



Champagne cork popping revisited through high-speed infrared imaging: The role of temperature

G rard Liger-Belair^{a,b,*}, Marielle Bourget^c, Clara Cilindre^{a,b}, Herv  Pron^c, Guillaume Polidori^c

^a *Equipe Effervescence, Groupe de Spectrom trie Mol culaire et Atmosph rique (GSMA), UMR CNRS 7331, Universit  de Reims Champagne-Ardenne, UFR Sciences Exactes et Naturelles, BP 1039, 51687 Reims Cedex 2, France*

^b *Laboratoire d'Enologie et Chimie Appliqu e (URVVC), UPRES EA 4707, UFR Sciences Exactes et Naturelles, Universit  de Reims, BP 1039, 51687 Reims Cedex 2, France*

^c *Laboratoire de Thermom canique, Groupe de Recherche en Sciences Pour l'Ing nieur (GRESPI), Universit  de Reims Champagne-Ardenne, UFR Sciences Exactes et Naturelles, BP 1039, 51687 Reims Cedex 2, France*

ARTICLE INFO

Article history:

Received 23 July 2012

Received in revised form 12 October 2012

Accepted 18 November 2012

Available online 5 December 2012

Keywords:

Champagne

Sparkling wines

CO₂

Cork stopper

Infrared imaging

ABSTRACT

Champagne cork popping out of standard 75 cL bottles was examined through high-speed infrared imaging for three various champagne temperatures (namely, 4, 12, and 18  C). The cloud of gaseous CO₂ gushing out of the bottleneck while cork popping (invisible in the visible light spectrum) was visualized. Both the volume of gaseous CO₂ gushing out of the bottleneck, and its overall dynamic behavior were found to depend on the champagne temperature. The velocity of the cork popping out of the bottleneck was also measured, and found to logically increase with the champagne temperature. By considering that gases under pressure in the bottleneck experience adiabatic expansion while cork popping, a thermodynamic model was built that accounts for the major physical parameters that influence the volume of gaseous CO₂ gushing out of the bottleneck, its drop of temperature, and its total energy released while cork popping. Only a small fraction of the total energy released while cork popping was found to be converted into the form of cork's kinetic energy (only about 5%), whatever the champagne temperature.

  2012 Elsevier Ltd. All rights reserved.

1. Introduction

Since the end of the 17th century, champagne has been a world-wide renowned and festive French sparkling wine. From a strictly chemical point of view, Champagne wines are multicomponent hydroalcoholic systems supersaturated with dissolved CO₂ formed together with ethanol during the second fermentation process, called *prise de mousse* (promoted by adding yeasts and a certain amount of sugar inside bottles filled with a base wine and sealed with a cap). Champagnes, or sparkling wines elaborated through the same method, therefore hold a concentration of dissolved CO₂ proportional to the level of sugar added to promote this second fermentation (for a recent review see for example Liger-Belair et al. (2008) and references therein). The concentration of dissolved CO₂ in champagne (in grams per liter) is roughly equivalent to half of the concentration of sugar (in grams per liter) added into the base wine in order to promote the *prise de mousse*. Traditionally, 24 g/L of sugar are added in the base wine to promote the *prise de mousse*. Therefore, a standard champagne holds close to 12 g/L of dissolved CO₂ molecules after this second fermentation in a closed

* Corresponding author at: Equipe Effervescence, Groupe de Spectrom trie Mol culaire et Atmosph rique (GSMA), UMR CNRS 7331, Universit  de Reims Champagne-Ardenne, UFR Sciences Exactes et Naturelles, BP 1039, 51687 Reims Cedex 2, France. Tel.: +33 3 26 91 88 25.

E-mail address: gerard.liger-belair@univ-reims.fr (G. Liger-Belair).

bottle (i.e., about 9 g per each standard 75 cL bottle). Those 9 g correspond to a volume close to 5 l of gaseous CO₂ under standard conditions for temperature and pressure (Liger-Belair, 2005; Liger-Belair et al., 2008).

Actually, during this second fermentation process, dissolved CO₂ and gaseous CO₂ under the cork progressively establish equilibrium – an application of Henry's law which states that the partial pressure of a given gas above a solution is proportional to the concentration of the gas dissolved into the solution. After the *prise de mousse*, champagne ages in a cool cellar for at least 15 months in order to develop its so-called bouquet (Priser et al., 1997; Tominaga et al., 2003; Alexandre and Guilloux-Benatier, 2006). Bottles then undergo disgorging. Caps are removed in order to remove the sediment of dead yeast cells. Bottles are then quickly corked with traditional cork stoppers to prevent an excessive loss of dissolved CO₂. After corking the bottle, dissolved and gaseous CO₂ quickly recover equilibrium. Dissolved CO₂ progressively desorb from the liquid medium to promote the raise of gaseous pressure under the cork, which finally and quickly recovers a stable value. A bit of dissolved CO₂ is therefore inevitably lost at this step. Experiments with early disgorged champagne samples were done recently, and the characteristic concentration of dissolved CO₂ inside the bottle was found to be of order of 11 g/L (Autret et al., 2005; Liger-Belair et al., 2009a,b, 2010; Mulier et al., 2009; Cilindre et al., 2010). Nevertheless, because the solubility of CO₂ into the

