Vapour pressure and adiabatic cooling from champagne: slow-motion visualization of gas thermodynamics

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Vapour pressure and adiabatic cooling from champagne: slow-motion visualization of gas thermodynamics

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Abstract

We present two simple demonstration experiments recorded with high-speed cameras in the fields of gas dynamics and thermal physics. The experiments feature vapour pressure effects as well as adiabatic cooling observed upon opening a bottle of champagne.

S Online supplementary data available from stacks.iop.org/PhysED/47/608/mmedia

Introduction

The recent introduction of inexpensive high-speed cameras [1] offers a new experimental approach to many simple but fast-occurring events in physics, e.g. [2–8]. In extension of experiments in the field of mechanics of solids [3] and fluids [9], we present here examples of thermodynamic processes. Most processes in thermal physics are quite slow. The timescales associated with changes in temperature depend on the mass of objects, specific heat, etc and therefore macroscopic solid or liquid objects usually have time constants much larger than seconds [10, 11]. On a microscopic scale solids can well have time constants down into the ms and μs range [12]; however, even the respective qualitative observations require additional microscope optics. Therefore we present here two rapid processes associated with the thermodynamics of gases. In addition we will give simple qualitative and quantitative descriptions of the underlying physics.

Thermodynamics of gases: vapour pressure within a test tube

The first experiment may be called the vapour pressure cannon. We fix a test tube (mass: 12.2 g) with well-defined geometry (inner diameter: 14.0 mm, outer diameter: 15.5 mm, length: 16.0 cm) using a wooden clamp. It is filled to about half of its volume with water and closed with a rubber stopper of truncated cone geometry (length: 20.5 mm, upper diameter: 13.0 mm, lower diameter: 17.5 mm, mass: 5.6 g). The experiment consists in heating the water with a camping burner (or Bunsen burner) such that the vapour pressure within the closed volume of the test tube rises. Once it reaches a critical value, typically within less than a minute, the stopper is ejected and leaves the tube with high

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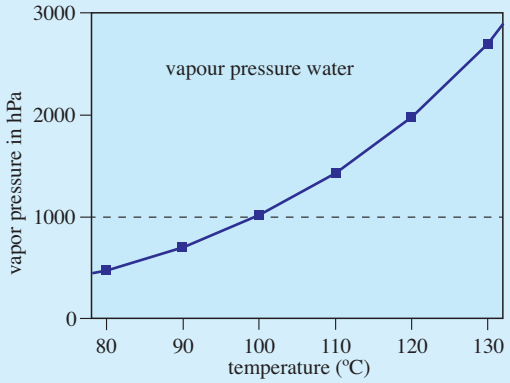

Figure 1. Vapour pressure of water as a function of temperature.

speed. Take-off happens when the force acting upon the stopper from the inside due to vapour pressure exceeds the frictional force, which mostly depends on how deeply (i.e. with how much force) the stopper was inserted into the tube. Figure 1 (left) shows the vapour pressure above the water surface as a function of temperature. Clearly, temperatures as low as 120 °C already give rise to an internal pressure of about twice the atmospheric pressure, i.e. a pressure difference to atmospheric pressure of 10^5 Pa.

In order to get a feeling about the actually occurring temperatures, the experiment was recorded with an IR camera [12, 13]. At the start (figure 2(a)) the water level can be seen easily since the tap water has a different temperature than the tube. Upon heating, one may still observe part of the optically thin gas flame with the LW IR camera used; however, outside of the flame, temperatures more or less resemble the actual surface temperature of the test tube. Figure 2(b) was recorded a few seconds before the stopper was ejected. The temperature profile along the line in figure 2(b) is shown in figure 2(c), revealing that there is—as expected—a strong gradient from the flame region to the top due to the low thermal conductivity of glass. The water which starts boiling comes into contact with the colder walls above the previously cold liquid level within the test tube. However, the vapour pressure above the liquid cannot effectively conduct the heat fast enough to the walls; therefore, the uppermost part is still cooler than 100 °C, although the water is boiling and vapour pressure is already building up. Obviously (figure 2(c)) the test tube walls in contact with the boiling water already have temperatures well above 115 °C. This explains easily why the stopper is pushed outward. In principle measurements like that of figure 2 can be used to estimate internal pressure; however, we only performed one of these IR temperature measurements to verify our expectations. Since results vary between experiments depending on how strongly the stopper was pushed into the test tube and since the temperature also depends on time—we would need to measure the temperature at precisely the moment of ejection—we prefer to use high-speed videos and analyse the motion of the stopper to derive the internal pressure within the test tube at the moment of stopper ejection.

