



## The Role of Glass Shapes on the Release of Dissolved CO<sub>2</sub> in Effervescent Wine

BEAUMONT FABIEN,<sup>1\*</sup> CILINDRE CLARA,<sup>2</sup> ABDI ELLIE,<sup>3</sup>  
MAMAN MARJORIE,<sup>4</sup> and POLIDORI GUILLAUME<sup>1</sup>

<sup>1</sup>GRESPI EA 4694, Université de Reims, 51687 Reims Cedex 2, France.

<sup>2</sup>GSMA, UMR CNRS 7331, Université de Reims, 51687 Reims Cedex 2, France.

<sup>3</sup>Montclair State University, Center of Pedagogy, New Jersey, USA.

<sup>4</sup>Jérôme Lohez Scholarship Foundation 124 W 60th Street, NY 10023, USA.

### Abstract

This study is based on the findings that a glass of sparkling wine that releases its dissolved CO<sub>2</sub> too quickly will see the effervescence and aromas carried by the bubble disappear prematurely. Thus, a thorough knowledge of the processes related to the release of gaseous CO<sub>2</sub> is fundamental for the consumer as well as the oenologist or the glassmaker. In this study, the contribution of the glass shape on the gradual release of dissolved carbon dioxide was assessed during the first ten minutes following the pouring process. Measurements carried out on 4 glasses showed that for the same quantity of wine and under identical tasting conditions, the dissolved CO<sub>2</sub> concentration evolved differently from one glass shape to another. The results showed that in the first 10 minutes after the pouring process, INAO glass loses 34% of its initial dissolved CO<sub>2</sub> concentration compared to 58% for the flute "effervescent". Ultimately, these results demonstrate the existence of a close link between the glass shape and the amount of dissolved CO<sub>2</sub> which is the main parameter in the tasting of sparkling wine. The link between the amount of dissolved gas, the glass shape and the release of aromas from the wine is a huge challenge which will be the subject of future studies.



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### Introduction


Most of the scientific studies on the role of the glass during a tasting have been implemented over the

past two decades. The role of the glass on the aromatic perception has resulted in numerous publications.<sup>1,2,3</sup> Most authors have focused on the

**CONTACT** Beaumont Fabien ✉ [fabien.beaumont@univ-reims.fr](mailto:fabien.beaumont@univ-reims.fr) 📍 GRESPI EA 4694, Université de Reims, 51687 Reims Cedex 2, France.



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impact of the glass shapes to evaluate the perception of flavors in flat wines.<sup>4,5,6</sup> As expected, the shape of the glass influences the perception of the wine although the discrepancies are quite limited. Hirson *et al.*,<sup>7</sup> found that the differences were accentuated after 5 and 10 minutes, time necessary to establish a balance between aromatics in the wine. Among the tested glasses, we can find the international Standards Organization (ISO) wine-tasting glass (also called INAO glass) which is very suitable for red and white wine. This glass has also improved color discrimination by maximizing the depth of the wine in relation to volume.<sup>8</sup> Other authors have been interested in the physicochemistry of wine, which is intimately linked to aromatic perception. In a study, Arakawa *et al.*,<sup>9</sup> developed an experimental method for visualizing the ethanol that escaped from a flat wine during tasting. The investigation showed that the shape of the ethanol cloud depended on the shape of the glass. The release of carbon dioxide which causes the birth of the bubbles in sparkling wines also remains the subject of several studies.

Marchal, Rondot, & Thuillier<sup>10</sup> have published an article on the influence of carbon dioxide and serving conditions on the sensory perception of sparkling wines. Alongside, Liger-Belair *et al.*,<sup>11,12</sup> have considered the role of the glass on the gradual release of carbon dioxide and ethanol during tasting. In another analysis, Liger-Belair *et al.*,<sup>13</sup> measured CO<sub>2</sub> losses during the pouring process and analyzed how wines need to be served. Other researchers have considered the CO<sub>2</sub> perception and its influence on flavor.<sup>14,15,16</sup> It was evidenced that CO<sub>2</sub> can neutralize odor perception and cause a pungent sensation in the nose.<sup>17</sup> However, its sparging action potentially increases the release and accumulation of aromatic compounds in the head space above the wine.<sup>4</sup>