Nomenclature

ΔH_{diss}	dissolution enthalpy of CO ₂ molecules in the liquid phase, $\approx 24\,800$ J/mol	P_0	pressure of ambient air, equivalent to 1 bar
k_H	Henry's law constant of CO ₂ molecules in champagne, in g/L/bar	R	ideal gas constant, $\approx 8,31$ J/K/mol
m	total mass of CO ₂ trapped within the bottle, in g	T	temperature, in K
M	mass of the cork stopper, $\approx 10 \pm 0,2$ g	T_f	final temperature of gas phase CO ₂ , after adiabatic expansion, in K
E_K	kinetic energy of the flying cork gushing out of the bottleneck ($1/2MU^2$), in J	U	cork velocity, in m/s
E_T	total energy released while cork popping, assuming adiabatic expansion of the gas phase CO ₂ trapped in the bottleneck, in J	V	volume of champagne within the standard bottle, $\approx 0,75$ L
P	pressure of gas phase CO ₂ trapped in the bottleneck, under the cork, in bar	v	initial volume of gas phase CO ₂ trapped in the bottleneck, under the cork, $\approx 0,025$ L
		v_f	final volume of gas phase CO ₂ gushing out of the bottleneck, after adiabatic expansion, in L
		γ	ratio of specific heats of gas phase CO ₂ , $\approx 1,3$

wine is strongly temperature-dependent (the lower the temperature of the wine, the higher the gas solubility), the partial pressure of gaseous CO₂ in the bottleneck is therefore also strongly temperature-dependent (the lower the temperature of the wine, the lower the partial pressure of gaseous CO₂). Moreover, because the driving force behind the popping process is the force exerted by gases under pressure in the bottleneck on the base of the cork stopper (called the *miroir*), the champagne cork popping process is therefore definitely under the influence of the champagne temperature.

Even if it is far safer to uncork a bottle of champagne with a subdued sigh, most of us would admit to having popped open a bottle of champagne with a bang, as wonderfully captured in the photograph displayed in Fig. 1, taken by Jacques Honvault, a master of stop action photography (Liger-Belair and Polidori, 2011). However, every year, the combination of warm bottles of champagne or sparkling wines with careless cork-removal technique results in serious eye injuries and even permanent vision loss (Archer and Galloway, 1967; Kuhn et al., 2004; Sharp, 2004). The American Academy of Ophthalmology has even declared that champagne cork-popping is one of the most common holiday-related eye hazards (see American Academy of Ophthalmology, 2009). It is worth noting that Dom Pierre Pérignon, the French Benedictine monk widely credited with inventing champagne and developing efficient corks stoppers, was blind at the end of his life. Nevertheless, let's mention that none of the differential diagnosis of Dom Pérignon's blindness done by experts was attributed to eye injury caused by accidental cork popping (Bullock et al., 1998).

Recently, the cork popping process was visualized at a single champagne temperature of 12 °C (Liger-Belair and Polidori, 2011; Liger-Belair, 2012). Nevertheless, and to the best of our knowledge, no scientific study dealing with the temperature dependence of the cork popping process has been reported up to now. In this article, champagne cork popping out of standard 75 cL bottles was examined, through high-speed infrared imaging, for three various champagne temperatures (namely, 4, 12, and 18 °C). The temperature dependence of the fast-traveling cork velocity was accessed, and the cloud of gaseous CO₂ gushing out of the bottleneck during the cork popping process (completely invisible in the visible light spectrum) was visualized and followed with time while diffusing in ambient air (for each given temperature). Our observations were discussed on the basis of a thermodynamic model that accounts for the major physical parameters that influence both the volume of gaseous CO₂ gushing out of the bottleneck, and its total energy released while cork popping.

2. Materials and methods

2.1. The batch of champagne corked bottles

A batch of standard commercial Champagne wine, recently elaborated in 75 cL bottles, with a blend of 100% chardonnay base wines (vintage 2008 – Cooperative Nogent l'Abbesse, Marne, France), was used for this set of experiments. Bottles were elaborated with 24 g/L of sugar added in the base wine to promote the



Fig. 1. Stop-action photograph of a cork popping out of a champagne bottle (Photograph by Jacques Honvault) (a), and side view of a traditional champagne cork stopper freshly-uncorked from a standard champagne bottle used in this set of experiments (b); it clearly appears that it is composed of two different parts: (i) an upper part composed of agglomerated cork granules, and (ii) a lower part made of two massive cork slices stuck together (Photograph by Gérard Liger-Belair).

prise de mousse, so that the same amount of about 9 g of CO₂ was produced into every bottle of this batch.

After a classical period of aging of 15 months, bottles were then corked with traditional natural cork stopper (from a same batch of corks), as the one shown in Fig. 1. Each cork stopper is composed of two well-distinct different parts: (i) a upper part composed of agglomerated cork granules, and (ii) a lower part made of two massive cork slices stuck together. The mass M of each cork is about $10 \pm 0,2$ g. It is also worth noting that, into every bottle of this batch, the volume of the headspace under the cork is equal to 25 mL. After having been corked with cork stoppers, bottles were stored in a cool cellar, at 12 °C. To examine the role of champagne temperature on champagne cork popping, three temperatures were chosen, namely, 4, 12, and 18 °C, respectively. 24 h before each set of experiments, bottles were stored at the desired temperature in a controlled-temperature room.

2.2. Dissolved CO₂ solubility in champagne and pressure of gas phase CO₂ under the cork

Generally speaking, the solubility of a given gas into a solution is strongly temperature-dependent. Agabaliantz (1963) thoroughly examined the solubility of dissolved CO₂ as a function of both temperature and wine parameters. For a typical sparkling wine elaborated according to the *méthode traditionnelle*, Agabaliantz established the temperature dependence of the dissolved CO₂ Henry's law constant, denoted $k_H(T)$. Thermodynamically speaking, the temperature dependence of Henry's law constant can be conveniently expressed with a Van't Hoff-like equation as follows (Liger-Belair, 2005):

$$k_H(T) = k_{298K} \exp \left[-\frac{\Delta H_{\text{diss}}}{R} \left(\frac{1}{T} - \frac{1}{298} \right) \right] \quad (1)$$

where k_{298K} is the Henry's law constant of dissolved CO₂ at 298 K ($\approx 1,21$ g/L/bar), ΔH_{diss} is the dissolution enthalpy of CO₂ molecules in the liquid phase (in J/mol), R is the ideal gas constant (8,31 J/K/mol), and T is the absolute temperature (in K). By fitting Agabaliantz data with the latter equation, the dissolution enthalpy of CO₂ in champagne was approached, and found to be $\Delta H_{\text{diss}} \approx 24\,800$ J/mol (Liger-Belair, 2005).