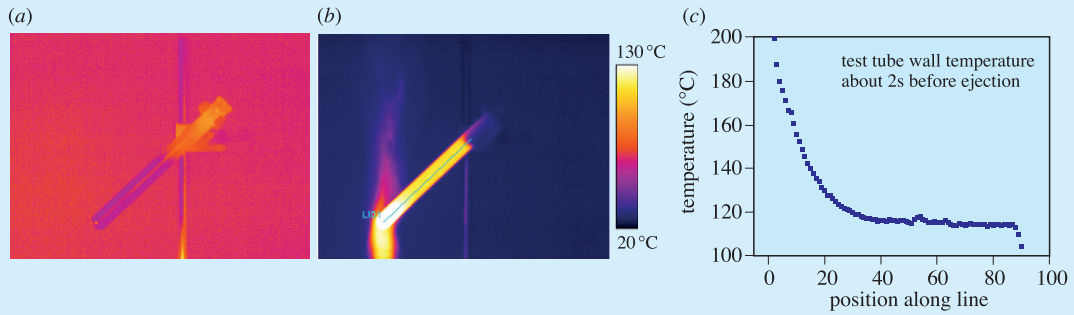

Figure 2. Example of an IR image of test tube with water before heating (*a*) and 1–2 seconds before stopper was ejected (*b*). The line graph (*c*) reveals that in this case wall temperatures at the upper part of the tube were well above 110 °C (analysis was done with emissivity $\varepsilon = 0.87$, which holds for glass for broadband detection from 8–14 μm).

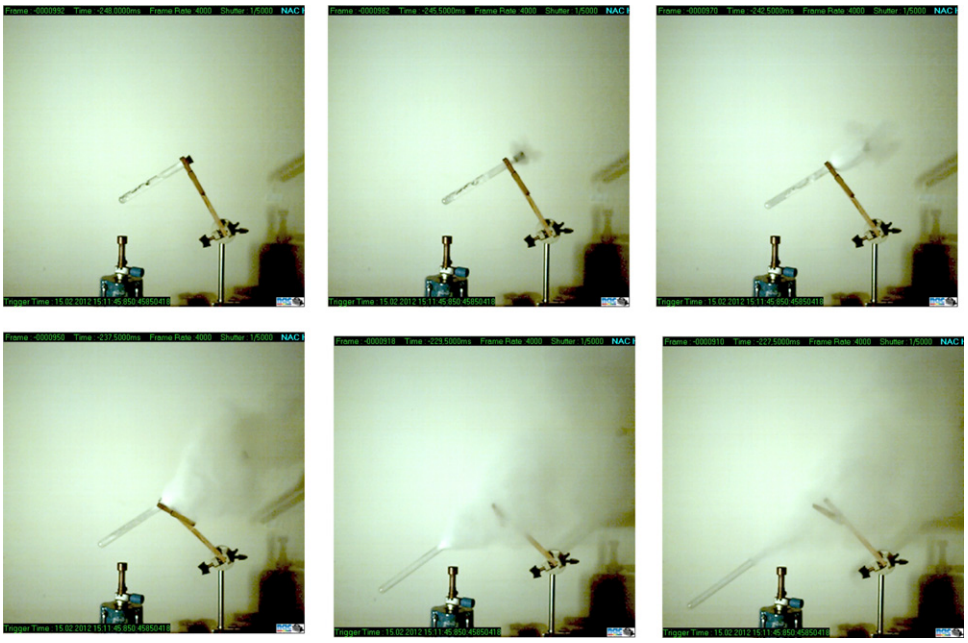

Figure 3. Ejection of a rubber stopper from a test tube due to vapour pressure. Sequence of snapshots recorded with 4000 Hz/shutter 1/5000 s at the following times: $t = 0$, +2.5 ms, +5.5 ms, +10.5 ms, +18.5 ms, +20.5 ms (for details, see the text).