In a study, Pron *et al.*,<sup>18</sup> used infrared imaging techniques to visualize CO<sub>2</sub> fluxes in sparkling wines. Controlling and monitoring the intensity of the effervescence was also performed through the development of specific glasses.<sup>19</sup> Furthermore, the knowledge of the parameters that affect or favor the nucleation of bubbles was discovered.<sup>20</sup> Although bubbles are suspected of promoting aromatic exhalation, no scientific studies have supported this hypothesis until 2009 when Liger-Belair *et*

*al.*,<sup>21</sup> have used the Munich's high-resolution mass spectrometer to analyze non-targeted compounds preferentially found in champagne droplets. It has been found that the aerosol formed during the bursting of the bubbles on the surface of the champagne is more concentrated in aromatic molecules than the wine itself.<sup>21</sup> After analysis, the scientists showed that this aerosol is much more concentrated - sometimes up to 30 times more - in several tens of organoleptic molecules than the wine in the heart of the flute. Among these molecules, the fatty acids, terpene compounds and other molecules involved in the flavor of the wine were found. Note that the mechanism that was identified to concentrate the aromas considered agreeable by a taster, but also the herbaceous or unpleasant aromas.<sup>22</sup> These unprecedented results clearly demonstrate the link between bubble bursting and the release of aromatic compounds from wine. Thus, the taste of a sparkling wine resulted from the complex interaction between the dissolved CO<sub>2</sub> content and the aromatic compounds - known as volatile organic compounds (VOCs) - dispersed in bubbles. In recent studies, it has been shown that carbonation increases the release of flavors from sparkling water.<sup>23,24</sup> These results suggest a strong causal link between the amount of dissolved CO<sub>2</sub>, which evolves according to several parameters, and the release of volatile aromatic compounds from the wine.

When choosing a tasting glass, the amount of CO<sub>2</sub> released over time is rarely the criterion that is put forward. What the consumer or oenologist is looking for is a glass that will promote firstly a lasting effervescence which is associated to a good wine in collective imaginary. The purpose of this study was to highlight differences, particularly in the gaseous phase, between tasting glasses. Knowing the close link between the amount of CO<sub>2</sub> and the effervescence process, a strong hypothesis is that aromatic perception is greatly influenced by the shape of the glass. Many publications have dealt with the subject, but few scientific studies have linked the glass shape with aromatic perception and/or degassing in sparkling wines. While the choice of glass is specific to each consumer, it is also intrinsically linked to our vision of champagne: a harmonious and lasting effervescence. This study is based on the observation that a glass

that releases its dissolved gas too quickly will see the effervescence and the aromas carried by the bubble disappear too quickly. The aim of this study is to determine the role of the glass shape (glasses distributed in supermarkets such as the coupe or the flute or intended for professionals such as INAO glass) on the kinetic of release of CO<sub>2</sub> once the wine is poured into the glass. The first results of the measurements carried out on four different glass shapes along with the methodology used in this study are described in the article.

### Materials and Methods

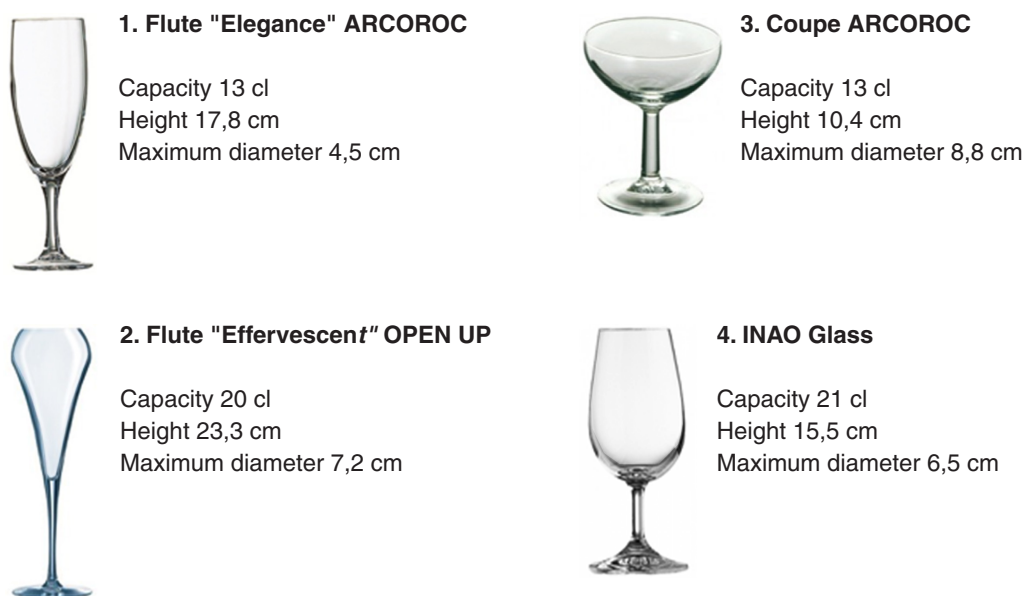
A sparkling wine was used, the initial concentration of dissolved CO<sub>2</sub> molecules was determined using carbonic anhydrase. This method is advisable by the International Bureau of Wine and Vine (OIV) to measure the CO<sub>2</sub> concentration in champagne and sparkling wines. 25 Successive measurements performed on six distinct bottles lead to an average content in dissolved CO<sub>2</sub> molecules of 7.45 g/l. In addition, the viscosity of the sparkling wine was similar to a standard champagne ( ). The four glasses of our study were filled with 10 cl of sparkling wine, they all have different shapes and filling heights (tables 1 and figure 1). It is worth noting that 100 ml does not correspond to the volume of wine poured into glasses during professional tasting sessions.

