For teachers

The gas we drink - Carbon dioxide in carbonated beverages

Task description

The students will break into groups of 3-5 and each group will carry out in school a number of experimental activities. First, they will study at school and at home the properties of gases and the physical and chemical properties of carbon dioxide. The emphasis will be on gas solubility in liquids and the gas laws. Secondly, they must think of and propose a simple method for determining the amount of carbon dioxide that is contained inside a carbonated beverage. Thirdly they must devise a method for determining the pressure that prevails inside a closed bottle or can containing a carbonated beverage. They will attempt to explain the observed phenomena and account the experimental errors involved. Finally, the teacher will carry out a demonstration of a carbon dioxide fountain, and the students working in groups will seek the explanation for the operation of the fountain.

Phase 1

This phase consists of an introductory lesson, during which under the guidance of the teacher students will revise in class their knowledge about gases, the atmospheric pressure, and gas laws, including the ideal-gas law. Particular emphasis will be placed on carbon dioxide and its properties. In addition they will perform simple experiments that contribute to studying and understanding the properties of gases, for instance: blowing a straw into a glass containing limewater in order to detect the presence of carbon dioxide in breadth; comparison of similar in size balloons filled with different gases (air, argon, and carbon dioxide); measurement of pH of various carbonated beverages.

The teacher will break the class into groups of 3-5. Each group is assigned the task to bring to school for the next lesson one or more bottled carbonated beverages. The bottles should be made of glass and have same content (e.g. 330 mL). In addition, students will be assigned the task to study further at home alone or working in their group about: (i) the physical

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and chemical properties of carbon dioxide, (ii) the solubility of gases in liquids and factors affecting it; (iii) experimental methods for collecting and measuring the volume of a gas.

Phase 2

The groups perform in the lab a number of preliminary experiments. They open bottled carbonated beverages and observe carbon dioxide escaping, and suggest an explanation. In addition, using two bottles with the same carbonated beverage, one having been kept in the fridge, the other in a warm place, and by attaching on the bottle's neck a stopper with a tube passing though it, observe and try to explain the amount of bubbles that escape from the tube's end into a container with water. In this way, they study the effect of temperature on the solubility of gases in liquids.

Following this, each group of students will have the task to build an appropriate experimental set-up for collecting and measuring the volume of carbon dioxide that is contained in a carbonated beverage. For this purpose, they will use materials from the school lab. The students will discuss within their group and suggest an experimental set up. The teacher will act as an advisor, commenting on the proposals and suggesting ways for improvements. He/she will not however give students a final answer. After the teacher approves the experimental set up, the students will start the activity.

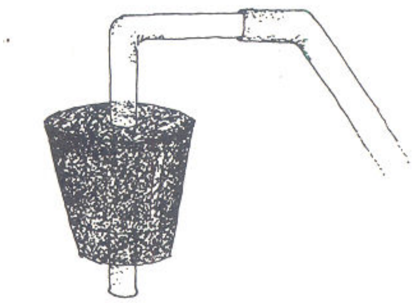
Part 1: Preparing the bottled carbonated beverage

The bottle must have been kept in the fridge for sufficient time, so that to acquire a low temperature. In this way, when the bottle is opened, there will be as less loss of carbon dioxide as possible.

Part 2: Making the plastic stopper with the glass tubing passing through it

We select a plastic cup that tightly fits on the glass stopper. We make a hole into the stopper and pass thin glass tubing through it, with a diameter of 3-4 mm. The one end of the tubing should go down into the bottle reaching just over its bottom, while the other end over the stopper is bent to make a 90^{o} angle. To this end, we attach a piece of plastic tubing, the other end of which is introduced into the base of a eudiometer.

SAFETY NOTE! It is best to prepare the stopper and tubing assembly for the students. Fire polish each end of the glass tubing - Heat it carefully in a hot flame until the sharp ends are smooth. Lubricate the tubing with glycerol or water, and carefully insert the tubing in the stopper with a twisting motion. You may make a bend before inserting the glass in the stopper.



