JOURNAL OF CHEMICAL EDUCATION

Communication

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Kinetic Explorations of the Candy−Cola Soda Geyser

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Supporting Information

ABSTRACT: Protocols for examining the kinetics of CO_2 escape from solution during the popular Diet Coke and Mentos experiment have been explored. The methods developed allow teachers to demonstrate and students to explore various physicochemical processes involved when Mentos candies are placed in Diet Coke. For example, a pH meter can be used to observe a slight decrease in acidity as dissolved CO_2 escapes the soda. Furthermore, a balance or CO_2 sensor can be used to directly measure CO_2 escape. Arrhenius analysis of degassing rates determined using these latter methods yielded an activation energy of 25 kJ mol^{-1} for the conversion of $CO_2(aq)$ to $CO_2(g)$. The materials required for the experiments are easy to acquire and set up; therefore these investigations are amenable for use in high school and undergraduate chemistry classrooms and laboratories

KEYWORDS: *General Public, High School/Introductory Chemistry, First-Year Undergraduate/General, Physical Chemistry, Inquiry-Based/Discovery Learning, Kinetics*

■ INTRODUCTION

When Mentos candies are dropped into a bottle of carbonated beverage, CO_2 gas bubbles rapidly form within and then escape from the carbonated water. The rapid degassing of the beverage causes a fountain of soda pop to jet upward and out of the mouth of the bottle—sometimes well over three meters high (see abstract image).[1] Because of its simplistic, impressive, and entertaining nature, this experiment is a great choice for use in inquiry-based lessons[2−5] and science camps.[5,6]

The fountain is believed to occur because Mentos candies have a rough surface that provides innumerable nucleation sites on which dissolved CO_2 in the beverage can form CO_2 gas bubbles:[2,4,7,8]

$$CO_2(aq) \rightarrow CO_2(g) \quad (1)$$

The rough nucleation sites likely contain air pockets into which $CO_2(aq)$ can rapidly enter the gas phase. Scanning electron microscope (SEM) images of the surface of Mentos candies are consistent with this proposal.[2] It is thought that rapid formation and expansion of bubbles that form at nucleation sites pushes the soda out of the bottle. Among many other things, Wint-O-Green Lifesavers,[2] sidewalk chalk,[5] and even ultrasound[8] have been used to provide nucleation sites in these nucleation induced soda degassing (NISD) experiments.

Huber and Massari studied NISD in samples of Diet Coke by constructing an ingenious clamp and hose assembly to quantify CO_2 release.[5] Data collected using this device had good precision and provided insight on various aspects of the process. For example, it was noted that chalk initiated the release of more CO_2 during NISD than did various flavors of Mentos candy, likely due to the increased roughness of the chalk over the candy. Furthermore, it was determined that more gas was released from soda at 7 °C than warmer temperatures. This is an important experimental result, because it is sometimes erroneously argued that the higher fountains observed at increased temperature occur because of decreased gas solubility at higher temperatures. This experimental observation that more gas is released from cooler sodas than warm ones drives home the point that substantially more CO_2 is initially dissolved−and therefore more gas is released−from the former over the latter. This point has also been echoed by others.[4]

The study by Huber and Massari illustrates the importance of developing methods to quantify aspects of NISD to gain insight into the various physicochemical processes involved. Therefore, we have attempted to design simple experiments to quantify kinetic aspects (how fast) of NISD to complement Huber and Massari's thermodynamic (how much) measurements. In this vein, we have used various sensors (a pH meter, a CO_2 gas sensor, and a balance) to monitor the time dependent release of CO_2 from soda. These experiments were designed with simplicity in mind, with the hopes that many others can mimic these experiments to probe the workings of NISD. The experiments (or modified versions) presented here have also been used as lecture demonstrations and laboratory experiments. Further details on how to conduct these experiments, including a student laboratory sheet, can be found in the Supporting Information.