In order to guarantee optimal reproducibility of the measurements, each glass types were identically engraved on their bottom. More details on the bubble production processes are given in a previous paper.<sup>26</sup>

### Experimental Set-up

Similar conditions of effervescence must be ensured from one measure to another. In order to remove any dust which could generate an undesirable parasitic nucleation site (bubbles released from the glass wall and not from the bottom of the glass) that would prohibit the replication of the experiment, each glass was cleaned before each series of measurements. With such a protocol, the nucleation of CO<sub>2</sub> bubbles was strictly limited to the bottom of the glass. The glasses were cleaned with a mixture of formic acid and distilled water and then rinsed with alcohol. This process is fully described in the article by Liger Belair *et al.*<sup>11</sup> A sparkling wine bottle was opened for each measurement in order to keep an identical dissolved CO<sub>2</sub> concentration from one experiment to another. For each series of measurements (i.e. filling a glass with 100 ml of wine from an unopened bottle) the number of "parasitic" sites located outside the central bubble column was counted.

If there were more than 3 to 4 parasitic nucleation sites, the series of measurements was considered



**Fig. 1: Dimensional characteristics of the glasses**

invalid and the glass returned to the cleaning phase. The experimental tests consisted in recording the evolution in time of the liquid's mass contained in a glass using an ultra-sensitive balance. Once the wine was poured, the vessel was carefully positioned on the base plate of the weighing chamber of a high-precision balance (Denver Instrument PI 314 with a total capacity of 310 g and a standard deviation of +/- 0.1 mg). The timer was started and progressive weight loss was measured during the first ten minutes followed by the pouring process. The precision balance was interfaced with a laptop computer that measured and recorded the liquid's mass every five seconds. An average and a standard deviation were calculated from several series of measurements. Four successive measurements were carried out for each type of drinking container.

**Results and Discussion**

**Impact of glass shape on the loss of dissolved CO<sub>2</sub> concentration over time**

The dissolved CO<sub>2</sub> contents measured using the OIV method immediately after the pouring process into each of the glasses are shown in Table 1. The concentration of CO<sub>2</sub> dissolved molecules was slightly different from one glass to another. Once poured into the glass, the wine no longer contain as much dissolved CO<sub>2</sub> in reason of the turbulence of the pouring process whose intensity depend according to the glass shape. Depending on the glass, between 0.5 and more than 1 g/l of dissolved CO<sub>2</sub> escaped during the pouring process and were definitively lost.<sup>13</sup>

