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Ring Vortex Scenario in Engraved Champagne Glasses

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Abstract : The simple idea this study rests on is that one cannot be concerned by the bubbling and aromatic exhalation events in champagne tasting without being interested in the study of the flow mixing mechanisms inside the glass. Indeed, a key assumption is that a strong link of causality may exist between inherent liquid-phase flow structures due to bubble motion and the flavors exhalation process. This is the reason why, to underscore the impact of glass-shape and glass-engravement conditions on mixing flow phenomena, classical flow visualization techniques were used to capture fluid motion in traditional flutes and coupes poured with champagne. Laser tomography combined with fluorescent dyes and solid tracers have been used to give the quasi-instantaneous velocity field from which streamline patterns are deduced as well as the vorticity convection.

Keywords : Flow Visualization, Ring vortex, Champagne wine.

1. Introduction

Fine sparkling wines and champagne are particular in that they are the result of a two-step fermentation process. After completion of the first alcoholic fermentation, some flat champagne wine (base wine) is bottled and then a mixture of yeast and sugar is added. Consequently, a second fermentation starts inside the bottle as the yeast consumes the sugar, producing alcohol and a large amount of CO_2. This is the reason why champagne has high % of CO_2 dissolved and the finished champagne wine can be under as much as 5-6 atmospheres of pressure. The gas gushes out in the form of tiny CO_2 bubbles as the bottle is opened (Liger-Belair, 2004).

From consumers and winemakers as well, the role bubbles usually play in champagne tasting is to awake the sight sense. Indeed, the magic image of champagne is intrinsically linked to the bubbles which act like "chains of pearls" in the glass of champagne and look like discrete jewelleries; they create a cushion of bubbles on the surface. Beyond this first visual aspect, the informed consumer will associate to the bubble behaviour one of the main ways to extract flavors; this is because the aroma and bouquet of sparkling wines are CO2 propelled into your nose and mouth. What is unknown and which constitutes the aim of the present paper is the consequence of the bubble behaviour on the dynamics of the champagne inside the glass and consequently on the CO2 propelling process.

2. Controlled effervescence

Generally speaking, two ways exist and sometimes coexist to generate bubble chains in champagne glasses. A random manner depending on the more or less strong presence of residual individualized cellulose fibers is responsible for natural effervescence (Liger-Belair et al., 2005). In such a case, glass surface is considered as perfectly smooth without specific treatment. Those cellulose fibers are released from the surrounding air or from the towel used during the wiping process. They act as nucleation sites in champagne and have recently been identified as tiny micro-channels of cylindrical shape. More details about the bubble formation mechanism can be found in Liger-Belair (2005).

Because natural nucleation is a very random and not easily controllable process (Liger-Belair et al., 2007a), another way to generate bubbles is to consider a perfect artificial and mechanical process presenting the advantage of being perfectly reproducible from one filling to another (Liger-Belair et al., 2007b). This way consists in creating artificial nucleation sites by means, for example, of an impact laser technique applied at the glass bottom surface by glassmakers. With such treatments, glasses are called engraved ones. This engravement method is commonly used by the Champagne houses during tasting. A close-up detail of a laser impact is reported in Fig. 1a. Each point of impact has a diameter of about 400 µm. To make effervescence so pleasant-looking to the eye, no less than twenty impacts can be used, the whole being usually circular in shape (see Fig. 1b).

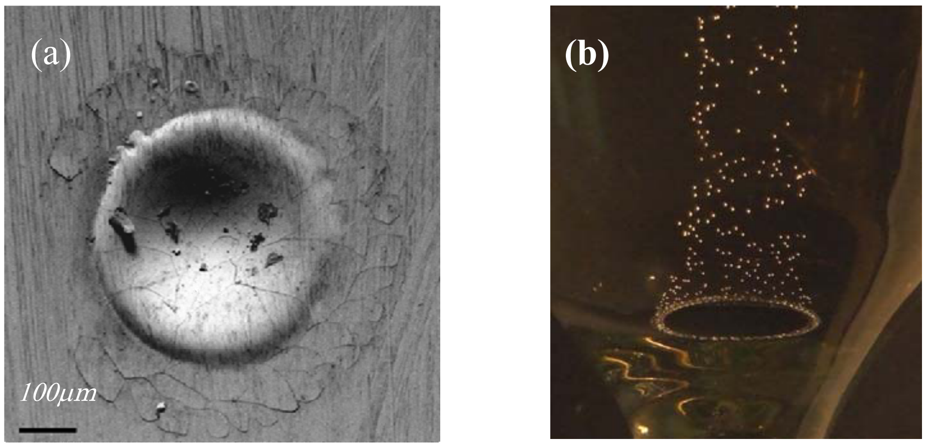

Fig. 1. Close-up detail of a laser impact (a); glass with an engraved circular crown (Polidori et al., 2008a)(b)