Received: April 7, 2016
Revised: June 28, 2016

DOI: 10.1021/acs.jchemed.6b00263
J. Chem. Educ. XXXX, XXX, XXX−XXX

■ USE OF A pH METER TO MONITOR KINETICS OF CO_2 DEGASSING DURING NISD

It is commonly (and correctly) noted that CO_2 escape which occurs during NISD is a physical process.[2] However, limiting the discussion to the physical aspects of dissolved CO_2 release from water conceals the fact that the process is accompanied by chemical changes. These changes occur due to the following equilibria:

$$CO_2(aq) + H_2O(l) \leftarrow \rightarrow H_2CO_3(aq) \quad (2)$$

$$H_2CO_3(aq) \leftarrow \rightarrow H^+(aq) + HCO_3^-(aq) \quad (3)$$

$$HCO_3^-(aq) \leftarrow \rightarrow H^+(aq) + CO_3^{2-}(aq) \quad (4)$$

When Mentos candies are added to soda, $CO_2(aq)$ escapes from solution (eq 1). The resulting loss of $CO_2(aq)$ drives eq 2 to the left by Le Chatelier's principle, which in turn causes eqs 3 and 4 to be driven to the left as well.[9] Overall, this results in a consumption of protons and concomitant increase in pH. Thus, the acidity of sodas should drop upon addition of Mentos candy. This process was observed by immersing a pH electrode in a freshly opened 12 oz bottle of Diet Coke and adding a single Mentos candy (Figure 1, solid line). This large rise in pH

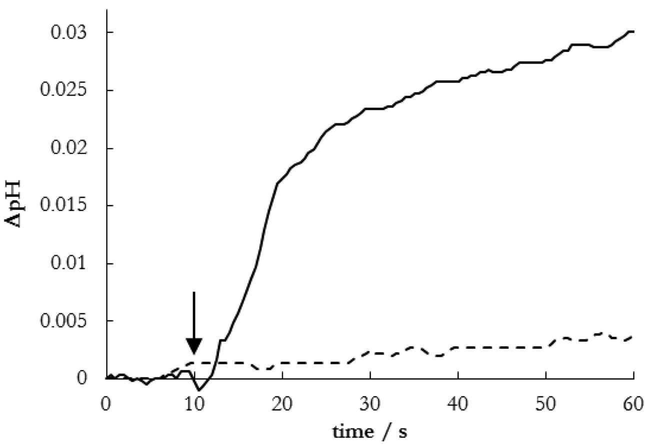

Figure 1. Change in pH observed upon addition of 1 Mentos candy at t = 10 s (indicated with arrow) to (solid line) a freshly opened 12 oz bottle of Diet Coke initially at 21 °C; (dashed line) Diet Coke boiled for 5 min and then allowed to cool to 21 °C. Initial pH of Diet Coke = 3.078; initial pH of boiled Diet Coke = 3.203.

was not observed upon adding a single Mentos candy to Diet Coke from which CO_2 had been purged by boiling for 5 min (Figure 1, dashed line). It was difficult to observe trends in the kinetics of the rise in pH under various conditions of temperature or other factors. Nevertheless, the observed rise in pH was consistent enough that this experiment can be routinely used to demonstrate of the effect of CO_2 escape from aqueous solution on pH. This result contrasts with a previous report in which no difference in pH was found in Diet Coke before and after adding Mentos candy.[2] This difference can be accounted for by noting that a pH meter with a precision of only 1 significant figure was used in the previous work, rendering the detection of small changes in pH unlikely.

■ USE OF A CO_2 SENSOR TO MONITOR KINETICS OF CO_2 DEGASSING DURING NISD

The use of a CO_2 gas sensor[10] was also explored as a method of monitoring the kinetics of NISD. To do so, an empty 2 L bottle was connected to a modified tornado tube (Figure 2).[11] A pair

Figure 2. Gas sensor apparatus consisting of a bottle of Diet Coke connected to an empty 2 L soda bottle (green) with a modified tornado tube (red). The 2 L bottle contains two holes: one to house the CO_2 sensor and another into which a Mentos candy is dropped.