The physicochemical equilibrium of CO₂ within a champagne bottle is ruled by both Henry's law (for both dissolved and gas phase CO₂) and the ideal gas law (for gas phase CO₂ in the headspace under the cork). Therefore, by combining the two aforementioned laws with mass conservation (since bottles are hermetically closed), the following relationship was determined, which links the pressure P of gas phase CO₂ under the cork (in bars) with both temperature and bottle's parameters as (Liger-Belair et al., 2008):

$$P \approx \frac{mRT}{4,4 \times 10^3 v + k_H RTV} \quad (2)$$

where m is the total mass of CO₂ within the bottle (in g), T is the champagne temperature (in K), k_H is the solubility of CO₂ given in Eq. (2) (in g/L/bar), V is volume of champagne within the bottle (in L), and v is the volume of the gaseous headspace under the cork (in L). For standard champagne bottles, with $V = 75$ cL, a gaseous volume in the headspace of $v = 25$ mL, and a total mass of CO₂ trapped within the bottle of $m = 9$ g (as the ones used in our experiments), the temperature dependence of the pressure P under the cork is displayed in Fig. 2 (together with the temperature dependence of dissolved CO₂ solubility).

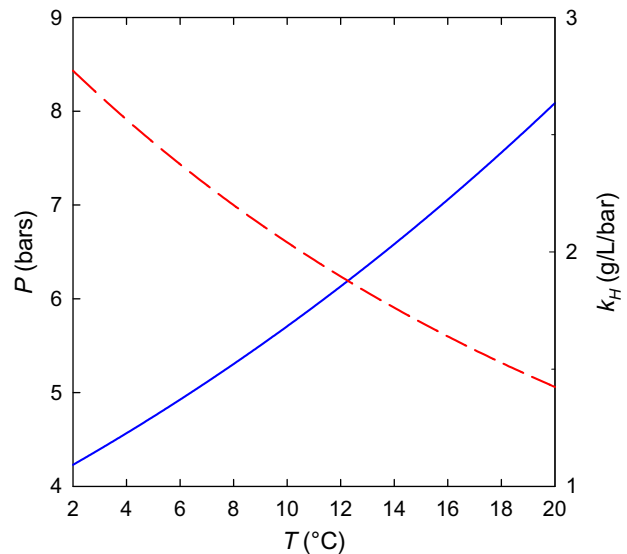


Fig. 2. Temperature dependence, between 0 and 20 °C, of both the gas phase CO₂ pressure under the cork (blue solid line), and the dissolved CO₂ Henry's law constant in champagne, following the Van't Hoff-like Eq. (1) (red dashed line), for a typical champagne with 12,5% (v/v) of ethanol and 10 g/L of sugars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Infrared imaging technique

A visualization technique based on the Infrared (IR) thermography principle has been used to film the gaseous CO₂ fluxes outgassing from champagne (invisible in the visible light spectrum) (Gordge and Page, 1993). The CO₂ 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 μm. Consequently, the best way to visualize the flow of gaseous CO₂ desorbing from champagne is to fit the camera with a band-pass filter (centered on the CO₂ emission peak), as shown in a recent article (Pron et al., 2010). The experimental device consists of a CEDIP middlewaves Titanium HD560M IR digital video camera, coupled with a CO₂ filter (Ø 50,8 mm × 1 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 20 cm behind the bottleneck. The IR video camera

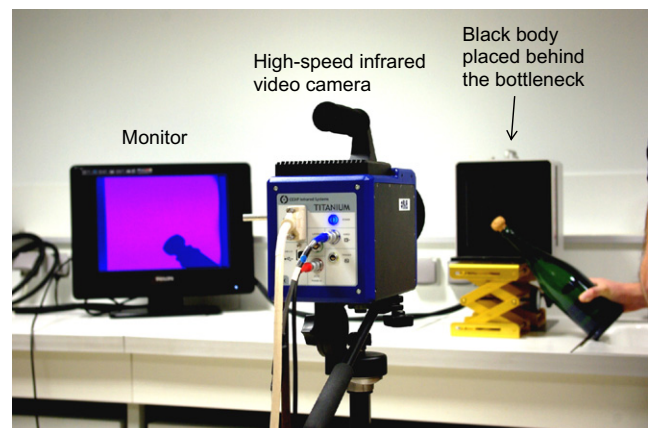


Fig. 3. Setup used to visualize, through high-speed infrared imaging, the fast-traveling cork and the cloud of gaseous CO₂ gushing out of the bottleneck while cork popping.

was used at a 100 frames per second (fps) filming rate. The shutter speed of the digital camera is of order of 1 ms. A photograph of the whole set-up is displayed in Fig. 3. It is worth noting that the same set-up was recently used in order to capture the cloud of gaseous CO₂ released above champagne glasses, under standard tasting conditions, whether champagne was poured in a flute or in a coupe (Liger-Belair et al., 2012).

Moreover, high-speed infrared imaging of cork popping allowed the possibility to retrieve the cork velocity (during the 30 first centimeters of the cork trajectory, which correspond to the field of view covered by the objective of the IR video camera). The cork's velocity was approached by dividing the distance traveled by the cork between two successive frames, by the 10⁻² s time interval between sequential image captures. For each given champagne temperature, three cork popping processes were conducted to produce one single average velocity (with standard deviations corresponding to the root-mean-square deviations of the values provided by the three successive cork popping).