We recorded a number of experiments where the stopper was pressed into the test tube with different applied pressures. With little force, the stopper is ejected alone and the clamp takes the recoil. However, for large force, the recoil due to the stopper and moreover the water which is ejected from the open end of the tube can lead to acceleration of the tube such that the clamp can no longer hold it. Figure 3 (for the video see the supplementary data available at stacks.iop.org/PhysED/47/608/mmedia; we recommend a player such as VLC, which allows adjustment of the presentation speed) depicts an overview of such an experiment recorded with 4000 fps and an integration time of 1/5000 s. While the stopper is ejected and water together with vapour is pushed out from the tube, the tube is accelerated. The clamp is first bent and then can no longer hold the tube, which accelerates as long as water is ejected. The motion is therefore due to the well-known rocket propulsion effect. One could study this further by attaching the clamp to the stopper so that the test tube was free right after ejection.

Figure 4 (for the video see the supplementary data available at stacks.iop.org/PhysED/47/608/mmedia) shows a close-up of a similar experiment recorded with 1000 fps, i.e. such experiments can of course also be recorded with inexpensive high-speed cameras operating at 1000 frames s^{-1}. One can nicely see that the high-pressure vapour which is ejected faster than the stopper immediately leads to a condensation cloud, which hides the stopper after a few ms.

The ejection of the stopper requires the pressure difference Δp between the internal and external pressures of the test tube to be large enough such that

$$\Delta pA \geq F_{\text{frict}}, \tag{1}$$

where F_{frict} is the frictional force between the stopper and the inner glass surface and A is the cross-sectional area of the test tube. This means that according to Newton's law the start of the motion of the stopper is described by $ma = \Delta pA$, i.e. the initial acceleration of the stopper is given by

$$a = \frac{\Delta pA}{m}, \tag{2}$$

where m is the mass of the stopper. For constant acceleration, the velocity of the stopper can be approximated as $v = at$. This is probably only

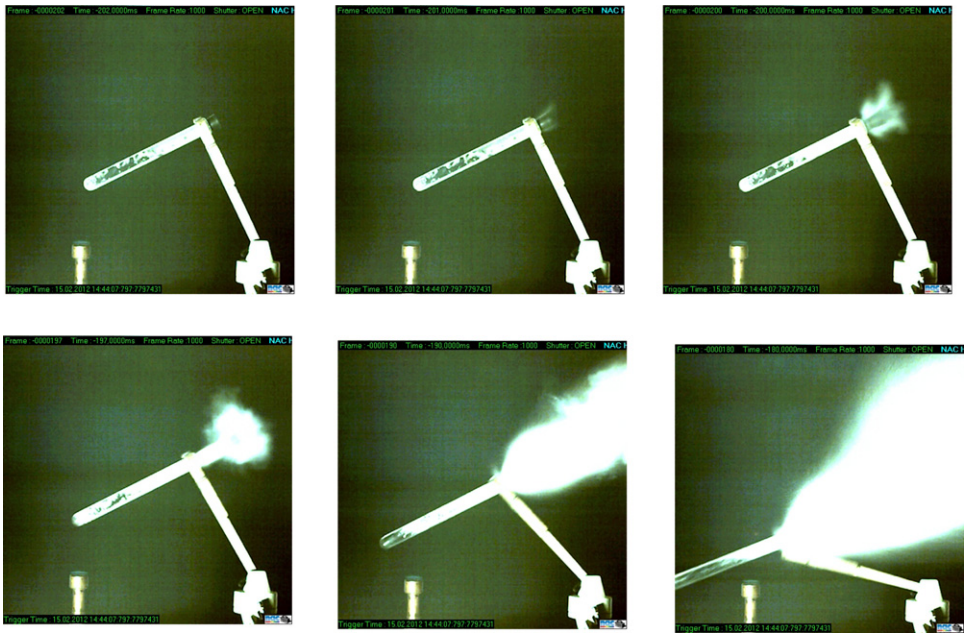

Figure 4. Ejection of a rubber stopper from a test tube due to vapour pressure. Sequence of snapshots recorded with 1000 Hz/shutter open at the following times: $t = 0$, $+1$ ms, $+2$ ms, $+5$ ms, $+12$ ms, $+22$ ms (for details, see the text).