The mass transfer between the liquid, gaseous and atmospheric phases resulted in a progressive mass loss which were measured by micro-weighing.<sup>11</sup> These measurements will enable to determine the total CO<sub>2</sub> volume flux F<sub>T</sub>. This characterized the gas release intensity, specific to each glass shape. For each glass, four successive micro-weighing were carried out. The measurements were obtained from four successive pouring and allowed to deduce the average mass loss for each of the glasses. Cumulative mass loss is the combination of liquid evaporation, bubble bursting and the release of CO<sub>2</sub> through a diffusion process. The mass loss due to evaporation of the liquid can be determined by measuring the mass loss for each glass filled with 100 ml of previously degassed wine. Thus, the cumulative mass loss due to CO<sub>2</sub> desorption can be obtained by subtracting the mass loss due to evaporation from the cumulative mass loss (evaporation + CO<sub>2</sub> desorption). In oenology, a characteristic parameter of a sparkling wine is the concentration of dissolved CO<sub>2</sub>.<sup>27</sup> This is expressed in g/l and is given by the following relationship:

$$C_L(t) = C_i - \frac{m(t)}{V_l} \quad \dots(1)$$

Where Ci is the initial concentration of CO<sub>2</sub> dissolved in wine (measured once the wine has been poured into the glass), m(t) is the cumulative CO<sub>2</sub> mass loss over time expressed in g, and V<sub>l</sub> corresponds to the volume of wine poured into the glass, in this case

**Table 1: Pertinent parameter linked with each glass shape filled with 100 ml of sparkling wine. Initial concentration in dissolved CO<sub>2</sub> is the average of two successive measurements**

Glass Shape	Liquid level after pouring, h (in mm)	Radius of aperture of the glass, r (in mm)	Surface area offered to gas discharge, A (in cm <sup>2</sup> )	Initial concentration in dissolved CO <sub>2</sub> , (in g.l-1)
Flute << Elegance >>	94	42	13.8	6.29 ± 0.01
Flute << Effervescent >>	99	72	40.7	6.86 ± 0.31
Coupe	29	86	58	6.98 ± 0.18
INAO Glass	43	61	29.2	6.68 ± 0. 75

0.1 I. The evolution of dissolved gas concentration CL (g/l) is shown in Figure 2.

In a sparkling wine glass, carbon dioxide is evacuated in two forms: first, the nucleation in the form of bubbles and second, the molecular diffusion at the air/liquid interface (invisible to the naked eye). In addition, during their migration towards the surface, the bubbles put the liquid in motion by a viscous driving process. This movement, totally invisible to the naked eye but revealed by laser tomography,<sup>28</sup> will allow a continuous mixing of the wine which will accelerate the discharge of CO<sub>2</sub> by a diffusion process.

In previous experimental studies, we have shown that the bubble induced flow patterns is closely linked to the shape of the glass<sup>25</sup> and participates widely to the release of dissolved CO<sub>2</sub> by a diffusion process. The results in Figure 2 suggest that the shape of the glass is significant regarding the kinetics of CO<sub>2</sub> release, although this is not conclusive in the first moments after pouring. It is obvious that for the same quantity of wine and under the same tasting conditions, the differences are important. The purpose of this study is to describe each of the parameters involved in the release of CO<sub>2</sub> over time.

**CO<sub>2</sub> Volume Fluxes Released from each Glass**

The most relevant parameter for characterizing the gradual release of gaseous CO<sub>2</sub> from a glass

of sparkling wine during a tasting is the total CO<sub>2</sub> volume flux.<sup>29</sup> The Total CO<sub>2</sub> volume fluxes, denoted FT (cm<sup>3</sup>/s), was the sum of two terms: the loss due to CO<sub>2</sub> volume flux liberated by the bubbles, denoted F<sub>B</sub>, and the CO<sub>2</sub> volume fluxes discharged by diffusion through the free surface area denoted F<sub>S</sub>.

Finally, total CO<sub>2</sub> volume fluxes released from a glass of sparkling wine during a tasting can be expressed as:

$$F_T \approx F_B + F_S \quad \dots(2)$$

and

$$F_T = \left( \frac{RT}{MP} \right) \frac{\Delta m}{\Delta t} \quad \dots(3)$$

R is the ideal gas constant (equal to 8.31 J/K/mol), T is the wine temperature (K), M is the molar mass of CO<sub>2</sub> (44 g/mol), P represent the ambient pressure (close to 10<sup>5</sup> N/m<sup>2</sup>), the mass loss Δ<sub>m</sub> between two consecutive data being expressed in g, and Δ<sub>t</sub> being the time period from one data record to the next (i.e. 5s in our study).