3. Results and discussion

3.1. Visualizing the cloud of gaseous CO₂ during the cork popping process

Time-sequences displayed in Fig. 4 illustrate the champagne cork popping step as seen through the objective of the IR video camera, for bottles stored at 4, 12, and 18 °C, respectively. Because

CO₂ molecules absorb the 4.245 μm wavelength found in the IR spectrum emitted by the blackbody, the presence of gaseous CO₂ in front of the blackbody is betrayed as a dark zone in the field of view of the camera. Therefore, the gaseous CO₂ trapped in the headspace under the cork appears as a gray cloud gushing out of the bottleneck during the cork popping process. It is worth noting that, due to the limited shutter speed of the high-speed IR video camera (of order of 1 ms), our imaging device is unable to completely “freeze” the cork popping out of the bottleneck. Actually, the cork travels a characteristic distance of order of 1 cm during this 1 ms period of time, which produces a blur effect in the wake of the fast traveling cork, as seen in Fig. 4.

Raw black and white IR images, and corresponding false color close-up views of the bottleneck, while cork popping, are displayed in Fig. 5. Such an image processing analysis provides a better contrast between the gaseous CO₂ zone and ambient air. Undoubtedly, the lower the champagne temperature, the smaller the cloud of gaseous CO₂ which escapes during the cork popping step, despite the same initial volume of 25 mL of gaseous CO₂ trapped in the headspace under the cork (before uncorking). Moreover, in addition to the temperature dependence of the volume occupied by gases gushing out of the bottleneck, it seems that the dynamics of the gas volume itself depends on the champagne temperature. Actually, the higher the champagne temperature, the more gaseous CO₂ seems to “stagnate” down (close to the bottleneck).

We are logically tempted to wonder why such differences may be observed as concerns the temperature dependence of both the gas volume gushing out of the bottleneck and its overall dynamic

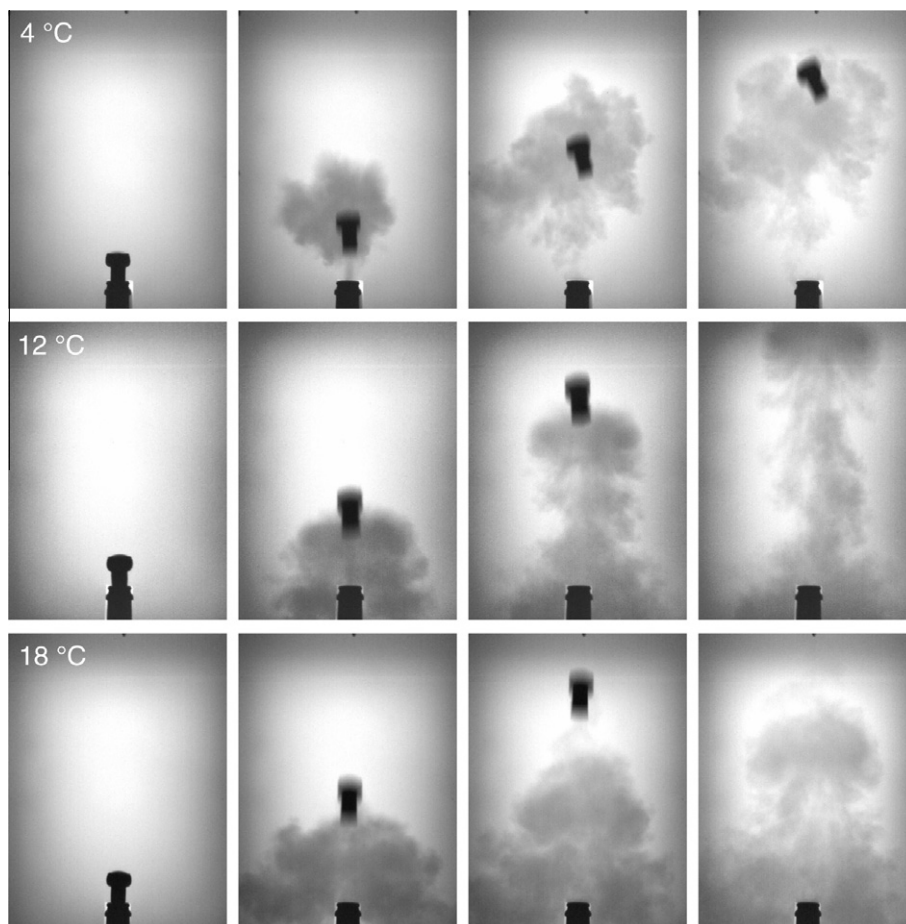


Fig. 4. Time-sequences showing the flow of gaseous CO₂ gushing out of the bottleneck while cork popping, as seen through high-speed infrared imaging, for bottles stored at 4, 12, and 18 °C, respectively. The time interval between each frame of each time-sequence is 10 ms.

