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

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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 CO_2 gushing out of the bottleneck while cork popping (invisible in the visible light spectrum) was visualized. Both the volume of gaseous CO_2 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 CO_2 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.

1. Introduction

Since the end of the 17th century, champagne has been a worldwide renowned and festive French sparkling wine. From a strictly chemical point of view, Champagne wines are multicomponent hydroalcoholic systems supersaturated with dissolved CO_2 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 CO_2 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 CO_2 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 CO_2 molecules after this second fermentation in a closed 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 CO_2 under standard conditions for temperature and pressure (Liger-Belair, 2005; Liger-Belair et al., 2008).

Actually, during this second fermentation process, dissolved CO_2 and gaseous CO_2 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 CO_2. After corking the bottle, dissolved and gaseous CO_2 quickly recover equilibrium. Dissolved CO_2 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 CO_2 is therefore inevitably lost at this step. Experiments with early disgorged champagne samples were done recently, and the characteristic concentration of dissolved CO_2 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 CO_2 into the

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Nomenclature

ΔH_{diss}	dissolution enthalpy of CO_2 molecules in the liquid phase, ≈24 800 J/mol
k_H	Henry's law constant of CO_2 molecules in champagne, in g/L/bar
m	total mass of CO_2 trapped within the bottle, in g
M	mass of the cork stopper, =10 ± 0,2 g
E_K	kinetic energy of the flying cork gushing out of the bottleneck ($1/2MU^2$), in J
E_T	total energy released while cork popping, assuming adiabatic expansion of the gas phase CO_2 trapped in the bottleneck, in J
P	pressure of gas phase CO_2 trapped in the bottleneck, under the cork, in bar
P_0	pressure of ambient air, equivalent to 1 bar
R	ideal gas constant, =8,31 J/K/mol
T	temperature, in K
T_f	final temperature of gas phase CO_2, after adiabatic expansion, in K
U	cork velocity, in m/s
V	volume of champagne within the standard bottle, =0,75 L
v	initial volume of gas phase CO_2 trapped in the bottleneck, under the cork, =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, ≈1,3

wine is strongly temperature-dependent (the lower the temperature of the wine, the higher the gas solubility), the partial pressure of gaseous CO_2 in the bottleneck is therefore also strongly temperature-dependent (the lower the temperature of the wine, the lower the partial pressure of gaseous CO_2). 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 Ophtalmology has even declared that champagne cork-popping is one of the most common holiday-related eye hazards (see American Academy of Ophtalmology, 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 CO_2 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 CO_2 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) a 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).