Once you POP, you can’t stop!
Group #24
Monday, November 24th, 2008

1. What is “flux”?
   Amount changing per area during an amount of time.
   Talk about “experience with drinking flat soda and how it tastes bad”, carbonation is what

2. What are some of the properties that will affect the flux/loss of carbon dioxide in soda?

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Pressure</th>
<th>Equilibrium</th>
<th>Concentration Gradient</th>
<th>Rate of Diffusion</th>
</tr>
</thead>
</table>

Experiment #1:

Cold Refrigerator: 3-4 ºC
   USDA recommendation

Room Temperature: 22 ºC
   ~70º F

Hot Car: 65.5 ºC
   General Motors, Canada
   45 minutes on 95º F day

Equation #1
\[ N_{\text{CO}_2} = \frac{D_{\text{CO}_2/H_2O}}{\Delta z} \Delta C_{\text{CO}_2} \]
Diffusional Mass Transfer Equation

Term Definitions:
- \( N_{\text{CO}_2} (mol/m^2s) = \) flux
- \( D_{\text{CO}_2/H_2O} (m^2/s) = \) diffusivity coefficient specific to \( \text{CO}_2/H_2O \)

Variable Relationships:
- Dependency on Temperature
  \[ D(2) = D(1) (T(2) / T(1))^{2/3} \]

Equation #2
\[ N_{\text{CO}_2} = (D_{\text{CO}_2/H_2O} + E_m) \Delta C_{\text{CO}_2} \]
Convective Mass Transfer Equation

\( \Delta C_{\text{CO}_2} = \) change in concentration
\( \Delta z (m) = \) change in distance
\( E_m = \) eddy mass transfer

3. Which of these equations would be used to calculate the rate/flux of carbon dioxide leaving in experiment #1? Equation #1
   “Why don’t you shake your soda before you open it?” Fizzy = explosion.

4. From previous chemistry experience, what are a few good laboratory procedure techniques?
   Multiple Trials, Consistency, High Accuracy, Standardize Equipment
Experiment #2:

Data Collection:
- Temperature = _________________(°C)
- Time = _________________________(s)
- String Length = ________________(m)

Useful Conversions:
- Circumference = \(\pi D\)
- Volume = \(\frac{4}{3}\pi r^3\)

5. Assuming your balloon is a perfect sphere, what was your balloon volume?
   *Heat AND velocity = explosion!!!!!!*

6. Can you calculate the flux of carbon dioxide into your balloon? Which equations would you use? What extra information might you need that you haven’t been given?
Once you POP, you can’t STOP!
Teaching Mass Transfer Flux Dependence on Temperature and Velocity Using Dissolved Carbon Dioxide Gas in Liquid Soda Pop

Alexander Harris, Aubrey A. Parker, Huey Shann Sue, Jenny S. Ou, Lola Eniola-Adefeso
Chemical Engineering Department, University of Michigan, Ann Arbor, 48104
Submitted: December 9th, 2008

Introduction
Soda pop is one of the most popular drinks among Americans today. According to a new study\(^1\), the average American will drink over 50 gallons of soda annually. One of the unique features of soda is it’s “fizz”. This “fizz”, is produced by dissolved carbon dioxide escaping out of the liquid sugar-water solution. Once too much carbon dioxide leaves the soda-pop, the pop is less desirable to the drinker and a common phrase is to call the soda “flat”. The ability and rate of the dissolved carbon dioxide to escape out of the liquid solution depends on many conditions, such as pressure, temperature, and etc.

Diffusive Mass Transfer: An Overview
Flux is defined as the amount of a given quantity that flows through a unit area per time, where molecular diffusion is the mechanism by which gaseous carbon dioxide escapes motionless liquid soda. Molecular diffusion is the gradual transport of a molecule from areas of high concentration to low, powered by the random motion of molecules. The ability, ease, and speed of a molecule to move through a group of other molecules for a given concentration gradient are lumped into a term known as the diffusion coefficient \(D_{AB}\). The diffusion coefficient is a function of the temperature and pressure of the system: in this case, the soda pop. As the temperature of the soda pop increases, the diffusion coefficient increases, leading to the diffusion rate of carbon dioxide increasing as well. As more carbon dioxide escapes the surface of the soda, the soda will become “flat” faster.