of scissors was used to widen the opening in the tornado tube so that a Mentos candy could freely fall through it. The 2 L bottle served as a reservoir for overflowing, degassing soda, and CO_2 released. A hole was cut in the top of the 2 L so that the gas sensor could be vertically inserted. Another hole was cut near the sensor hole to allow a Mentos candy to be dropped into the system. The entire apparatus was held at an angle by a ring stand and clamp so that spewing fountain material did not come into contact with the sensor. When we were ready to perform the experiment, a 12 oz bottle of Diet Coke was opened, its plastic ring seal was removed, and the bottle was connected to the bottom end of the tornado tube. To initiate NISD, a Mentos candy was dropped through the hole in the 2 L bottle, and the moment the candy fell into the Diet Coke was recorded. The CO_2 concentration in the 2 L bottle was monitored until the gas sensor was saturated with CO_2 (Figure 3). The rate of degassing was calculated as

$$\text{rate} = \frac{[CO_2]_{\text{final}} - [CO_2]_{\text{initial}}}{t_{\text{final}} - t_{\text{initial}}} \quad (5)$$

where $[CO_2]$ is the gas concentration measured by the sensor in the 2 L bottle, t is time, "final" represents conditions at sensor saturation, and "initial" represents conditions at the instant the candy entered the soda.

The CO_2 concentration in the 2 L bottle displayed an initial lag phase during which the CO_2 concentration remained low. The time required for foam bubbles to build up, collapse, and release dense, slow-rising $CO_2(g)$ might be responsible for this

DOI: 10.1021/acs.jchemed.6b00263
J. Chem. Educ. XXXX, XXX, XXX−XXX

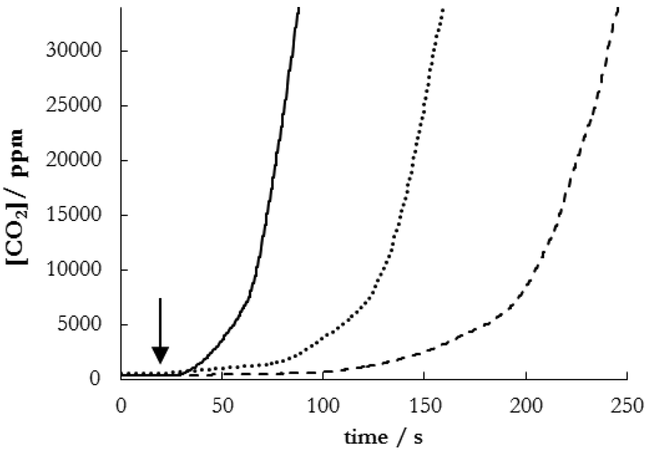

Figure 3. Kinetics of CO_2 degassing from a 12 oz bottle of Diet Coke to which Mentos candy was added at t = 20 s (indicated with arrow). Diet Coke initially at (solid line) 30 °C, (dotted line) 18 °C, (dashed line) 6 °C.

lag phase. It is interesting to note that lag phase kinetics is mechanistically consistent with nucleation events, as is observed in amyloid fibril formation.[12] In contrast to the experiments with the pH meter, a clear trend was observed with varying temperatures, with cola at 6 °C degassing at a slow rate (Figure 3, dashed trace), cola at 18 °C degassing at a moderate rate (Figure 3 dotted trace), and cola at 30 °C degassing rapidly (Figure 3, solid trace). Degassing rates at temperatures ranging from 8 to 30 °C followed Arrhenius behavior (Figure 4), and

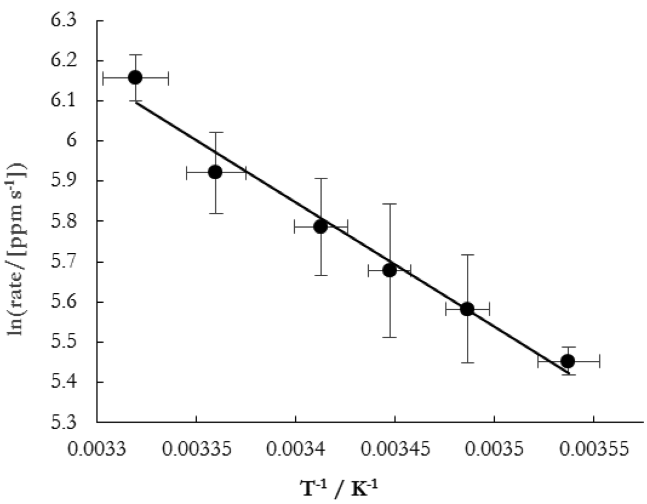

Figure 4. Arrhenius plot of the rate of degassing from Diet Coke. Each data point represents at least 3 and as many as 8 trials; a total of 37 trials were used to generate the plot. R^2 = 0.97 for the linear fit.