The total volume fluxes of CO<sub>2</sub> released at the air/wine interface of a glass of sparkling wine during the first 10 minutes following the pouring process are shown in Figure 3, results are derived from equation (3). As shown in Figure 3, one can state

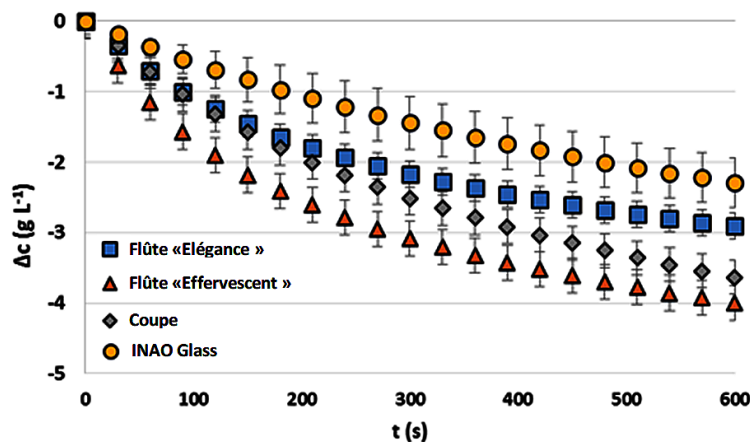


Fig. 2: Gradual loss of the dissolved CO<sub>2</sub> concentrations (g/l) as determined by equation (1) over the first ten minutes following the pouring process; each data in each time series is the arithmetic average of four successive data resulting from four successive pourings; the standard deviations represent the root mean square deviations of the values from the four successive data records

that the total CO<sub>2</sub> volume fluxes varied greatly from one glass to another. In addition, it should be noted that the "effervescent" glass releases more dissolved gas than the other glasses within the first 4 minutes following the pouring process. It is worth noting that in this glass, the total CO<sub>2</sub> volume flux was divided by ten during the first ten minutes after the pouring process. By comparison, the total CO<sub>2</sub> volume flux was divided by 3.5 for INAO glass which releases its dissolved gas much more slowly. These results were noteworthy because they clearly demonstrated that depending on the glass' shapes, the gas is not released with the same intensity although this observation is only valid in the first moments following the pouring process. It was demonstrated that the volume of CO<sub>2</sub> released by the bubbles was proportional to the filling height h. The relationship between the CO<sub>2</sub> flux released by the bubbles FB (cm<sup>3</sup>/s) and the filling height h is given by Liger Belair, Parmentier, & Jeandet<sup>29</sup>:

$$F_B = Nfv \approx \frac{Nfd^3}{2} \approx 9,7 \times 10^{-15} N \frac{T^{\frac{11}{2}}}{\eta} \left(\frac{1}{\rho g}\right)^{2/3} \left(\frac{C_L - k_H P}{P}\right) h \dots(4)$$

f is the frequency of bubble generation from a single nucleation site (s<sup>-1</sup>), d is the diameter of a bubble (cm) and v its volume (m<sup>3</sup>), T is the wine temperature

(K), N is the number of nucleation site, h is the liquid height (m), C<sub>L</sub> is the concentration of dissolved CO<sub>2</sub> in the wine (g/l), k<sub>H</sub> is the Henry constant (kg/m<sup>3</sup>/atm), P is the ambient pressure (atm), ρ is the liquid density (kg/m<sup>3</sup>) and g is the gravity (m/s<sup>2</sup>).

The equation (4) allows us to deduce that the higher the filling height, the higher the CO<sub>2</sub> flux released by the bubbles increases (bubble growth proportional to the power 1/3 of the distance travelled). It is interesting to note that the size of the bubbles will have an impact on the flow of CO<sub>2</sub> released by the bubbles but also on the diffusion of this same gas at the air/wine interface. The laws of physics indicate that there is a correlation between the velocity of the mixing processes in a liquid supersaturated with carbon dioxide and the rate of diffusion of this gas released to the surface. Since the velocity of these mixing processes is dependent on that of the bubbles, a strong hypothesis is that the release of CO<sub>2</sub> at the air/liquid interface will be accelerated by the swirling motion of the liquid in glasses with a high filling height (glasses "Elegance" and "Effervescence").