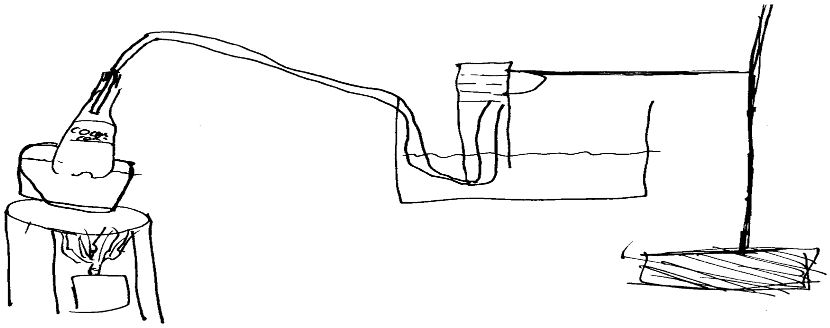
Picture 1 – The stopper with the glass tubing passing through it, plus the plastic tubing attached to the glass tubing.

Part 3: How to collect and measure a gas

The setting up with the reversed measuring cylinder filled with water is a difficult task for students. Filling the cylinder with water, without any bubbles, and its fastening requires certain skills and experience.

Part 4: How to heat the bottle with the bottled beverage

The bottle is placed into a beaker containing cool (tap) water. The beaker is then heated with a Bunsen burner, with the flame adjusted so that heating is slow. In this way, collection of the carbon dioxide gas takes place slowly, allowing a better execution of the experiment.



Picture 2 – Actual drawing by a group of students of the used experimental set up.

Phase 3

Each group performs its own experiment, using their own bottled beverage. They record their measurement and report it to the rest of the class. The findings from different bottled beverages are collected and Table 1 in *Student's Notes* is filled in. In this way students have the chance to compare and evaluate their findings. A discussion of possible errors in this measurement will then be made. The following questions aim at testing understanding of the issues that are relevant to the above activity.

Questions and Answers

1. *What factors affect the solubility of a gas in a liquid?*

   The nature of the solvent and of the solute (in terms of polarity of their molecules) plays an important role for solubility. The rule "***same dissolves same***" is a useful rule of thumb. The solubility of a gas is affected by temperature (it lessens with temperature), and by pressure (it increases with pressure).

2. *Some kind of fish requires more dissolved oxygen in water than other kind. Salmon, for example, is found only in northern seas, where the water temperature is under 15^{o}C. Explain this observation in relation to oxygen's solubility in water.*

   In cold climates, the solubility of oxygen in the sea is higher, and this satisfies the increased need of some fish for oxygen.

3. *In lakes that are at high altitudes life seldom appears in the water. There is no fish in these lakes. Explain this observation.*

   At high altitudes the pressure is lower, hence the solubility of oxygen in the water of the lakes is small.

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4. *In water tanks with cultivated fish, water is sometimes not renewed properly, and in summertime a number of fish die. Explain this observation.*

   Because of high temperatures during summer the available in the water oxygen is reduced, and this causes the problem.

5. *Carbon dioxide is an approved food additive in the European Union, and its code number is E 290. For what reasons is carbon dioxide added to carbonated beverages?*

   Carbon dioxide offers to carbonated water and to beverages a pleasing flavour. It also protects from bacteria and microbes. The carbon dioxide that reaches our stomach when we drink the beverages is absorbed very fast; at the same time the absorption of the liquid beverage increases, causing a feeling of digestion and relief.

6. *Compare the pH of a carbonated beverage immediately after you open it, and then after having collected the contained carbon dioxide.*

   Initially the beverage has a slightly acidic pH because of the presence of carbonic acid (H_2CO_3, a weak acid). When carbon dioxide escapes, pH increases, taking a value around 7, and making the beverage lose its pleasing acidic taste.