the slope of the plot (= E_a/R) yielded an activation energy, E_a, of 25 ± 2 kJ mol^{-1} for the Mentos-induced degassing of Diet Coke. This result is in fair agreement with E_a found for the degassing of CO_2 from swimming pool water (20.9 kJ mol^{-1}).[13] Because this activation energy and the overall enthalpy change, ΔH, for the degassing of CO_2 from water (+20.3 kJ mol^{-1})[14] are almost the same, these values can be taken as estimates of one another for this process. It is therefore worth mentioning that ΔH for the dissolution of CO_2 from Champagne is +24.8 kJ mol^{-1}.[15] Thus, it is reasonable to suspect that E_a for the degassing of CO_2 from Diet Coke would also be slightly higher than that of water.

■ USE OF A BALANCE TO MONITOR KINETICS OF CO_2 DEGASSING DURING NISD

It was also found that a balance could be used to monitor CO_2(g) escape during NISD. Bottles of Diet Coke were placed on an Ohaus Scout Pro balance (600 g capacity, 0.01 g precision) connected via USB to a computer. Logger Pro software was used to record mass at a frequency of one measurement per second. Because of the forceful degassing that occurs when a Mentos candy is placed in a bottle of soda, foamy liquid spilled out of the bottle during most trials. Therefore, the cola was placed in a plastic container to prevent liquid from damaging the balance and to ensure that the balance only measured mass lost due to escaping CO_2, but not liquid. Using wooden skewers and masking tape, a simple delivery system for the Mentos candy was fashioned (Figure 5).

Figure 5. Arrangement of balance and apparatus to deliver candy into soda.

Skewers were secured together to form a "7" shape and attached to the plastic container so that candy could rest just above a bottle of soda. The candy was placed on a small platform secured to the top end of the "7".

To perform the experiment, the container/skewer apparatus was placed on the balance, a freshly opened bottle of soda was placed in the assembly, and a Mentos candy was placed on the platform. The mass vs time readings on Logger Pro were observed to ensure that a baseline was established, and then the candy was carefully nudged so that it fell into the bottle of soda. The time at which the Mentos candy fell into the soda was recorded. After the candy fell into the soda, degassing ensued and foamy liquid spilled over into the bowl of the apparatus. Data were collected for at least 1 min or until the mass stabilized for several seconds. The rate of degassing was taken as the mass lost during the first 10 s after the Mentos candy entered the soda.

DOI: 10.1021/acs.jchemed.6b00263
J. Chem. Educ. XXXX, XXX, XXX−XXX

Consistent with the experiments monitoring NISD kinetics with a gas sensor, a clear trend was observed with varying temperature, with cola losing CO_2 faster at higher temperatures (Figure 6). While it is evident that more gas was evolved at higher temperatures (Figure 6), this was due to faster degassing kinetics and not because of lower gas solubility at higher temperatures. These experiments were not monitored until complete degassing occurred, rendering references to gas solubility irrelevant. It is advisable to present this clarification to students to avoid perpetuating the misconception that lower gas solubility at higher temperatures results in higher fountains.

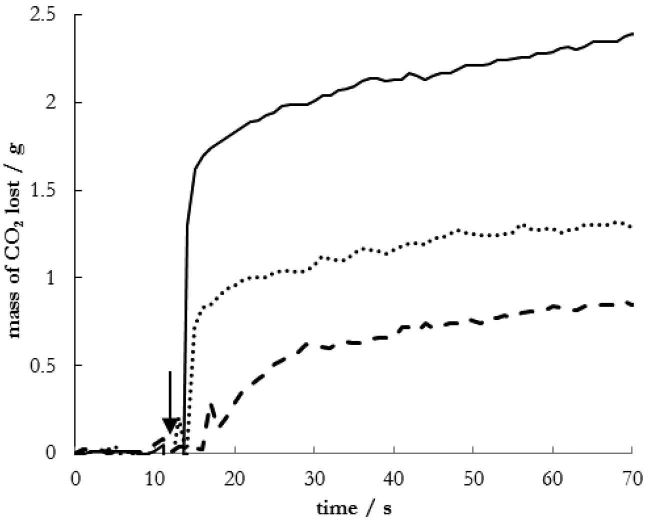

Figure 6. Kinetics of mass lost due to degassing of CO_2 from a 12 oz bottle of Diet Coke to which one Mentos candy was added at t = 12 s (indicated with arrow). Diet Coke initially at (solid line) 34 °C, (dotted line) 23 °C, (dashed line) 5 °C.

