filter ($\text{Ø } 50.8 \text{ mm} \times 1 \text{ mm}$ thick; Laser Components SAS). In complement, the technique involves an extended high-emissivity (0.97) blackbody (CI systems provided by POLYTEC PI), used at a controlled uniform temperature of 80 °C and placed approximately 30 cm behind the glass. The IR video camera was used at a 10 frames per second (fps) filming rate.

RESULTS

Initial Concentration of Dissolved CO_2 Inside the Bottles, after Uncorking but before Pouring. To enable a statistical treatment, four successive CO_2 -dissolved measurements were systematically

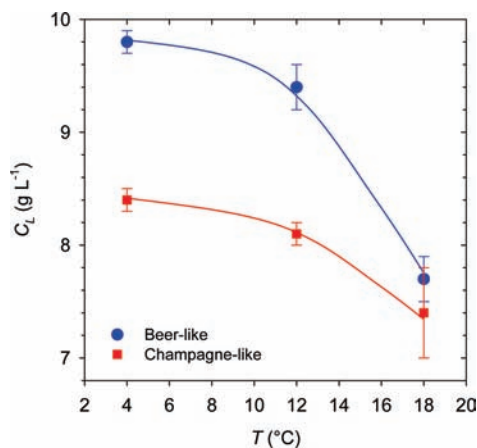


Figure 4. Concentrations of dissolved CO₂, as chemically measured once champagne was poured into the flute, for both ways of serving champagne and for each champagne temperature. Each data point is the arithmetic average of four successive values provided by four successive pourings (for both ways of serving champagne); standard deviations correspond to the root-mean-square deviations of the values provided by the four successive data recordings.

done on four distinct bottles by the use of carbonic anhydrase (just after uncorking a bottle, but before pouring). The champagne wine elaborated in 2008 was found to initially hold (before pouring) a concentration of CO₂-dissolved molecules of $c_i = 11.4 \pm 0.1 \text{ g L}^{-1}$. This average concentration of dissolved CO₂ is quite close to those found recently in others champagne samples, with the same technique (12–14), and with a nondestructive and unintrusive method based on a nuclear magnetic resonance technique (21).

Impacts on the Losses of Dissolved CO₂ of Both Ways of Serving Champagne and the Role of Temperature. Concentrations of dissolved CO₂ data, denoted as c_L , as chemically measured immediately after pouring champagne into the flute, are displayed in **Figure 4** (for both ways of serving and for each champagne temperature). It is clear from **Figure 4** that the higher the temperature of champagne, the lower its concentration of dissolved MCO₂ after pouring. Moreover, it also clearly appears that the beer-like way of serving champagne has a significantly less impact on its concentration of dissolved CO₂ after the pouring step.

It is worth noting that ambient air is considered as a huge thermal tank which quickly thermalizes the volume of gaseous CO₂ outgassing from champagne during the pouring step. Therefore, by considering the gaseous flux of CO₂ discharging from champagne as an ideal gas, the volume of gaseous CO₂ discharging during the pouring step, denoted as $V_{20^\circ\text{C}}$, is expressed as follows:

$$V_{20^\circ\text{C}} = \frac{\Delta c v_f RT}{M_{\text{CO}_2} P_0} \quad (2)$$

with Δc being the loss of dissolved CO₂ concentration during the pouring step (i.e., $\Delta c = c_i - c_L$, expressed in g L^{-1}), v_f being the volume of champagne poured into the flute (in L, namely, 0.1 L in the present case), R being the ideal gas constant ($8.31 \text{ J K}^{-1} \text{ mol}^{-1}$), T being the ambient temperature (in K, namely, 293 K in the present case), M_{CO_2} being the molar mass of CO₂ (44 g mol^{-1}), and P_0 being the atmospheric pressure (close to 10^5 Pa).