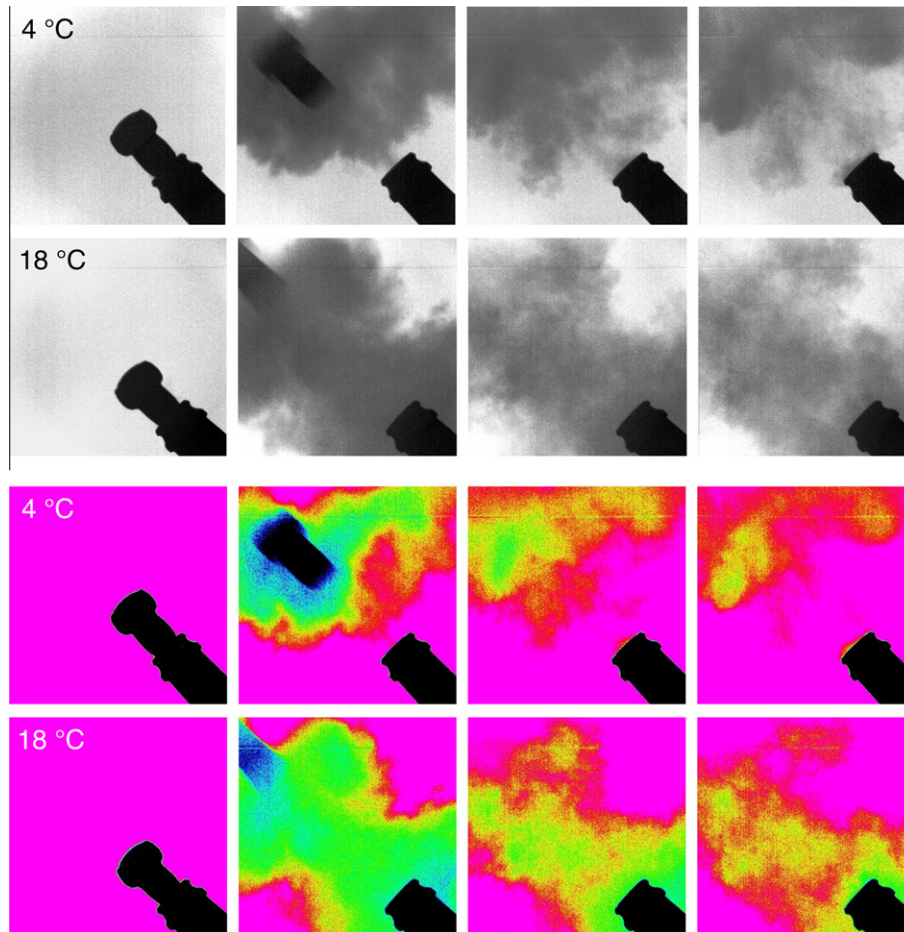


Fig. 5. Close-up raw infrared imaging of champagne-cork popping, and corresponding false color time-sequences showing the flow of gaseous CO₂ gushing out of the bottleneck while cork popping, for bottles stored at 4, and 18 °C, respectively. The time interval between each frame of time-sequences is 10 ms.

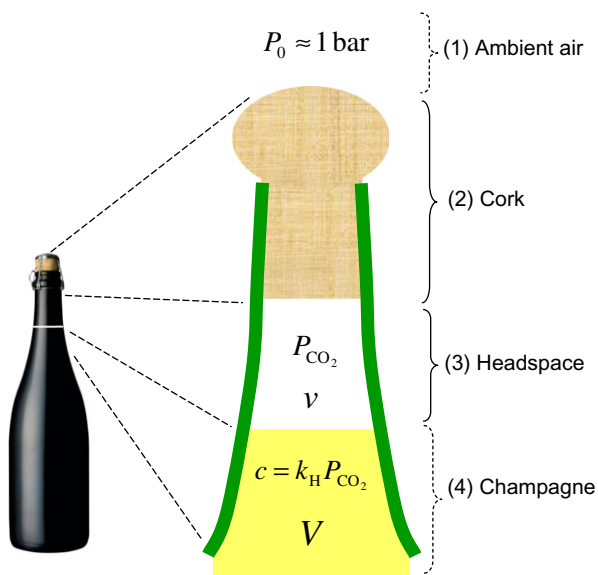


Fig. 6. Scheme of the traditional 75 cL bottle neck, and compilation of the various bottle, headspace, and champagne parameters included in the thermodynamic model.

behavior. The aim of the following paragraph is to build a thermodynamic model which describes, qualitatively and quantitatively, this phenomenon.

3.2. An adiabatic expansion while cork popping

The scheme displayed in Fig. 6 compiles the various physico-chemical and geometrical pertinent parameters of our thermodynamic model. While cork popping, the gaseous volume in the headspace under the cork instantaneously experiences a drop of pressure (from the pressure inside the bottle before opening – strongly temperature dependent, as seen in Fig. 2 – to the ambient pressure close to 1 bar). Assuming adiabatic expansion experienced by the gaseous volume v (considered as ideal) under pressure in the headspace, the final volume v_f of gaseous CO₂ gushing out of the bottleneck while cork popping is expressed as:

$$v_f = v \times \left(\frac{P}{P_0}\right)^{1/\gamma} \quad (3)$$

where P_0 is the ambient pressure (equivalent to 1 bar), and γ is the ratio of specific heats of the gas volume experiencing adiabatic expansion (mainly composed of gaseous CO₂ and being equal to 1.3).

By replacing, in the latter equation, P by its theoretical expression found in Eq. (2), the following relationship is deduced, which links the final volume of gaseous CO₂ gushing out of the bottleneck with its initial temperature T before cork popping:

$$v_f \approx v \times \left(\frac{mRT}{4,4 \times 10^3 v + k_H RTV}\right)^{0.77} \quad (4)$$

The temperature dependence of the final volume v_f of gaseous CO₂ gushing out of the bottleneck assuming adiabatic expansion is

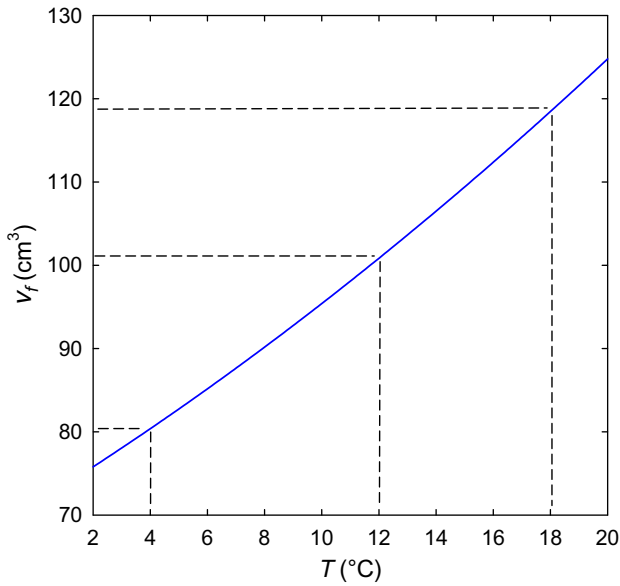


Fig. 7. Theoretical volume v_f of gaseous CO_2 (in cm^3), which expands out of the champagne bottleneck (assuming adiabatic expansion while cork popping), as a function of the initial champagne temperature T . This graph was built by replacing in Eq. (4), each parameter by its numerical value corresponding to our batch of bottles.