a rough estimate—at these slow velocities, air resistance can safely be neglected; however, the actual acceleration due to the pressure difference will decrease upon ejection as the inner gas streams out of the tube; this means that, e.g., for linearly decreasing pressure difference with time, the average velocity could easily be a factor of two smaller within the same acceleration period. From figure 4, it can be seen that the stopper is ejected within at most 2 ms. Using this value as the acceleration time, we can estimate the stopper velocity from the inner diameter of 14 mm and the mass of 5.6 g to be v (m s^{-1}) = $5.5 \times 10^{-5} \Delta p$ (N m^{-2}). Quantitative analysis of figure 4 revealed a stopper velocity of 11 m s^{-1} within the first 1 ms. This is consistent with a pressure difference of 2×10^5 N m^{-2}, which, according to figure 1, can already be achieved for vapour temperatures slightly above 130 °C.

One may also evaluate the motion of the test tube itself (figure 3) after having left the clamp. The test tube accelerates due to the rocket principle: water vapour is streaming out at high velocity. Initially, half its volume was filled with water, with a mass of about 12 g. Most of this, about 10 g, is vaporized and ejected within 16 ms, with initial vapour velocities of up to 35 m s^{-1} (figures 3 and 4 show that the much slower stopper is soon hidden behind the vapour). For a rough estimate we assume the mass flow $\Delta m/\Delta t$ to be constant: $\Delta m/\Delta t = 10$ g/16 ms = 0.625 kg s^{-1}. Now, also assuming the initial velocity of 35 m s^{-1} to be constant during this period, we find a propulsion force of $F = \Delta mv/\Delta t = 21.8$ N. This force, if being caused by gravity, would correspond to a mass of 2.2 kg. Therefore it is easy to understand why the clamp cannot keep hold of the test tube. We mention that of course this analysis may be pursued further to estimate the velocity of the tube and clamp when the tube is released. One just needs to measure the period for which the tube is still accelerated by the mass flow of the vapour and from that estimate the final velocity of the released tube.

Adiabatic cooling upon opening a bottle of champagne

The most well-known rapid processes in thermodynamics of gases are adiabatic processes, i.e. those which happen so fast that the gas cannot exchange thermal energy with a surrounding heat

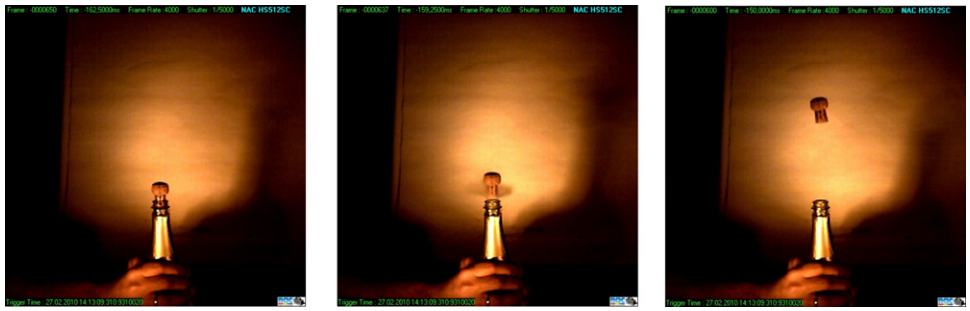

Figure 5. The condensation cloud observed for adiabatic expansion of CO_2 upon opening of a bottle of champagne in rather dry air (for details, see the text).

bath. Most common examples in teaching are adiabatic compression, e.g. when using an air pump to inflate a tyre, or adiabatic expansion when a gas streams out very fast from a nozzle, e.g. that of a tyre. In the first case, most students know by personal experience that the pump cylinder gets warm since the compressed air heats up adiabatically and subsequently this hot gas heats up the pump. In the second case, when air is, e.g., streaming out fast from the valve of a tyre with initially 3–4 bar pressure, it again has no time to exchange energy with the surroundings. Since it does work while expanding, it uses up its internal thermal energy and cools down. In most cases the gas itself is not detected (for exceptions see [12]), therefore secondary cooling of the valve may be detected or the cooling of objects like paper placed in the cold gas stream [12].