Besides, **Table 1** compiles the losses of dissolved CO₂ concentrations (with regard to the initial concentration before pouring) as well as the corresponding volume of gaseous CO₂ escaping during the pouring step. Recently, kinetics of the losses of dissolved CO₂ were done, for several champagne temperatures, during the first 10 min following pouring (12). It is worth noting

Table 1. Losses of Dissolved-CO₂ Concentrations in Champagne during the Pouring Step (in g L^{-1}) and Corresponding Volumes of Gaseous CO₂ Discharged from Champagne (Converted to cm^3) for Both Ways of Serving at Three Champagne Temperatures

temperature	champagne-like		beer-like	
	ΔC (g L^{-1})	V_{CO_2} (cm^3)	ΔC (g L^{-1})	V_{CO_2} (cm^3)
4 °C	3.0 ± 0.2	166 ± 11	1.6 ± 0.2	88 ± 11
12 °C	3.3 ± 0.2	182 ± 11	2.0 ± 0.3	110 ± 17
18 °C	4.0 ± 0.5	221 ± 28	3.7 ± 0.3	204 ± 17

that during the few seconds of the champagne-like way of serving, champagne loses approximately as much dissolved CO₂ as that during the first 10 min following pouring, thus confirming the role played by turbulence and by air entrapment with regard to gas discharging during the pouring step. To prolong the drink's chill and to help the champagne retain its CO₂ content (and therefore its effervescence), the champagne-like way of serving is certainly not the most appropriate.

Visualizing the Cloud of Gaseous CO₂ during the Pouring Step.

Time-sequences displayed in **Figures 5** and **6** illustrate the pouring steps, as seen through the objective of the IR video camera, for both ways of serving champagne (at 4 °C and at 18 °C, respectively). The higher the champagne temperature is, the more easily dissolved CO₂ escapes during the pouring process. The impact of temperature on the volume of gaseous CO₂ which escapes during the pouring step therefore clearly appears when filming it with the IR video camera, thus confirming the tendency underscored by the chemical measurements of losses of dissolved CO₂ after the pouring step (with both ways of serving champagne).

It is also worth noting that the flow of gaseous CO₂ escaping when pouring champagne seems to flow down from the opening of the flute, by licking the glass walls rather than by diffusing isotropically all around it. This observation betrays the fact that gaseous CO₂ is approximately 1.5 times denser ($\rho_{\text{CO}_2} = 1.87 \text{ g L}^{-1}$ at 20 °C) than dry air is ($\rho_{\text{air}} = 1.20 \text{ g L}^{-1}$ at 20 °C) and therefore tends to naturally flow down.

DISCUSSION

Molecular Mechanism Behind the Loss of Dissolved CO₂ during Serving. The principle behind the diffusion of gas species from a supersaturated liquid medium is the starting point of our discussion. Molecular diffusion is actually the mechanism behind the progressive desorption of dissolved gas species from the free surface area of a supersaturated liquid medium (as dissolved CO₂ molecules continuously do from the free air/champagne interface once the bottle is uncorked). The number of CO₂ moles that cross the air/champagne interface per unit of time is ruled by

$$\frac{dN}{dt} = \iint_{\text{air/champagne interface}} \vec{J} \times d\vec{S} \quad (3)$$

where \vec{J} is the flux of CO₂ molecules defined by first Fick's law, $\vec{J} = -D \times \nabla c$. In the latter equation, D is the diffusion coefficient of CO₂ molecules in the liquid matrix, and ∇c is the gradient of dissolved CO₂ molecules between the champagne bulk and the air/champagne interface in equilibrium with the gaseous CO₂ in the vapor phase outside the liquid phase.