3. Experimental set-up

For the present study, we used engraved glasses at the bottom (see Fig. 1b), which is the most encountered situation, in order to highlight the strong effect played by bubbles on the whole flow dynamics. To reach the flow dynamics, the analysis is based on the laser tomography visualization technique (Merzkirch, 1987) associated with adequate tracers. Filling experiments have been carried out at room temperature to avoid damaging condensation on the glass surface. Once poured with champagne, the glass is lighted in its symmetry plane with a 1mm planar argon laser sheet (see Fig. 2).

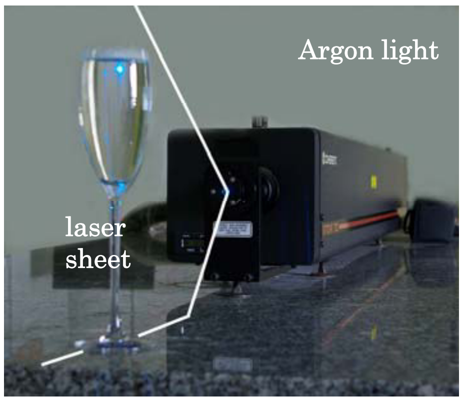

Fig. 2. Experimental set-up

Because glasses are circularly engraved at their bottom, the resulting flow exhibits an axisymmetrical behaviour as will be seen further. In this situation, a 2D examination in the axisymmetry plane can be considered as sufficient to investigate the whole 3D flow. Two types of tracers have been used. The first one is Rilsan particles having a density (d=1.060) approaching that of Champagne (d=0.998).These particles are quasi-spherical in shape and are neutrally buoyant (75 µm < diameter <150 µm) (Polidori and Padet, 2002). Moreover, they exhibit a high degree of reflectivity when illuminated by a 2mm thick laser sheet. Champagne is, before pouring, suitably and homogeneously seeded with Rilsan particles in an attempt to get the flow features from instantaneous velocity fields and deduced streamline patterns for example. To better highlight the vortical structures and to access the streakline patterns, fluorescent dyes of sulforhodamine B and fluorescein have carefully been injected in the lighted plane in complement to the first flow visualization method.

4. Bubbles : driving force behind liquid motion

After release from the nucleation site, CO_2 molecules of the liquid continue to diffuse into the rising bubble. Hence, bubbles continue to increase in size when rising through the liquid. The final average bubble size depends on several parameters, such as the growth rate k during ascent, the bubble velocity V and the distance travelled z by the bubble from its nucleation site. In Champagne, the growth rate k is estimated to be k=370µm/s (Liger-Belair, 2005). Introducing a numerical prefactor α=0.7, the semi-empirical formulae for the calculation of the bubble velocity and the bubble diameter D are defined as follows (Liger-Belair, 2005):

$$D(z)=6\left(\frac{\nu k}{2\alpha\rho g}\, z\right)^{\frac{1}{3}} \quad ; \quad V(z)=\left(\frac{2\alpha\rho g k^2}{\nu}\, z^2\right)^{\frac{1}{3}} \qquad (1)$$

Champagne physical properties: $\nu=1.48\ 10^{-3}$ kg.m^{-1}.s^{-1} and $\rho=998$ kg.m^{-3}.

The increase in size of bubble and the evolution of its velocity are plotted in Fig. 3a. In standard tasting and pouring conditions, for high effervescence levels, the velocity of the bubble once reached the liquid surface can be estimated as V=0.11 m/s in a coupe and V=0.23 m/s in a flute.