While these effects are well known, adiabatic cooling can offer more interesting thermal phenomena. We studied the phenomena which occur upon uncorking a bottle of champagne. Champagne and other sparkling wines [14] are produced such that above the liquid within the bottle there is a small volume of several cm^3 composed of a little bit of residual air, but mostly of CO_2 at a high pressure of typically 3–4 $\times$ 10^5 N m^{-2} (3–4 bars). When the safety clamp around the cork is removed, the cork does not take off immediately, since the truncated cone shape of the cork leads to very high frictional forces with the glass of the bottle neck. On the one hand one may cautiously try to loosen the cork by twisting it a bit, on the other hand the pressure within the bottle can be increased even more by warming up the liquid and/or the gas above it, e.g. by holding the bottle with warm hands. This finally leads to ejection of the cork. Figure 5 shows an example of this event. Upon releasing the cork, the gas streams out rapidly through the wide nozzle-like bottle neck. This adiabatic expansion cools the escaping gas appreciably. These gas molecules suffer many collisions with the surrounding air molecules, including water vapour. Therefore some of the adjacent air is also cooled down before thermal equilibrium at room temperature is established again.

The initial cooling of adjacent air packages can lead to observable condensation clouds if enough water vapour is present and the cooling temporarily leads to temperatures below the dew point within the air (and, of course, if condensation nuclei are present which is usually the case in room air). Figure 5 (for the video see the supplementary data available at stacks.iop.org/PhysED/47/608/mmedia) was a first successful experiment where we could observe a condensation cloud of the ejected gas for up to about 2 ms.

In order to improve the set-up, we performed a number of additional tests (unfortunately, not too many since each experiment costs a new bottle of champagne). In order to increase the relative humidity well above the regular 50% or so, we poured hot water on the table on which the bottle was standing and surrounded the set-up from all sides except part of the back (to be able to touch the bottle) with glass. The relative humidity was measured to be around 70% at the position of the bottle neck during the experiment (figure 6, for the video see the supplementary data available at stacks.iop.org/PhysED/47/608/mmedia), i.e. higher than in figure 5. Unfortunately, loosening of the

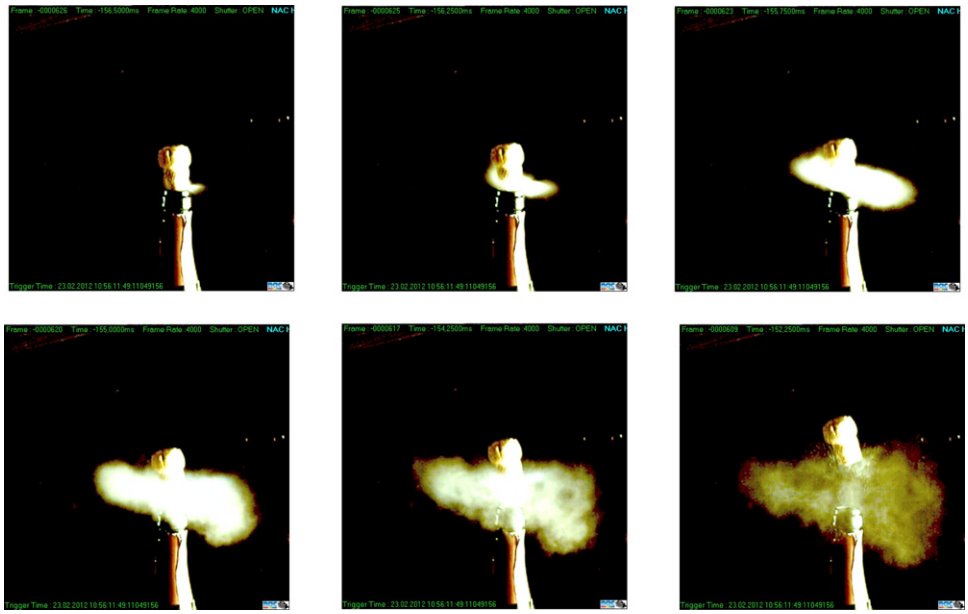

Figure 6. The condensation cloud observed for a few ms during adiabatic expansion of CO_2 upon opening of a bottle of champagne in air with relative humidity of around 70% (for details, see the text).