By assuming a linear gradient of dissolved CO₂ between the champagne bulk and the air/champagne interface, ∇c may be rewritten as $\Delta c/\delta$, with δ being the thickness of the boundary layer where a gradient of dissolved CO₂ exists, and $\Delta c = c_L - c_i$ being the difference in dissolved CO₂ concentrations between the liquid bulk (denoted c_L) and the air/champagne interface

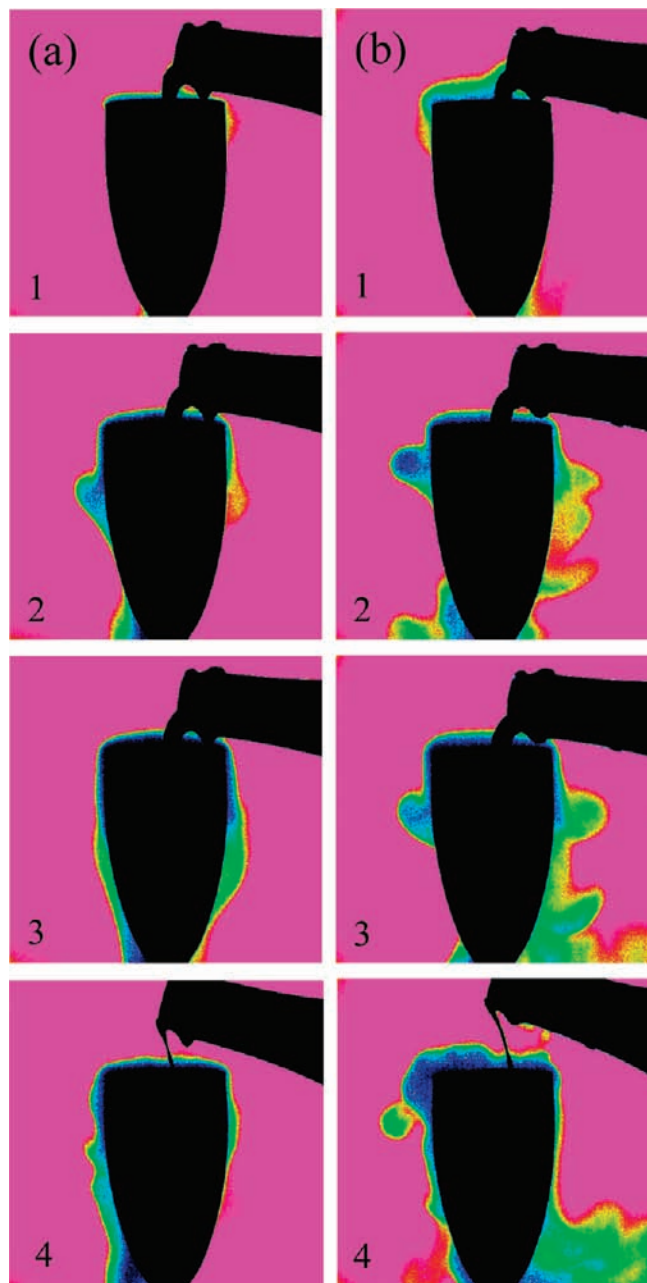


Figure 5. Time-sequences illustrating the champagne-like pouring step as seen through the objective of the IR video camera for a bottle stored at 4 °C (a) and for a bottle stored at 18 °C (b).

(denoted c_l) in equilibrium with the gaseous CO_2 in the vapor phase (see **Figure 7**).

Generally speaking, desorption of dissolved gas species is ruled by pure diffusion or by diffusion–convection, whether the supersaturated liquid medium is perfectly stagnant or in motion (22). In a purely diffusive case, a boundary layer depleted with dissolved gas molecules progressively expands near the free surface area, i.e., δ progressively increases, so that the diffusion of gas species outgassing from the liquid medium inexorably and quickly slows down. In the case of a liquid medium agitated with flow patterns, convection forbids the growth of the diffusion boundary layer by supplying the liquid near the free surface area with dissolved gas molecules freshly renewed from the liquid bulk (22). Generally speaking, the higher the velocity of the mixing flow patterns, the thinner the thickness of the diffusion boundary layer, and, finally, the higher the volume fluxes of gas species outgassing from the