Convective Mass Transfer: An Overview
Convective mass transfer is the process in which mass transfer is induced by an external velocity. Each specific case of convective mass transfer leads to different equations and different types of analysis, but the general theme of convective mass transfer is that the passing fluid is able increase the concentration gradient, therefore increasing the mass flux. In our case, convective mass transfer is induced by the motion of the liquid soda. In this experiment, the process of carbon dioxide escapes the liquid soda due to the motion of the soda pop is considered convective mass transfer.

Purpose and Objective
With better understanding of the mechanisms and dependent condition which lead to carbon dioxide flux, a soda drinker will be better able to preserve the carbonation, “fizz”, of soda. By keeping the soda temperature low and stationary (no convective velocity imposed), the diffusion rate of carbon dioxide will be lowered, hence, maximizing the soda pop “fizz” longevity

The goal of this experiment is to showcase two types of mass transfer, and the conditions that affect them. Diffusion and its dependence on temperature will be highlighted in the first portion of the experiment, whereas convective mass transfer and its dependence on fluid velocity will be highlighted in the second portion of the experiment. The carbon dioxide flux will be measured, by calculating the volume of the attached latex balloon. Therefore, by assuming ideal gas and balloon being a perfect sphere, one can calculate the amount of moles of carbon dioxide that escaped from the soda, and the rate for a given time.
Experimental

Materials
(20) Two-Liter Plastic Bottle Sodas $0.91 (per soda)
(20) Large Balloons: 30+cm diameter $2.99 (per package containing 20)
(1) Electric Kettle (or Hot Plate)
(3) Non-Mercury Thermometers
(2) Fifty-Liter Stainless Steel Cooking Pots
(1) Ice Box/Cooler
(17) 50-cm Strings
(17) Meter Sticks
(17) Markers $21.19 (Kroger Grocery)

***Note: This experiment is designed for a class size of 17 students. Prices are based from those at Kroger Grocery store using a Kroger discount card.

Sampling and Treatment
Careful measures should be taken to ensure all soda bottle samples are identical. Consistent with proper laboratory technique, the sodas used should be the same in all parameters. Ginger Ale is the recommended type of soda because it has a light color and a high concentration of carbon dioxide, so as to make the diffusing gaseous bubbles clearly visible for students. All soda bottles should be stored at room temperature. Five minutes before students arrive, the cap of each soda bottle should be unscrewed/loosened to equilibrate the pressure; do not, however, leave the caps off for long periods of time because this will cause loss of carbonation before the experiment begins. Carefully position one large balloon over the top of each soda bottle, making sure not to tear the balloon or spill soda into the balloon.

Method
Once students arrive, they should each be given a Student Worksheet (see attachment) and their own soda bottle, complete with attached balloon. Students should be instructed to set the bottles aside for Experiment #2 while watching the instructor set up for Experiment #1.

Experiment #1
Before students arrive, the instructor should prepare an ice bath at 3-4°C using a 50-Liter stainless steel cooking pot, and a hot bath near 65°C. The ice bath represents the temperature range for refrigerators, as recommended by the USDA for minimal bacteria growth. The hot bath represents the internal temperature of a car left for 45 minutes on a hot summer day, according to experiments done by General Motors.

Three soda bottles are to be used for Experiment #1 on the Student Worksheet. Experiment #1 uses Equation #1 (Diffusive Mass Transfer), to show the relationship between flux ($N_A$), diffusivity ($D_{AB}$), and temperature ($T$). Simultaneously, 3 soda bottles, completed with balloons, should each be placed in the cold, room temperature(20°C, control), and hot baths. The time should be noted, and all three soda bottles and their appropriate baths for Experiment #1 should be set aside while Experiment #2 is performed by the students.

Experiment #2
Each student will be competing against his/her peers in Experiment #2 Experiment #2 uses Equation #2, Convective Mass Transfer, to show the relationship between flux ($N_A$), diffusivity ($D_{AB}$), and velocity (proportional to $\epsilon_m$). On the instructor’s command, each student will stir, shake, or agitate his/her soda bottle at the speed with which he/she believes will cause the greatest loss of carbon dioxide, or flux of “fizz”, from the surface of the soda in the bottle to the attached balloon. The instructor should caution
students not to lose any soda to the balloon, as this can happen when the bottles are shaken too hard or are squeezed. The student with the largest balloon circumference at the end of 45 seconds is the winner. Circumference can be measured by wrapping a piece of string around the largest, middle portion of the balloon, marking the string, then lying the string flat and measuring to the mark with a meter stick.