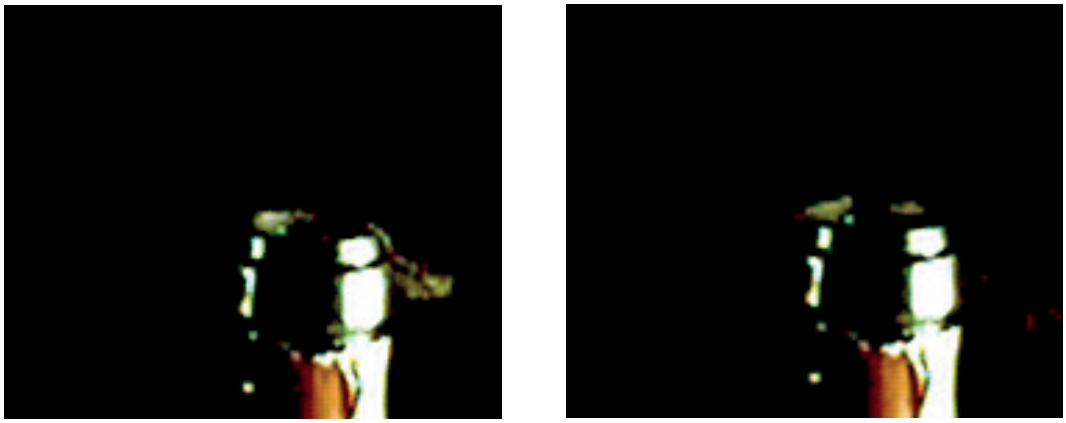

Figure 7. Slow flows of condensed water vapour (15 ms between images) after the bottle is opened.

cork led to a slightly asymmetric ejection and hence to a similarly asymmetric gas flow out of the bottle. Figure 6 clearly reveals that the condensation cloud was much more pronounced and lasted up to 9 ms. This only temporarily observable adiabatic condensation cloud with a few ms duration has nothing to do with the slow cold gas flows after the ejection of the cork which are sometimes visible (figure 7, for the video see the supplementary data available at stacks.iop.org/PhysED/47/608/mmedia). The latter occur after the bottle is opened if the air is subsequently cooled by the now exposed cold liquid and/or partially escaping cold CO_2 from the champagne.

A quantitative analysis of the experiment starts with the cork ejection. The bottle's inner diameter is 17.8 mm, giving a cross-sectional area of $\approx$2.5 cm^2. The cork was ejected with an initial velocity of 12 m s^{-1} (43.2 km h^{-1}). Neglecting air resistance, this cork velocity is sufficient to reach a height of about 7.3 m.

The velocity of 12 m s^{-1} can be understood—similarly to the test tube experiment above—from the internal pressure. Assuming $\Delta p = 4 \times 10^5$ N m^{-2}, we find an initial force on the cork of $F = \Delta pA = 100$ N. Using the mass of the cork, $m = 9.1$ g, the initial acceleration is given by equation (2) to be $a = F/m \approx 11\,000$ m s^{-2}.

The initial acceleration only lasts for about 1–2 ms. If there were constant acceleration for 1 or 2 ms, one would find a velocity of about 11 or 22 m s^{-1}. In reality, similarly to the test tube experiment, the acceleration process is rather complex: the pressure decreases rapidly within the first 2 ms as the gas streams around the cork, i.e. the acceleration decreases as a function of time. If it decreased linearly from 11 000 m s^{-2} to zero within 2 ms, one would again find a velocity of 11 m s^{-1} for the cork. Due to the unknown acceleration and respective time the above analysis should only be considered as giving order of magnitude estimates.

Besides the dynamics of the cork, one may also evaluate the initial velocity with which the forming condensation cloud spreads out. Within the first 0.25 ms, the condensation cloud has moved a greater distance than the cork (here 23 mm) and its initial velocity was about 92 m s^{-1}. This spreading velocity of the condensation front is still much less than the average velocity of the individual gas molecules which for CO_2 treated as an ideal gas should be around 375 m s^{-1} at 20 °C (or 305 m s^{-1} at −80 °C). For an ideal gas, the mean free path between collisions, $\lambda \approx 10^{-2}$ cm/p[hPa], is about 100 nm for 1000 hPa and only about 20 nm for 5000 hPa. Obviously, each gas molecule will have experienced more than 10^6 collisions within the first 0.25 ms. During the collisions, the adjacent gas is effectively cooled down while the CO_2 molecules get warmer. The condensation front will at first propagate very fast, but as less and less condensation is taking place it eventually stops.