**Diffusive CO<sub>2</sub> Volume Flux**

The diffusive volume flux of CO<sub>2</sub> called FS (cm<sup>3</sup>/s) represents the volume flux of CO<sub>2</sub> released by

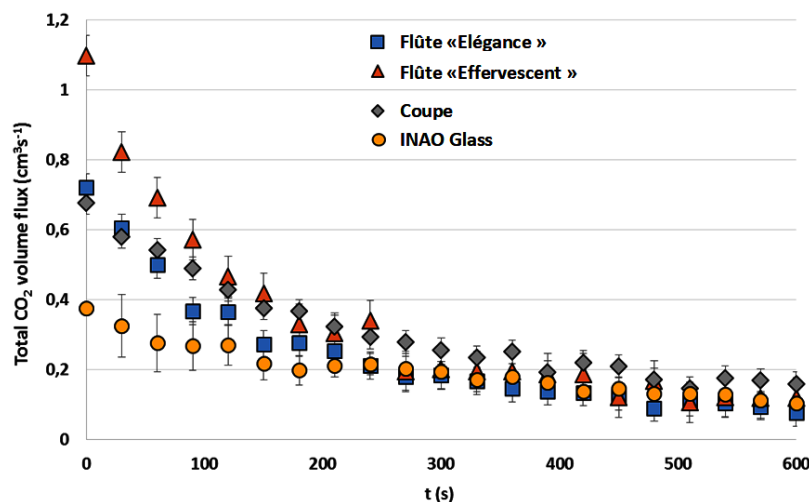


Fig. 3: Total CO<sub>2</sub> volume fluxes recordings (cm<sup>3</sup> s<sup>-1</sup>) as determined with equation (3), desorbing from each glass shape respectively filled with 100 mL of effervescent wine, all along the first ten minutes following the pouring process; each data in each time series is the arithmetic average of four successive data resulting from four successive pourings; the standard deviations represent the root mean square deviations of the values from the four successive data records



diffusion at the air/wine interface. To obtain the diffusive flow of CO<sub>2</sub> released at the air/liquid interface, simply subtract the flux of CO<sub>2</sub> released by the bubbles  $F_B$  from the total flux  $F_T$ :

$$F_S = F_T - F_B \quad \dots(5)$$

Knowing the CO<sub>2</sub> volume fluxes released by the diffusion process and by the bursting of bubbles, it is possible to represent on the same graph (Figure 4) the part corresponding to each of the fluxes  $F_B$  and  $F_S$ . The part relating to the diffusive flux of CO<sub>2</sub>  $F_S$  are represented in orange on figure 4. It also indicates the percentage it represents in relation to the total volume flux of CO<sub>2</sub>.

The results of Fig. 4 indicate that the ratio between the two fluxes  $F_S$  and  $F_B$  varies greatly depending on the glass. The results show us that the diffusive flux  $F_S$  depends on the area of the air/wine interface of each glass. Thus, in view of Table 1 and to the features of each glass, it is noticeable that the coupe has the largest exchange area (58 cm<sup>2</sup>) and the lowest filling height (29 mm). For the coupe, gas release is made easier by the great interface area.<sup>11</sup> Furthermore, the bubbles do not grow in size due to the low filling height. The "effervescent" flute has a large exchange area (40 cm<sup>2</sup>) and a high filling height (99 mm). This is why this glass has the highest cumulative losses. The "elegance" flute and the INAO

glass show an identical trend with about 1/4 of the total CO<sub>2</sub> volume flux released by effervescence, the rest being released by diffusion.

### Role of CO<sub>2</sub> During a Tasting

In the mouth, in addition to the mechanical action linked to the bubbles bursting, CO<sub>2</sub> exerts a chemical sting, totally independent of the bursting of the bubbles.<sup>21</sup> The dissolved CO<sub>2</sub> activates biochemical detectors, enzymes, contained in acid-flavored receptor cells. The dissolved CO<sub>2</sub> thus causes a chemical sting which would participate in large part in the mouthfeel. The hypothesis is that the stinging sensation experienced during a tasting will be accentuated in a glass that has both an exchange area (interface air/wine) and a narrow opening diameter (Flute "Elegance" and INAO glass). It should be noted that an excess of gaseous CO<sub>2</sub> can cause a highly unpleasant tingling sensation.<sup>15</sup> On the other hand, a glass that has an exchange area and a larger opening will allow the CO<sub>2</sub> to be diluted on the free surface (coupe) but will consequently promote degassing by diffusion. The opening is also important because by being tightened, it will trap CO<sub>2</sub> which is 1.5 times denser than air. This is the case with the "Flute effervescent", which has a large exchange surface area and a tightened opening diameter. Many studies conducted over years reported a strong link between the amount of dissolved CO<sub>2</sub>, and the release of aromas from