**Expected Outcome and Discussion**

For these sets of experiments, the focus is a comparison between two experimental groups and the control group, isolating only one variable that will affect the flux of carbon dioxide. Therefore, many terms of the equations will be equivalent to one another and canceled out to simplify the equations.

For Experiment #1, if the sodas are assumed to be identical in every way, other than temperature, then the flux of carbon dioxide is proportional to the diffusion coefficient $D_{AB}$. The diffusion coefficient, $D_{AB}$ is dependent on temperature through the relation,

$$D_{AB,2} = D_{AB,1} \left( \frac{T_2}{T_1} \right)^{\frac{3}{2}}$$

This leads to a simple relationship between the carbon dioxide flux and temperature. The key to this experiment is not to calculate exactly the flux, but rather to show the dependence of gaseous carbon dioxide flux on the temperature of the liquid fluid it is dissolved in.

Similar steps are taken in the reduction of Equation #2, $N_A = - (D_{AB} + \varepsilon_m) \frac{\delta C_A}{\delta z} + \frac{C_A}{C} (N_A + N_B)$

This equation can be simplified by assuming identical initial soda conditions between control, experimental group 1 and experimental group 2, by having the only difference is the fluid velocity. If these assumptions are met, then $N_A \alpha \varepsilon_m$. It is known that $\varepsilon_m$ is proportional to the fluid velocity, $v_f$. Therefore, it can be shown that $N_A$ is proportional to $v_f$.

<table>
<thead>
<tr>
<th>Experiment #1 Equations</th>
<th>Experiment #2 Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Flux Relationship</td>
<td>$N_A = - (D_{AB} + \varepsilon_m) \frac{\delta C_A}{\delta z} + \frac{C_A}{C} (N_A + N_B)$</td>
</tr>
<tr>
<td>Simplified Relationship</td>
<td>$N_A \alpha D_{AB}$</td>
</tr>
<tr>
<td>Additional Relationship</td>
<td>$D_{AB,2} = D_{AB,1} \left( \frac{T_2}{T_1} \right)^{\frac{3}{2}}$</td>
</tr>
<tr>
<td>Overall Simplified Relationship</td>
<td>$N_A \alpha \varepsilon_m$</td>
</tr>
</tbody>
</table>

Table 1: Equations used in Experiments #1 and #2 extracted from *Transport Processes and Separation Process Principles.*

After repeating the experiments several times, the predicted outcome was proved to be correct, and it is surprisingly more “visible” than expected. However, these two experiments are simplified for the purpose of high school teaching. In reality, mass transfer of carbon dioxide in pop is much more complex than it appears to be. For example, the temperature gradient within the soda pop may vary the diffusivity of the carbon dioxide; the convective velocity applied may not be linear but rather, rotational in this experiment. Therefore, the instructor should note that this experiment setup is solely for highlighting the dependence of diffusivity on temperature and dependence of flux on velocity only.
Conclusion

Experiment #1 shows that diffusive mass transfer increases as temperature increases because of the dependence relationship between temperature and the diffusive mass coefficient of gaseous carbon dioxide in liquid soda pop. Thus, the flux of carbon dioxide leaving the surface of the soda pop increases when temperature increases, filling the balloon to larger size.

Experiment #2 shows that convective mass transfer increases as the velocity of the container increases because of the dependence relationship between velocity and the eddy mass coefficient. Thus, the flux of carbon dioxide leaving the surface of the soda also increases when velocity by shaking or other agitation increases.

“Once you POP, you can’t STOP” is an interesting set of simple experiments which can be used to demonstrate mass transfer concepts to high school students. The experiments are economically, environmentally, and time efficient, costing less than $25, avoiding toxic chemicals, and lasting 10-30 minutes depending on execution. Before our presentation to the students, however, we ourselves were surprised with the outcome of our experiment. We did not expect to be able to see the effect of carbonation in soda pop using a balloon, but were delighted when the balloons reached up to 30cm, in circumference using both heat and shaking.

The set of experiments proved successful in our preliminary presentation to four high school students and one teacher from Ypsilanti, as well as two professors and one GSI from the Chemical Engineering Department at the University of Michigan. Students were able to grasp the general concepts of gas diffusion dependence on temperature and velocity, while having a fun competition, while teachers and professors enjoyed its simplicity for educational purpose. Our group was not only successful in showing students a few basic mass transfer principles, but we also were able to hold their attention spans and their interest. This experiment was simple enough to understand, but also proved practical in its every day relevance for providing the reasons behind the optimal way to store soda: cold and unshaken.
REFERENCES