Let us try to get a rough estimate of the involved energies and gas volumes or masses. For an adiabatic process we have

$$p^{1-\kappa} T^{\kappa} = \text{const.}, \tag{3}$$

where $\kappa = c_p/c_V$ is the ratio of specific heat capacities. For molecular gases, κ depends on the number of degrees of freedom of the molecule. For CO_2 at room temperature (and also slightly below), $\kappa \approx 1.30$. Assuming $p_1 = 5 \times 10^5$ Pa, $p_2 = 1 \times 10^5$ Pa and T_1 (=10 °C) ≈283 K, we find for a purely adiabatic expansion a final temperature $T_2 \approx 195$ K (≈ −80 °C). This value seems quite reasonable from adiabatic expansion experiments with compressed CO_2 in technical gas containers. Letting CO_2 expand from such a container by using valves and pressures of a few atmospheres usually creates dry CO_2 ice, which at normal pressure in the surroundings only starts to form at temperatures below −78.5 °C.

To reach the state after expansion, the gas has cooled down and the work for expansion $\Delta W = p\Delta V$ is related to the change of internal energy ΔU of the gas via the first law of thermodynamics

$$\Delta U = \delta Q - \Delta W, \tag{4}$$

where δQ denotes the exchange of heat during the process. The sign convention here means that if $\Delta V < 0$, i.e. if there is a compression, ΔW is negative, since work is done from outside which increases the internal energy. For adiabatic processes, $\delta Q = 0$. For the adiabatic expansion, the gas does work while decreasing its internal energy. This goes along with a temperature change of the gas by

$$\Delta U = c_v m \Delta T. \tag{5}$$

The mass of the gas is found from the gas volume in the bottle. Assuming $V \approx 5$ cm^3 and a density of CO_2 of around 2 kg m^{-3} = 2 mg cm^{-3}, we find a gas mass $m \approx 10^{-2}$ g. The specific heat at constant volume c_V at room temperature is around 0.65 J g^{-1} K^{-1}, which—with $\Delta T \approx$ 90 K—gives $\Delta U \approx 0.59$ J. This is the total drop in internal energy of the CO_2.

We now assume that upon collisions of cold CO_2 molecules with the adjacent gas, the air will cool down from room temperature of around 20 °C to dew point temperature (which for 70% relative humidity is around 14.5 °C, i.e. $\Delta T_{\text{dp}} =$ 5.5 K) and then its water vapour will condense to small droplets. Assuming as a limiting case that we will use all of the available internal energy drop ΔU of the CO_2 for the thermal energy ΔQ for this process and that all of the water vapour within the air will condense (which seems unreasonable) we can find an estimate of the gas volume in which condensation takes place. We start with

$$\Delta Q = c_{V,\text{air}} m_{\text{air}} \Delta T_{\text{dp}} + \Lambda m_{\text{W}}, \tag{6}$$

where $m_{air} = \rho V_{air}$ is the mass of air including water vapour and $m_W = \rho_W V_{air}$ is the mass of the water vapour within this air volume. Λ denotes the heat of condensation of water, which is around 2250 kJ kg^{-1}. Saturated air with 100% humidity at 20 °C corresponds to 17.3 g m^{-3}, hence we have $\rho_W = 12.1$ g m^{-3} for the air with 70% relative humidity. From $\Delta Q = (c_{V,air}\rho_{air}\Delta T_{dp} + \Lambda\rho_W)V_{air}$ we can estimate the minimum volume of air V_{air} (probably of toroidal form, see figure 5), which may be cooled down enough to form the observed condensation cloud. We find $V_{air} \approx 18$ cm^3, which as a lower limit is consistent with the observed results.

Conclusions

High-speed imaging can visualize and also help to quantitatively understand fast thermodynamic processes in a subsequent slow-motion analysis. We have only shown two examples dealing with vapour-pressure-induced effects and adiabatic cooling, but hopefully many more will be investigated and reported in the future.

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