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Why does champagne bubble?

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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?

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 upward in a glass filled with liquid containing CO_2.

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

The first question is answered by the fact that the liquid contains dissolved CO_2 in higher concentration than that in the air above the liquid. In the process of manufacturing a gas-oversaturated liquid, CO_2 is added under a pressure of 2 - 5 atmospheres. Then the bottles are filled with the liquid. At this point, we note that the solubility of a gas in a liquid increases with the pressure of the gases over it. Above 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 Henry-Dalton laws, the concentration of a dissolved substance in a saturated state is proportional to the pressure.

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.

The second question directs our attention to the mechanism of formation and release of the bubbles. It can easily be seen that the gas in the liquid collects in small bubbles which start to rise when they have reached a critical size. The bubbles do not form throughout the body of the liquid but are formed at apparently random points on the surface of the glass. Microscopically small regions of damage and impurities on the glass surface furnish sites at which bubbles can form. The sites on the otherwise homogeneous liquid-glass boundary initiate the relatively energetic, large-scale formation of the bubble surfaces.

The effect of such sites comes from the fact that irregularly broken particles (of kitchen salt, for example) make ideal seeds. Putting some salt into soda water brings about a veritable, rising „storm“ of bubbles while the salt is sinking through the liquid. The bubbles themselves are good seeds which causes the formation of more rising bubbles.

A newly formed bubble does not detach itself immediately from the glass surface. It breaks off only when it has reached a critical size for which the buoyant force is greater than the force of adhesion. However, this happens in a very short time since the buoyant force increases at a rate proportional to the volume while adhesive force grows, at best, at a rate proportional to the surface area of the bubble. Thus 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 constancy of the boundary conditions during the period of observation and, in particular, the uniform rate at which the dissolved CO_2 diffuses into the bubble. These phenomena can also be dealt with in a quantitative fashion (see **Pearling Dynamics**).

A careful observer will also notice that the separation between any two neighboring bubbles increases steadily as they move upward. Naturally, we try to understand this effect. Due to the small size of the bubbles and the low density of the CO_2 gas contained in them, the bubbles find the liquid to quite like a syrup. In such a situation, the retarding frictional force on the bubbles will increase with velocity, even at the small, observed velocities. In an interval of time barely perceptile to an observer, the retarding force would reach the value of the upward buoyant force if the volume of the bubble should remain constant. Then the rising bubbles would experience balanced buyont and retarding forces and reach a uniform terminal velocity (see **Pearling Dynamics**). The distance between the bubbles should remain constant.

However, if we watch the process more closely, we can see 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 an increased buoyant force and, consequently, in an increased acceleration. The fact that the friction opposing the upward motion of the bubbles reaches the initial value of the buoyant force almost instantly does not produce a uniform terminal velocity since the buoyant force increases significantly faster (proportional to volume) than does the frictional force. The buyoant force stays a bit ahead of the frictional force. As the radius of the bubble doubles (a typical behavior in a normal glass of water), an eigthfold increase in volume and the buoyant force occurs.

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 this explanation, the growth is brought about by hydrostatic pressure in the carbonated liquid. The hydrostatic pressure decreases with height. But upon reflection, it becomes clear that the influence of the hydrostatic pressure on the size of the bubbles is negligible. When we treat a bubble as an ideal gas, the product of volume and pressure in conditions which are otherwise the same can be considered to be constant. 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 hydrostatic pressure at the base of a column of water about 10 meters high, this would mean a column of water 80 meters high. The column in a champagne or soda water glass 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 content.

Pearling Dynamics

We assume that the rate of increase 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 so that

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

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

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

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 $u = \gamma kT/p$ remains constant and is the speed at which the radius of the bubble increases. Due to the increase in size, the rise of the bubbles accelerate upward. 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, respectively. It is presumed that the density of the gas in relation to that of the liquid can be neglected and that the bubble is so small and rises so slowly that it retains its spherical shape. We assume that the buoyant force F is balanced by the viscous force (Stokes' law)

(5) $F_S = 6\pi\eta r v$

$\eta(20^0C) = 0.001 kgm^{-1}s^{-1}$ 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 forces from equation (4) and equation (5) and solving for v, we obtain

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

This value corresponds to our observation.

References:

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

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

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