7. *In carbonated beverages gaseous carbon dioxide is dissolved, Sometimes, we refer to these beverages as containing carbonic acid. What is the relation of carbonic acid to carbon dioxide?*

   A small part of carbon dioxide (less than 1%) reacts with water forming carbonic acid, which then ionizes providing H_3O^+ :

$$CO_2 + H_2O \Leftrightarrow H_2CO_3$$

$$H_2CO_3 + H_2O \Leftrightarrow H_3O^+ + HCO_3^-$$

$$HCO_3^- + H_2O \Leftrightarrow H_3O^+ + HCO_3^{2-}$$

Phase 4

Working always in groups, the students must devise a way to measure the gas pressure inside an unopened canned beverage. The students have one short period (45 minutes) to plan their strategy, and one extended period (75 minutes) to complete their investigation in the laboratory. They may use any of the standard equipment in the lab.

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The experiments and the discussion for this and the following phase are based on:

Hans de Grys, *Determining the pressure inside an unopened carbonated beverage* Journal of Chemical Education, Vol. 84, No. 7, 1117-1119.

Various possible solutions

The "Ideal-Gas equation" Solution

This approach makes use of the ideal gas law. When performed carefully it usually generates a fairly accurate answer. To use the ideal gas law to calculate the pressure inside the can, one needs to know the temperature of the gas, the volume of the gas, and the number of moles of gas. Measuring the temperature is straightforward, especially if the students allow the bottles or cans to sit at room temperature and come to thermal equilibrium with the lab environment. Drinks that are still slightly cool from the refrigerator can be measured with a thermometer upon opening, although error is introduced here as the drink tends to warm up during the course of the experiment.

Students must measure the mass of the sealed bottle first, then carefully open it listening for the characteristic *pssssst* of escaping carbon dioxide. Immediately, they find the new mass of the opened can on the balance and record their data. In this way students can measure the mass of CO_2 that escapes when the gas sitting above the drink goes from its unknown higher bottling pressure down to atmospheric pressure. Typically masses range from 0.1 to 0.2 g for the escaping gas, depending largely on the temperature. A conventional 12-oz can of soda has a mass in the range of 380–390 g, so it is important that the balance have a capacity of at least 400 g as well as accuracy to at least ± 0.01 g (a milligram balance is preferable, but not strictly necessary). A little stoichiometry yields the moles of carbon dioxide that left the container immediately upon opening.

Finally, the students need to find the volume of the gas space in the can. Only the headspace where the gas resides (and not the volume of the liquid nor the entire volume of the can) is the measurement of interest. Also, at equilibrium, the carbon dioxide that is dissolved in the aqueous solution does not directly contribute to the pressure of the gas in the unopened bottle.

Another method is to empty the entire can to find the volume of the soft drink, the total capacity of the can, and volume of the headspace by subtraction. This is not terribly accurate. A better way is to pop the top and then slowly and carefully add water from a very small graduated cylinder or graduated pipet. Students keep track of how much water they add and stop when the total level of the liquid rises to the top of the can. Typical volumes for the headspace are around 14–16 mL.

NOTE: The pressure calculated in this manner does not represent the total pressure inside the can before it was opened, but rather the “gauge pressure”, or the added pressure above ambient atmospheric pressure. Even after the explosive opening *pssssst*, there is still carbon dioxide gas occupying the headspace, exerting a pressure equal to the ambient atmospheric pressure. Thus, if one wishes to calculate the total pressure of gas in the can before it was opened, the current atmospheric pressure in the room must be added to the calculated gauge pressure.

Capturing the Gas

A second strategy centers around trying to capture the gas that is trapped in the headspace. This technique involves submerging the can in a container of water and constructing a gas trap of some kind to catch the escaping carbon dioxide by water displacement. The apparatus usually involves a eudiometer or graduated cylinder to measure the volume of the gas, and a funnel and rubber tubing to try to catch the escaping gas when the container is opened.