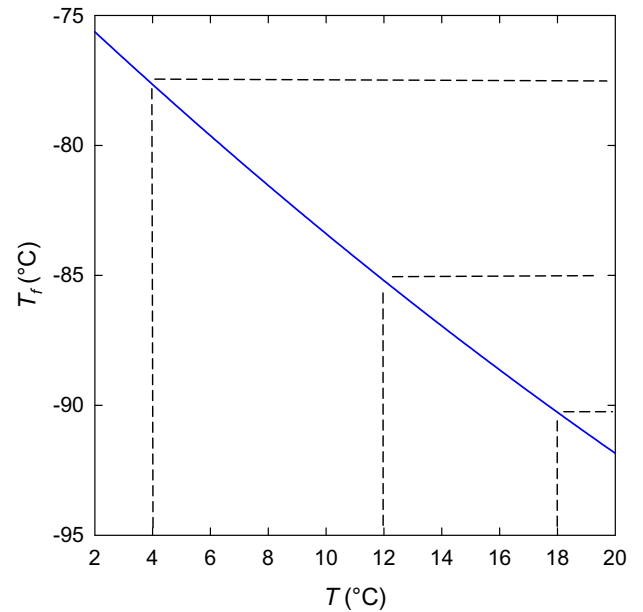


Fig. 8. Theoretical final temperature T_f of gaseous CO_2 vapors (in $^\circ\text{C}$), which expands out of the champagne bottleneck (assuming adiabatic expansion while cork popping), as a function of initial champagne temperature T . This graph was built by replacing in Eq. (6), each parameter by its numerical value corresponding to our batch of bottles.

displayed in Fig. 7. It can clearly be seen from Fig. 7 that v_f increases with the champagne temperature, as it was indeed experimentally noticed (see Figs. 4 and 5).

This adiabatic expansion of gas phase CO_2 trapped in the head-space under the cork during cork popping is also inevitably linked with a drop of temperature of the gaseous volume flowing out of the bottle. By combining Eq. (3) with the ideal gas law which states that $Pv = nRT$ (with n being the number of moles of gas experiencing adiabatic expansion), the corresponding theoretical drop of temperature experienced by the gas volume may be accessed by the following and well known relationship:

$$T_f = T \times \left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} \quad (5)$$

By application of Eq. (5), and by replacing P by its theoretical expression found in Eq. (2), the following relationship is deduced, which links the final temperature T_f of gaseous CO_2 gushing out of the bottleneck with its initial temperature T before cork popping:

$$T_f \approx T \times \left(\frac{4,4 \times 10^3 v + k_H RTV}{mRT}\right)^{0.23} \quad (6)$$

The dependence of the final temperature T_f of gaseous CO_2 gushing out of the bottleneck with the initial champagne temperature is displayed in Fig. 8. Paradoxically, and quite counter intuitively, the higher the initial champagne temperature, the lower the temperature reached by the volume of gaseous CO_2 gushing out of the bottleneck and experiencing adiabatic expansion. Now, it is worth noting that the lower the temperature of the volume of gaseous CO_2 , the higher its density. The ability of gaseous CO_2 to stagnate more easily as it gushes from bottles stored at higher temperatures could therefore be explained by the rise of its density linked with higher drops of pressure during adiabatic expansion (and therefore with lower temperatures reached by the gas phase CO_2 gushing from champagne stored at higher temperatures).

It is worth noting that, when opening a bottle of champagne (or carbonated beverage in general), anyone of us has also already noticed wisps of fog forming right above the bottle neck, as nicely



Fig. 9. Evidence for the formation of fog above a freshly-uncorked bottle of champagne. (Photograph by Françoise Peretti, collection CIVC).

captured by the photograph displayed in Fig. 9. Contrary to popular belief, this cloud of fog is not formed by the gaseous CO_2 gushing out of the bottleneck (indeed invisible in the visible light spectrum, and made visible only through infrared imaging). Actually, this

sudden and huge drop of temperature (of several tens of °C during adiabatic expansion) causes the instantaneous condensation, into the form of tiny droplets of fog, of water vapor and ethanol vapor traces found in the close vicinity of the bottleneck (Batt, 1971; Liger-Belair et al., 2008; Volmer and Möllmann, 2012).

3.3. Does the cork velocity depend on the champagne temperature?

How does the cork's velocity behave depending on the champagne temperature? The average velocity U reached by a popping cork stopper as a function of champagne temperature is displayed in Fig. 10. Despite natural variability, it seems that the average cork velocity increases with champagne temperature, which is rather consistent with the fact that the driving force exerted on the cork's base by gas phase CO₂ under pressure in the bottleneck increases indeed with champagne temperature (see Fig. 2). Following the recent work by Volmer and Möllmann (2012), it is worth noting that the spreading velocity of the condensation front was found to be much more important (≈ 90 m/s) than both the cork velocity (≈ 10 – 15 m/s) and the spreading velocity of gas phase CO₂ during adiabatic expansion.

A question nevertheless remained open. Which fraction of the potential energy released while cork popping is converted into the form of kinetic energy with the flying cork stopper, and how does it depend on the champagne temperature? The next paragraph provides a detailed answer based on classical thermodynamics arguments.