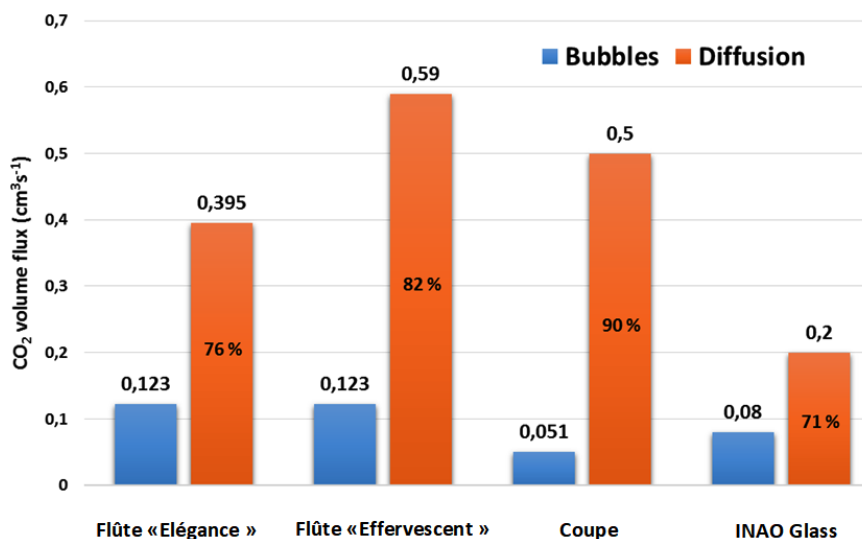


Fig. 4: flux released by bubbles  $F_B$  and by diffusion at the surface  $F_S$ , within following the pouring process, diffusion flux at the surface  $F_S$  expressed in % of the CO<sub>2</sub> total flux  $F_T$

the wine.<sup>23,24</sup> This suggests that some glass shapes facilitate the release of flavors. This strong hypothesis remains to be confirmed and will be the subject of future studies aimed at validating the link between the release of aromatic compounds from wine and the shape of the glass.

### Conclusion

This study focused on how the glass shapes can affect the gradual release of the Carbon Dioxide during the tasting. Measurements have been completed in individual tasting conditions and at room temperature on 4 glasses of different shapes filled with 100 ml of sparkling wine. Measurements have shown that INAO glass releases its dissolved gas more slowly than the other glasses studied with a 34% loss of its initial dissolved CO<sub>2</sub> concentration in the first ten minutes following the pouring process. This is the first analytical proof that this glass shape will retain its effervescence and potentially the aromas carried by the bubbles longer than the other glasses studied. Conversely, in the same period of time, the flute "effervescent" lost nearly 60% of its initial dissolved CO<sub>2</sub> concentration. Moreover, in this glass, the total CO<sub>2</sub> volume flux released immediately after the pouring process was almost 3 times higher than in the INAO glass. In addition, the contribution of bubble bursting to the release kinetics of dissolved CO<sub>2</sub> was estimated from a mathematical model, as well as the part relating to diffusion at the free surface. Thus, due to its low filling height, in the "coupe" glass, the contribution of bubble bursting to

the total CO<sub>2</sub> volume flux was about 60% lower than that estimated in the "elegance" and "effervescent" glasses one minute after the pouring process. The part due to the release of CO<sub>2</sub> by a diffusion process at the free surface was also estimated for the four glasses studied. One minute following the pouring process, the coupe which have an exchange area of 58cm<sup>2</sup>, released 90% of its CO<sub>2</sub> content by a diffusion process. With regard to these results, it is asserted that a glass with both a high filling level and a wide exchange area as the flute « effervescent » will release its dissolved CO<sub>2</sub> content very quickly. In such a glass shape, the effervescence will disappear prematurely, which will certainly affect the sensory perception. Although specific to each consumer, the choice of glass is intrinsically linked to the image we have of champagne: a harmonious and long-lasting effervescence. Complementary studies will be necessary in order to determine the contribution of the glass shape on sensory and aroma perception during a tasting.

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### Conflict of interest

The authors declare that they don't have conflict of interest including any financial, personal or other relationships with other people or organizations that can influence their work.

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