This method is usually inferior for a number of reasons. First, some of the gas will inevitably escape, and some bubbles of carbon dioxide will not make it into the eudiometer. Second, there is some subjective judgment involved as to when the gas from the headspace has all been collected and when the device is beginning to collect carbon dioxide that is outgassing from the aqueous solution. The distinction is an important one, since the gas that was dissolved when the can was sealed did not contribute directly to the pressure.

Finally, the calculations are a little more complicated since the vapor pressure of water must be considered when finding the pressure of the collected carbon dioxide by water displacement. This method also does not provide the volume of the initial headspace, and therefore a second can of beverage is required to get this additional information.

With an advanced chemistry class, it is possible to resort to Henry’s law to determine the pressure (see Teacher’s Notes). Other methods as well as comments on accuracy and precision are also given in Teacher’s Notes.

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Phase 5

In this phase there will be a revision of all the activities, the findings, and their interpretation. Students will discuss errors entering the various proposed and executed methods. Finally, the Teacher will carry out a demonstration of a *carbon-dioxide fountain.*

Accuracy and Complexity

No one is arguing that any of the above methods will generate extremely accurate or precise figures for the pressure inside a sealed beverage can. Some measurements involved are subject to relatively large uncertainty, such as 5% or more for volume measurements of the headspace owing to the constant effervescence of the drink. And even the more accurate models described above include some working assumptions or simplifications. Moreover, experience has shown that the exact pressure varies somewhat from brand to brand and even from can to can.

Since the solubility of carbon dioxide varies so dramatically with temperature, it is important to consider carefully the temperature of the can when evaluating the accuracy of the pressure. A graph of carbon dioxide's solubility in water at different temperatures could be readily used in creating a rough graph of a particular soda's gauge pressure at those temperatures.

Some students may want to shake the can first as a way of altering the pressure inside. Interestingly, this seems to have a pretty small effect on the pressure that is measured by these different methodologies. This result seems to support the idea that while shaking a sealed can of beverage may redistribute the gas inside (and consequently contribute to foamy eruptions) it does not cause much (if any) of the dissolved CO_2 to come out of solution.

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Carbon-dioxide fountain

A *Tested Demonstration* published in the *Journal of Chemical Education*,
submitted by: *Seong-Joo Kang and Eun-Hee Ryu*
checked by: *Mark Case*

The ammonia fountain has been a classic popular demonstration. It has also been used in connection with problem solving (Tsaparlis & Kampourakis, 2003). The experiment is suitable for understanding the solubility of gases in liquids, acid–base interactions, matter flow by pressure difference, and other concepts. Seong-Joo Kang and Eun-Hee Ryu have developed the carbon dioxide fountain using consumer chemicals.

Alka-Seltzer is often taken for acid indigestion. The active ingredients in Alka-Seltzer are sodium bicarbonate, citric acid, and aspirin. When an Alka-Seltzer tablet is dissolved in water, sodium bicarbonate reacts with acid to generate carbon dioxide gas:

$$3NaHCO_3(aq) + \underset{\text{citric acid}}{H_3C_6H_5O_7(aq)} \rightarrow 3CO_2(g) + 3H_2O + Na_3C_6H_5O_7(aq)$$

$$NaHCO_3(aq) + \underset{\text{aspirin}}{HC_9H_7O_4(aq)} \rightarrow CO_2(g) + H_2O + NaC_9H_7O_4(aq)$$

These reactions are used as a carbon dioxide gas source in the demonstration of the carbon dioxide fountain.

In a closed system, the dissolution of carbon dioxide into alkaline hydroxide solution, as described by the following equations, results in a pressure decrease:

$$2NaOH(aq) + CO_2(g) \rightarrow Na_2CO_3(aq) + H_2O$$

$$Na_2CO_3(aq) + H_2O + CO_2(g) \rightarrow 2NaHCO_3(aq)$$

The decrease in pressure is the driving force for the carbon dioxide fountain. As the gas dissolves in the alkaline solution reducing its pressure, water is driven by atmospheric pressure up from the beaker through the glass tube creating the fountain effect.

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