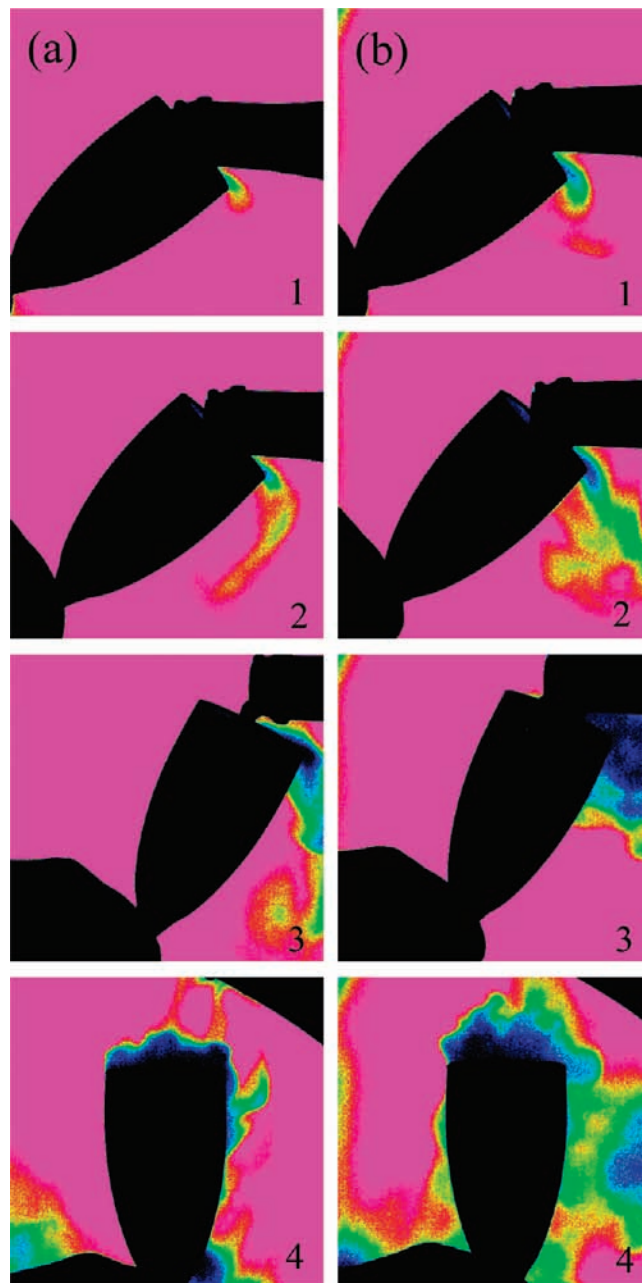


Figure 6. Time-sequences illustrating the beer-like pouring step as seen through the objective of the IR video camera for a bottle stored at 4 °C (a) and for a bottle stored at 18 °C (b).

supersaturated liquid medium. Pouring champagne into a flute is a hugely turbulent phase which induces the formation of various eddies and convection currents through the liquid phase. Therefore, the mechanism behind the loss of dissolved CO_2 molecules from champagne during the pouring step is undoubtedly ruled by diffusion–convection.

Role of Temperature. It clearly appears from **Table 1** that, the higher the temperature of champagne, the higher its loss of dissolved CO_2 during the pouring step. Why such a dependence?

The diffusion coefficient of the CO_2 molecule denoted as D , which rules the diffusion rate through the air/champagne interface as seen in eq 3, is strongly temperature-dependent. Actually, D may be derived through the well-known Stokes–Einstein equation as follows:

$$D \approx \frac{k_B T}{6\pi\eta a} \quad (4)$$

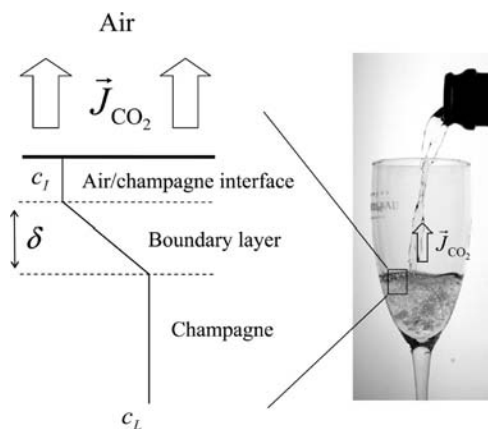


Figure 7. Details of the air/champagne boundary layer where a gradient of dissolved CO₂ exists; turbulence of the pouring process impacts the thickness of the boundary layer and therefore the flux of dissolved CO₂ diffusing from the air/champagne interface.

with k_B being the Boltzmann constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$) and a being the characteristic size of the CO₂ molecule's hydrodynamic radius ($a \approx 10^{-10} \text{ m}$).

It is worth noting that since the viscosity of champagne is strongly temperature-dependent, as seen in eq 1, the diffusion coefficient of dissolved CO₂ molecules is also in turn strongly temperature-dependent. By combining eqs 1 and 4, D may be rewritten as follows:

$$D \propto T \exp\left(-\frac{2806}{T}\right) \quad (5)$$

Following eq 5, the lower the champagne temperature is, the lower the diffusion coefficient of dissolved CO₂ molecules. Therefore, it is no wonder that the lower the champagne temperature is, the lower the loss of dissolved CO₂ during the pouring step, as reported in **Table 1**.

Besides, since the lower the champagne temperature the higher its viscosity, the flow patterns induced by turbulences of the pouring step certainly calm down more rapidly (by viscous dissipation) at low champagne temperatures, thus limiting also the loss of dissolved CO₂ molecules by diffusion through the air/champagne interface.

Role of Both Ways of Serving Champagne. As clearly seen in **Figure 4**, the beer-like way of serving champagne has much less of impact on its dissolved CO₂ concentration than the champagne-like way of serving, especially at low champagne temperatures (4 and 12 °C). The beer-like way of serving champagne is much softer than the champagne-like one. Turbulences in the flute are therefore expected to be much less important during the pouring step in case of the beer-like way of serving, thus reducing in turn the loss of dissolved CO₂ molecules by diffusion–convection in comparison with the champagne-like way of serving champagne. Moreover, turbulences being less important during the beer-like way of serving, the champagne is supposed to calm down even more rapidly at low champagne temperatures (by viscous dissipation), thus explaining the rather low loss of dissolved CO₂ during the beer-like way of serving (at low temperatures) compared with the champagne-like one. Therefore, the gap in the loss of dissolved CO₂ between 12 and 18 °C, for both ways of serving champagne (as seen in **Table 1** and in **Figure 4**), is interpreted as an effect of the lower viscosity of champagne at 18 °C.

In conclusion, measurements of the losses of dissolved CO₂ during champagne serving were done, at three champagne temperatures, and for two various ways of serving (i.e., a

champagne-like and a beer-like way of serving). The champagne-like way of serving was found to significantly impact its loss of dissolved CO₂ than the beer-like one. In light of these analytical results, since dissolved CO₂ is known to be of great importance in champagne and sparkling wine tasting, would not it be pertinent to revisit the way champagne should be served and especially when champagne and sparkling wines are to be compared in competitions?

Moreover, the higher the champagne temperature is, the higher its loss of dissolved CO₂ during the pouring process. The diffusion coefficient of CO₂ molecules and the champagne viscosity, both being strongly temperature-dependent, are suspected to be the two main parameters responsible for such experimental differences. Besides, a recently developed dynamic-tracking technique using IR thermography was also used in order to visualize the cloud of gaseous CO₂, which flows out of champagne, thus visually confirming the influence of temperature on its loss of dissolved CO₂. A complete mathematical model which includes the multiple ways of CO₂ discharge during the pouring process is indeed under construction.

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