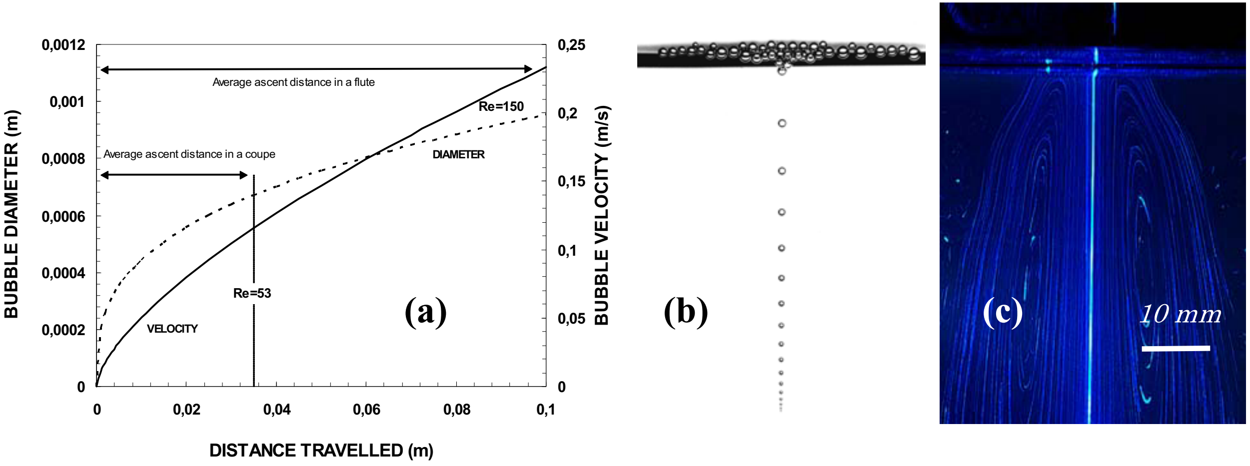

Fig. 3. Bubble diameter and velocity versus the distance traveled (a); typical bubble train from Liger-Belair (2004) (b); deduced vortex motion of the surrounding champagne wine evidenced with streamline patterns (c)

The Reynolds number based on the bubble diameter is estimated to be less than Re=150 in a flute and less than Re=53 in a coupe.

First of all, to get a precise idea of the role bubbles play on the fluid motion, let us consider a single nucleation site at the bottom of a champagne glass. Fig. 3b presents a typical bubble train during its ascending migration towards the champagne free surface. To go further with the crucial role bubble trains play on the surrounding liquid motion, a visualization of the flow is presented in Fig. 4c. The white central line corresponds to the bubble train path during the exposure time of the camera. It is amazing to see the amount of fluid that can be set in motion by viscous effects. In the plane of the photography, the fluid motion is characterized by a vortex-couple on both sides of the bubble chain. The extrapolation of a vortex-couple in a planar representation to a 3D generalized view yields the formation of a 3D small scale annular flow. This means that a unique fixed nuclear site on the glass surface enables to set the surrounding fluid into a single small scale ring vortex.

