Why does champagne bubble?

by Christian Ucke and Hans-Joachim Schlichting

In a glass of champagne, glittering, pearl-like bubbles rise. Why do most of them form at definite spots and according to which laws do they move to the surface?

Chains of bubbles rise upward in a freshly filled glass of champagne. The convex form of the liquid filled glass has a magnifying effect on the bubbles.

We come across this phenomenon in everyday life, not only with champagne but also with beer, mineral water and other drinks containing carbon dioxide (CO_2). Pearl-like strings of bubbles move upwards in a glass filled with liquid containing CO_2.

Why does the liquid release the gas dissolved in it and why does it do this in such a striking way?

The first question is answered by the hint that the liquid apparently contains more dissolved gas that corresponds to the prevailing, outer atmospheric pressure. In the process of manufacturing a gas-oversaturated liquid, CO_2 is added on it under a pressure of 2 - 5 atmospheres. Then the bottles are filled with this liquid. Here we come across the fact that the solubility of a gas in a liquid increases with the pressure of the gases over it. On the surface of a liquid in a closed bottle, an equilibrium pressure prevails under which as many gas molecules leave the liquid as return to it. According to the laws of Henry-Dalton the concentration of a dissolved substance in the state of saturation is proportional to the pressure.

The other question directs our attention to the mechanism of the formation and release of the bubbles. It can easily be seen that the gas in the liquid collects itself in small bubbles which start to rise when they have reached a certain size. An interesting fact in the process is that the bubbles do not form just anywhere in the liquid, but at definite, apparently indiscriminately distributed spots on the surface of the glass. As a rule, microscopically small damage or impurities on the glass wall are responsible for the formation of the bubbles. This lack of homogeneity in an otherwise extensively homogenous environnment can be regarded as the seed for the relatively energetic, large-scale formation of the bubble surfaces.

The effect of such seeds comes from the fact that irregularly broken particles, like kitchen salt, make ideal seeds. Putting some salt into soda water brings about a real „storm“ of bubble cascades while the salt is still sinking in the liquid. The bubbles themselves are ideal seeds which perpetuate and vitalize the formation of bubbles.

A bubble does not detach itself from the surface of the glass. It breaks off only when it has reached a critical size for which the buoyant force is greater than the force of adhesion. This happens in a very short time, indeed, as the buoyant force increases proportionally to the volume, and the force and adhesion grows, at best, proportionally to the surface area. At any rate, the force of adhesion increases more slowly than the buoyant force. After the detachment and rise of a bubble, another one is formed at once and, after reaching its critical size, it follows its predecessor at a characteristic distance, and so on.

The equality of sizes of the detaching bubbles and the equal distances between a newly detached bubbble and ist predecessor reflect the boundary conditions which remain constant during the time of observation of the process in particular the constant rate of diffusion in which the dissolved gas molecules get into the bubble. This fact can also easily be dealt with quantitatively (see **Pearling Dynamics**).

A careful observer will also notice that the separation distance between any two neighbouring bubbles increases steadily as they move upwards. Does the accelerating effect, brought about by the buoyant force on bubbles of a given size, express itself in this way? Due to the smallness of the bubbles and the low density of the CO_2 gas contained in them each bubble must find the liquid to be like a syrup. In such a situation the force of the friction, which increases with the velocity even at small velocities - and this means in a barely perceptile amount of time for the observer - has reached the rate of the buoyant force of a bubble in a certain size and has led to a uniform terminal velocity (see **Pearling Dynamics**). The distance between the bubbles should remain constantly.

If we watch the process more closely, we can see, however, that not only the distance between the bubbles but also their size increases as they rise. An expansion of the volume of a bubble results in increased buoyant force and, consequently, in increased acceleration. The fact that the friction opposing the upward motion of the bubbles reaches the rate of the buoyant force almost instantly has no effect upon this since the buoyant force increases significantly faster than the friction (namely proportionally to volume), is always a bit ahead. Doubling the bubble radius, a typical rate of growth of the bubbles in a normal water glass, always brings about an eigthfold increase of the buoyant force.

There remains only the problem of explaining how the growth of the bubbles comes about. At first sight there seems to be an obvious explanation, one which also appears in papers on this subject (e.g. see [1]), according to which it is brought about by the hydrostatic pressure in soda water, which decreases with height. On second thought it becomes clear that the influence of the hydrostatic pressure on the size of the bubbles is hardly perceptible. With an ideal gas (which has assumed here) the product of volume and pressure in conditions which are otherwise the same, can be considered to be constant (law of Boyle-Mariotte). Doubling the radius, i.e. increasing the volume eightfold, would thus bring about an eigthfold decrease of pressure. Since the atmsopheric pressure corresponds to the hydrostaic pressure of a column of water about 10 meters high, this would mean a column of water 8 meters high. The column in a champagne or soda water glas is, however, only several centimeters high.

The main reason for the increase in bubbles is that a detached bubble can continue taking gas from the liquid while it moves upwards towards the surface. The increase in the size of the bubbles during their rise is thus actually due to an increase in their gas mass.

Pearling Dynamics

We assume that the rate of seclusion of the number N of CO_2 molecules in a bubble with the radius r is proportional to the surface $A = 4\pi r^2$ of the bubbles

(1) $dN/dt = \gamma A$

Our further assumption is that the CO_2 in champagne obeys the ideal gas equation pV =NkT, whereby p, V, T and k denote pressure, volume, temperature and the Boltzmann constant, corrrespondingly. Since p and and T can be assumed constant during the time of observation, the time derivative of the equation of state is

(2) $$\frac{dN}{dt} = \frac{p}{kT} \cdot \frac{dV}{dt} = \frac{4pp}{kT} r^2 \frac{dr}{dt} \qquad with \qquad V = \frac{4p\, r^3}{3}$$

With equation (1) this results in $\frac{gkT}{p} = \frac{dr}{dt}$

The solution of the differential equation is

(3) $r = r_0 + u \cdot t$

Here, r_0 is the initial radius, and $u = \gamma kT/p = const.$ is the speed at which the radius of the bubble increases. Due to the increase in size, the rise of the bubbles accelerates. A quantitative relationship between the size of a bubble and its upward velocity is difficult to obtain [2]. For a bubble of a given size, however, the upward velocity can be estimated quite easily. A spherical bubble experiences the following buoyant force.

(4) $F = V(\rho_L - \rho_G)g = V \cdot \rho_L \cdot g$

V, ρ_L , ρ_G and g denote the volume of the bubble, the density of the liquid, the density of the gas (CO_2) and the acceleration of gravity, correspondingly. It is presupposed that the density of the gas in relation to that of the liquid can be neglected. The bubble is so small and rises so slowly that it retains ist spherical shape. We assume that the buoyant force F is compensated by viscous force (Stokes' law)

(5) $F_S = 6\pi\eta rv$

η (20^0C) = $0.001 kgm^{-1}s^{-1}$ is the viscosity of the liquid (water), r = 0.1mm is a typical radius of the bubble shortly after the detachment, and v is its upward velocity. Equating equation (4) with equation (5) and solving for v, we obtain

(6) $v = 2g\rho_L r2/9\eta = 2cm/s$

This value corresponds to our observation.

References:

[1] Walker, J.: Bubbles in a bottle of beer, Reflections on the rising, **245**, Dec. 1981, page 124

[2] Schafer, N.E., Zare, R.N.: Through a beer glass darkly, Physics Today **44,** Oct. 1991, page 48

C. Ucke (Technical University Munich/Germany) and H. J. Schlichting (University Essen/Germany) publish since several years papers about entertaining physics and physics toys in popular and educational physics journals