3.4. Total energy released while cork popping

During the adiabatic expansion of the gas phase CO₂ gushing out of the bottleneck, the total energy released while cork popping classically expresses as follows:

$$E_T = \int_v^{v_f} P dv \quad (7)$$

By combining Eq. (3) and Eq. (7), the latter equation transforms as:

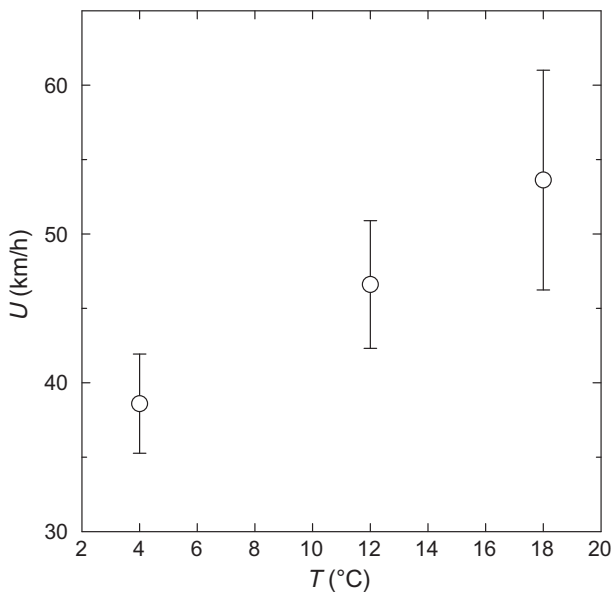


Fig. 10. Experimental temperature dependence of the champagne cork velocity after ejection from the bottleneck; each datum is the arithmetic average of three successive values recorded from three successive cork popping at a given temperature; standard deviations correspond to the root-mean-square deviations of the values provided by the three successive cork popping.

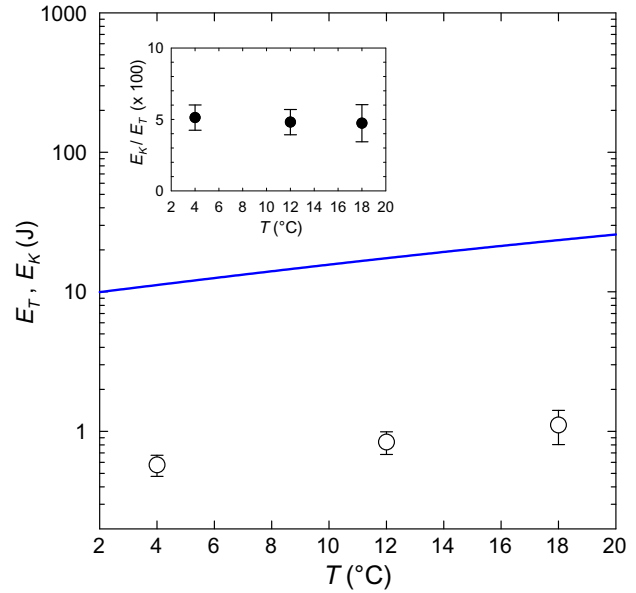


Fig. 11. Temperature dependence of the potential energy released while cork popping, denoted E_T , assuming adiabatic expansion of the gaseous volume of CO₂ trapped under the cork (blue line), compared with the kinetic energy ($E_K = 1/2MU^2$) of the cork popping out of the bottleneck (white dots); in the term $E_K = 1/2MU^2$, the mass of the cork stopper M is expressed in kg, and its velocity U in m/s; in the insert, the ratio (in percentage) of the cork's kinetic energy to the total potential energy released while cork popping is displayed.

$$E_T = P_0 v_f^\gamma \int_v^{v_f} \frac{dv}{v^\gamma} \quad (8)$$

Integrating Eq. (8) between the initial stage in the corked bottle and the final volume of gaseous CO₂ after complete adiabatic expansion, and developing leads to the following relationship:

$$E_T = P_0 v_f^\gamma \frac{1}{(1-\gamma)} (v_f^{1-\gamma} - v^{1-\gamma}) \approx P_0 v_f \frac{1}{(1-\gamma)} \left[1 - \left(\frac{v_f}{v}\right)^{\gamma-1} \right] \quad (9)$$

Finally, replacing in Eq. (9) v_f by its theoretical temperature dependence relationship (given in Eq. (4)) leads to the following equation, which links the total energy released while cork popping with the pertinent parameters of our system:

$$E_T \approx P_0 v \frac{1}{(\gamma-1)} \left[\left(\frac{mRT}{4,4 \times 10^3 v + k_H RTV} \right) - \left(\frac{mRT}{4,4 \times 10^3 v + k_H RTV} \right)^{0.77} \right] \quad (10)$$

By replacing each and every parameter by its numerical value allows us to retrieve the total energy released while cork popping as a function of champagne temperature, as displayed in Fig. 11. In the graph displayed in Fig. 11, the energy released into the form of cork's kinetic energy ($E_K = 1/2MU^2$) also appears for the three champagne temperatures, i.e., 4, 12 and 18 °C, respectively. It happens that only a small fraction of the total energy released while cork popping is converted into the form of cork's kinetic energy (only about 5% whatever the champagne temperature, as shown in the insert displayed in Fig. 11).

In conclusion, cork popping out of standard 75 cL champagne bottles was examined through high-speed infrared imaging. The cloud of gaseous CO₂ gushing, and expanding out of the bottleneck, while cork popping, was filmed, for three distinct champagne temperatures. Differences were observed as concerns the temperature dependence of both the gas volume gushing out of the bottleneck and its overall dynamic behavior. The velocity of the cork popping out of the bottleneck was also measured, and found to logically increase with the champagne temperature. By considering that gases

under pressure in the bottleneck experience adiabatic expansion while cork popping, a thermodynamic model was built which links the volume of gaseous CO₂ gushing out of the bottleneck, its drop of temperature, and the potential energy stored in the bottleneck, with the champagne temperature, the solubility of gaseous CO₂ in the liquid phase, and the volume of the bottleneck. Only a small fraction of the total energy released while cork popping was found to be converted into the form of cork's kinetic energy (only about 5%, whatever the champagne temperature). Most of the total energy seems therefore dissipated into the form of a sound shock wave (the very characteristic "bang"). In a future work, we plan to measure the amplitude/frequency of the sound to obtain the amount of sound energy released while cork popping. In the future we also plan to use a high speed classical video camera to capture the condensation cloud of fog, coupled with two IR high-speed video cameras filming the cloud of gaseous CO₂ from two different angles of view.