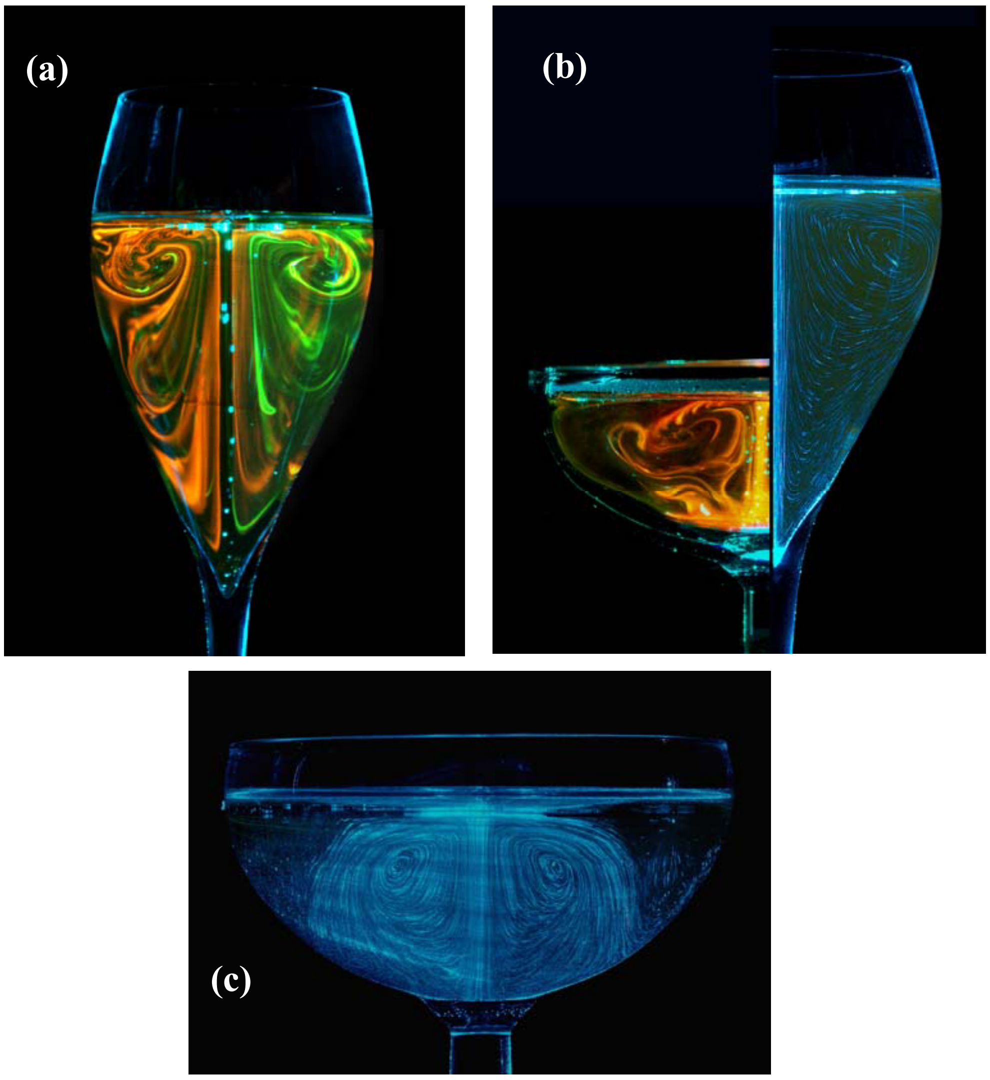

Fig. 4. Ring vortex motion. Visualization by fluorescent tracers in an engraved flute-glass (a) ; Fluorescent dye and Rilsan particles used indifferently (b); visualization by solid tracers in an engraved coupe-glass (c)

5. Ring vortex scenario

Flow visualizations have shown that a glass with an engraved circular crown exhibits a steady state of fluid motion reached ~ 30 s after the glass is poured. Similar trends have been observed whatever the flow visualization technique, either dye or solid tracers. Due to the high degree of reflectivity of bubbles, one clearly observes the formation of a rising gas column along the vertical glass axis from the treated bottom surface up to the free surface of the beverage. Consequently, a drive process of the surrounding fluid occurs to generate two large counter-rotative vortices (Polidori et al., 2008b,c) in the vertical lighted section as mentioned in Fig. 4a,b . These cells are located outside of the rising bubbles close to the wall of the glass in the case of a flute. Because this gas column acts like a continuous swirling-motion generator within the glass, the flow structure exhibits a quasi-steady two-dimensional behaviour with an axisymmetrical geometry. It is mentioned that in this case the whole domain of the liquid phase is homogeneously mixed.

To complete the trends previously observed, we present in Fig. 4c the whole resulting flow in an engraved traditional champagne coupe, much wider but shallower than the traditional champagne flute. It can be seen that, as for the previous glass model, the rising carbon dioxide bubble column causes the main fluid to move inside the glass. Nevertheless, two distinctive steady flow patterns are identified for such a glass shape. One pattern clearly exhibits a 2D axisymmetrical single swirling-ring (annulus) whose cross-section visualization reveals in Fig. 4c two counter-rotative vortices close to the glass axis. What strongly differs from the champagne flute is that this recirculation flow region does not occupy the whole volume in the glass.

As a consequence, a singular steady flow regime is observed in the external periphery of the glass which is also axisymmetrical and characterized by a dead-zone of no motion. The lack of particles in this dead-zone is not due to inhomogeneities in the fluid seeding process. It is the consequence of gravitational sedimendation phenomena ineluctably occurring in such no motion zones. It means that, for a wide-brimmed glass, only about half of the liquid bulk participates to the champagne mixing process, as shown in Fig. 5a.