Arrhenius behavior was observed in the degassing rates of Diet Coke at temperatures ranging from 7 to 41 °C (Figure 7). Once again, the slope of the Arrhenius plot yielded an activation energy of 25 ± 2 kJ mol^{-1} for the Mentos-induced degassing of Diet Coke, in agreement with the data collected with the gas sensor.

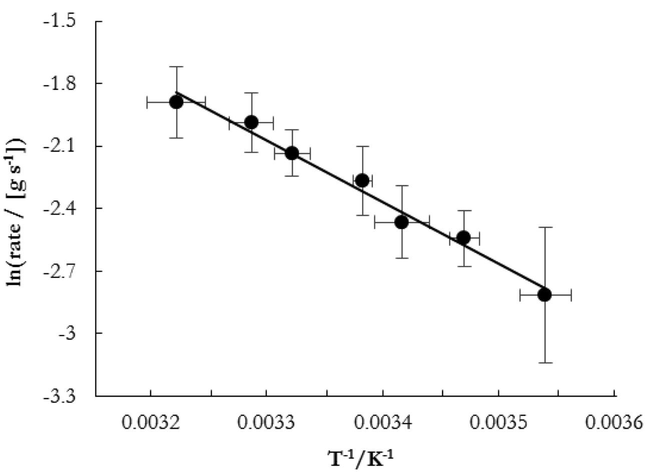

Figure 7. Arrhenius plot of the rate of mass lost from Diet Coke due to addition of Mentos candy. Each data point represents at least 5 and as many as 17 trials; a total of 58 trials were used to generate the plot. R^2 = 0.98 for the linear fit.

While preparing this manuscript, we discovered it was also possible to monitor time dependent mass loss in this experiment without using a balance interfaced to a computer. To do so, a running digital stopwatch was placed next to the digital readout on the balance. A video recording of the stopwatch and balance readout was made while conducting the degassing experiment. Data collection and analysis using this alternative method was more time-consuming than using a balance interfaced with a computer. However, it was noted that better time resolution was possible using this method. See the Supporting Information for data and more details.

■ CONCLUSION

The experiments described in this paper illustrate ways to explore physicochemical concepts and processes involved during NISD in the popular Diet Coke and Mentos experiment. A pH meter can be used to monitor the effect of CO_2 escape on the acidity of the soda. In addition, a gas sensor or balance can be used to measure rates of degassing and to find a reasonable value for the activation energy of the process (eq 1). These methods of measuring the kinetics of NISD can be used in lecture demonstrations or as student laboratory experiments. Indeed, we have developed a facile protocol for measuring Mentos-induced degassing rates from 12 oz soda bottles for use as an experiment in General Chemistry classes. This simpler method uses only a balance, a stopwatch, Mentos candy, and soda. Using this stripped-down method, students generally find the activation energy of CO_2 escaping from soda to be in the neighborhood of 23−29 kJ mol^{-1} (see Supporting Information for data and more details). Finally, the techniques described herein could provide a means for high school and under-graduate students to become involved in small research projects. For example, students could ascertain if E_a for CO_2 degassing from regular Coke is different from that of Diet Coke. Or perhaps students could investigate if E_a changes when using different nucleation initiators such as chalk or ultrasound. Thus, it is our hope that others might use the described techniques—or design new methods—to probe this system and gain further insight into the growing body of knowledge on the Diet Coke and Mentos Experiment.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00263.

Details on experimental procedures, description of how to carry out mass experiments using simple equipment, sample student laboratory sheet (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Emeric Schultz and the reviewers of this manuscript for helpful comments and suggestions.

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(9) Very little CO_3^{2-} is present in the acidic environment of soda, so the process in eq 4 contributes very little to the effect.
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DOI: 10.1021/acs.jchemed.6b00263
J. Chem. Educ. XXXX, XXX, XXX−XXX