Acknowledgment

Thanks are due to the Europôl'Agro institute and to the Association Recherche Oenologie Champagne Université for financial support, and to champagne Pommery and to Cooperative Nogent l'Abbesse for regularly supplying us with various champagne samples. Authors are also indebted to the *Région Champagne-Ardenne*, the *Ville de Reims*, and the *Conseil Général de la Marne* for supporting our research.

References

- Agabalianz, G.G., 1963. Bases scientifiques de la technologie des vins mousseux. *Bulletin de l'OIV* 36, 703–714.
- Alexandre, H., Guilloux-Benatier, M., 2006. Yeast autolysis in sparkling wines: a review. *Australian Journal of Grape and Wine Research* 12, 119–127.
- American Academy of Ophthalmology, 2009. A cork in the eye is no way to spend the holiday. <<http://www.aaopt.org/newsroom/release/20091217.cfm>>
- Archer, D., Galloway, N., 1967. Champagne-cork injury to the eye. *Lancet* 2, 487–489.
- Autret, G., Liger-Belair, G., Nuzillard, J.-M., Parmentier, M., Dubois de Montreynaud, A., Jeandet, P., Doan, B.T., Beloeil, J.-C., 2005. Use of magnetic resonance technique for the investigation of the CO₂ dissolved in champagne and sparkling wines: a non-destructive and unintrusive method. *Analytica Chimica Acta* 535, 73–78.
- Batt, R., 1971. Pop! Goes the champagne bottle cork. *Journal of Chemical Education* 48, 71.
- Bullock, J.D., Wang, J.P., Bullock, G.H., 1998. Was Dom Perignon really blind? *Survey of Ophthalmology* 42, 481–486.
- Cilindre, C., Liger-Belair, G., Villaume, S., Jeandet, P., Marchal, R., 2010. Foaming properties of various Champagne wines depending on several parameters: grape variety, aging, protein and CO₂ content. *Analytica Chimica Acta* 660, 164–170.
- Gordge, D., Page, R., 1993. Infrared imagery of an air/CO₂ axisymmetric jet. *Experiments in Fluids* 14, 409–415.
- Kuhn, F., Mester, V., Morris, R., Dalma, J., 2004. Serious eye injuries caused by bottles containing carbonated drinks. *British Journal of Ophthalmology* 88, 69–71.
- Liger-Belair, G., 2005. The physics and chemistry behind the bubbling properties of champagne and sparkling wines: a state-of-the-art review. *Journal of Agricultural and Food Chemistry* 53, 2788–2802.
- Liger-Belair, G., 2012. The physics behind the fizz in Champagne and sparkling wines. *European Physical Journal Special Topics* 201, 1–88.
- Liger-Belair, G., Bourget, M., Pron, H., Polidori, G., Cilindre, C., 2012. Monitoring gaseous CO₂ and ethanol above champagne glasses: flute versus coupe, and the role of temperature. *PLoS ONE* 7, e30628.
- Liger-Belair, G., Bourget, M., Villaume, S., Jeandet, P., Pron, H., Polidori, G., 2010. On the losses of dissolved CO₂ during champagne serving. *Journal of Agricultural and Food Chemistry* 58, 8768–8775.
- Liger-Belair, G., Polidori, G., Jeandet, P., 2008. Recent advances in the science of champagne bubbles. *Chemical Society Reviews* 37, 2490–2511.
- Liger-Belair, G., Polidori, G., 2011. Voyage au cœur d'une bulle de champagne. Odile Jacob, Paris, France.
- Liger-Belair, G., Villaume, S., Cilindre, C., Jeandet, P., 2009a. Kinetics of CO₂ fluxes outgassing from champagne glasses in tasting conditions: the role of temperature. *Journal of Agricultural and Food Chemistry* 57, 1997–2003.
- Liger-Belair, G., Villaume, S., Cilindre, C., Polidori, G., Jeandet, P., 2009b. CO₂ volume fluxes outgassing from champagne glasses in tasting conditions: flute versus coupe. *Journal of Agricultural and Food Chemistry* 57, 4939–4947.
- Mulier, M., Zeninari, V., Joly, L., Decarpenterie, T., Parvitte, B., Jeandet, P., Liger-Belair, G., 2009. Development of a compact CO₂ sensor based on near-infrared laser technology for enological applications. *Applied Physics B: Lasers and Optics* 94, 725–733.
- Priser, C., Etievant, P.X., Nicklaus, S., Brun, O., 1997. Representative Champagne wine extracts for gas chromatography olfactometry analysis. *Journal of Agricultural and Food Chemistry* 45, 3511–3514.
- Pron, H., Caron, D., Beaumont, F., Liger-Belair, G., Polidori, G., 2010. Dynamic-tracking desorption of CO₂ in Champagne wine using infrared thermography. *Journal of Visualization* 13, 181–182.
- Sharp, D., 2004. Safe bubbly. *Lancet* 364, 2165.
- Tominaga, T., Guimbertau, G., Dubourdieu, D., 2003. Role of certain volatile thiols in the bouquet of aged Champagne wines. *Journal of Agricultural and Food Chemistry* 51, 1016–1020.
- Volmer, M., Möllmann, K.-P., 2012. Vapour pressure and adiabatic cooling from champagne: slow-motion visualization of gas thermodynamics. *Physics Education* 45, 608–615.