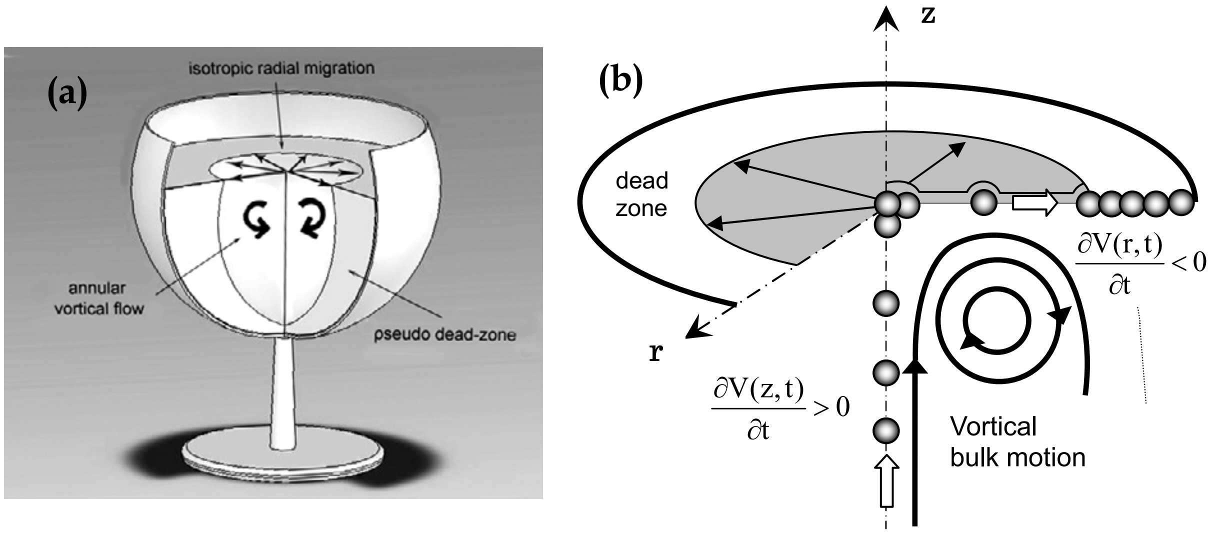

Fig. 5. Scheme of the isotropic radial bubble migration process, and identification of the two distinct zones in the bulk of the engraved champagne coupe (a); synopsis of the bubble trajectories (b).

There exists a strong relationship between the flavors exhalation process and the presence of numerous droplets issued from bursting bubbles (Liger-Belair, 2005). The bubble kinetic energy at the moment of collision with the liquid surface has a profound influence on the bubble rupture by overcoming the Champagne surface tension. Bubbles that do not burst immediately at surface follow the circumferential motion due to the annular fluid flow.

In the case of a coupe, the short ascent distance travelled by bubbles is the cause of liquid velocities lower than in the case of elongated glasses. So, due to both the low liquid swirling motion intensity and the short lifetime of the bubbles (see Fig. 5b), their surface motion is confined in a radial area whose diameter is less than the whole champagne free surface. This isotropic radial migration area is the location where most bubbles burst (Polidori et al., 2008a). That means that in a coupe glass, only about half of the surface participates to both the mixing process below the liquid surface and the "olfactive" droplet production above the Champagne surface. In the case of a flute, once bubbles have reached the surface, the circumferential component of the fluid velocity is sufficient to make them reach the glass edge. The whole liquid surface is concerned by the aroma exhalation process.

6. Relation between swirling motion and mechanisms of adsorption

During the bubble rise, surface active substances adsorb at the bubble interface, to finally reach and concentrate themselves at the free surface. Swirling motion previously discussed and induced by the continuously ascending bubble motion contributes to the progressive adsorption of surface-active materials by continuously bringing surface active materials from the champagne bulk to the air/champagne interface. Therefore, due to the two above-mentionned contributions, the amount of surface-active materials adsorbed at the air/champagne interface progressively increases as time proceeds after champagne is poured into a glass. Actually, due to their amphiphilic structure, some of the various organic compounds found in Champagne wines show surface-activity, including for example alcohols (ethanol, butanol, pentanol, phenyl-2-ethanol,etc.), some aldehydes (butanal, hexanal and hexenals), and organic acids (propionic, butyric acid, etc.), for example. The free surface of champagne is therefore strongly believed to be over concentrated with regard to surface active molecules (some of them being potentially aromatic thus participating to the global sensorial perception of a sparkling wine).

7. Remark on the role of engravement conditions on flow mixing

To give more details on the mixing flow process and to have a precise idea on the role of engravement, we present in Fig. 6 streamline patterns deduced from flow visualizations for the traditional champagne flute, under engravement conditions or not. To enable a better comparison between flow visualization into these two glasses, it is pointed out that initial pictures from which streamlines patterns have been drawn, have been taken at the same time t=60 s after champagne wine was poured into each glass.

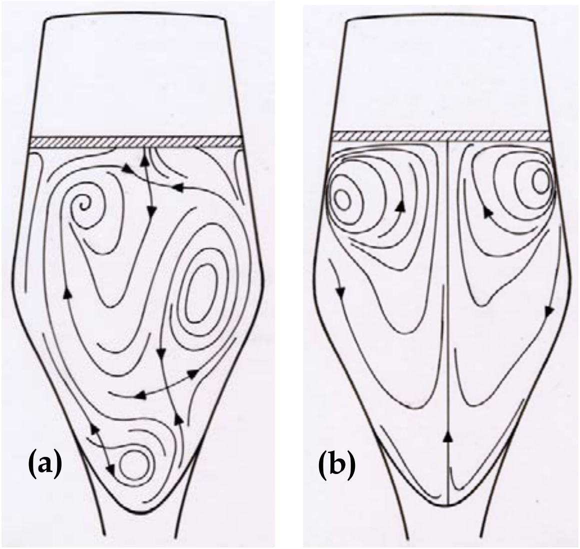

Fig. 6: Streamlines patterns in the traditional flute showing natural effervescence (a), and in the traditional champagne flute engraved at its bottom (b).

Strong differences appear in the flow behaviour according to whether the glass has sustained or not a specific surface treatment. In the case of the traditional champagne flute without surface treatment, the flow is asymmetric in the visualization section with large-scale eddies, whose number varies from an experiment to another. During the exposure time of the camera, the particle paths give the fluid velocity field from which streamlines can easily be drawn as lines tangent to these velocity vectors (Liger-Belair et al., 2008). The streamline patterns drawn in Fig 6a reveal a three-dimensional (3D) behaviour of the flow materialized for example by the presence of a spiral in shape focus. Sequences of the flow (data not shown) indicate that the highly rotational viscous flow cells evolve in time changing in size and location according to an arbitrary scheme. One could easily think that this situation is more convenient for the champagne mixing phenomena and consequently for the flavour exhalation process. Nevertheless, this mixing process is much less vigorous in time in terms of bubbling behaviour compared to the engraved glass (see Fig. 6b) where the gas column acts like a continuous swirling-motion generator within the glass. In the latter case the whole domain of the liquid phase is homogeneously mixed in time.

8. Conclusion

In sum, a classical flow visualization technique was used in order to capture the fluid motion in traditional flutes and coupes poured with champagne. It was found that glasses engraved around their axis of symmetry produce a rising gas column along the vertical glass axis which induces, in turn, recirculating flow regions. In case of the classical engraved champagne flute, the whole domain of the liquid phase is homogeneously mixed, whereas in the case of the engraved champagne coupe, the recirculating flow region does not occupy the whole volume in the glass. In the engraved coupe, a "dead-zone" of no motion was identified which inhibits the formation of the collar at the glass edge. Because the kinetics of flavour and gas release also strongly depend on the velocity of the recirculating flows close to the interface, we therefore strongly believe that this paper brings objective elements and clues in order to better understand the role of glass shape and engravement conditions on the "olfactive" behaviour of champagne and sparkling wines in a glass.

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Author Profile

Guillaume Polidori : He received his PhD in Fluid Mechanics in 1994 from the University of Poitiers in France. He became an associate professor in 1994 in the University of Reims in France. He then became a full professor in 2004 in the same University. His main research interests concern theoretical modeling in thermal convection and Flow Visualization applied to various scientific fields such as free convection, underwater swimming in sport science or mixing phenomena in Champagne tasting science.

Fabien Beaumont : He has been active in investigating swirling flows from flow visualization techniques since 2000. His other academic interests include free, mixed and forced convection and biomechanical sciences. He works on the development of specific equipments in these research fields.

Philippe Jeandet: He received his PhD and his Doctor of Science title in Plant Physiology and Biochemistry, respectively, in 1991 and 1996 from the University of Burgundy in France. He received an Associate Professor position from the University of Burgundy in 1993 and then moved to the University of Reims as a full Professor. His main research interests concern Physics of bubbles in Champagne, Physico-Chemistry of the foaming properties of Champagne and Sparkling, studies in grape and wine proteins, applications of spectroscopic methods to Enology.

Gérard Liger-Belair: He received his PhD in physical sciences in 2001 from the university of Reims in France. He received an associate professor position at the university of Reims in 2002, and a full professor position, in 2007, in the same university. He has been researching the physics and chemistry behind the bubbling properties of champagne and sparkling wines for several years. His book *Uncorked: the science of champagne* was published in 2004 by Princeton University Press and won the 2004 award for the Best Professional/Scholarly Book in Physics from the Association of American Publishers.