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Article

Scientific project in physics "carbonated liquids and carbonation level"

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SUMMARY

Carbonated soft drinks are widely used by people in everyday life to quench thirst and for medicinal purposes. Such drinks have a positive effect on digestion and swallowing. The problem of swallowing activation by carbonated beverages has previously been investigated. However, this past study did not address the important issue of stability of a carbonated beverage in an open vessel. Although it is obvious that the degree of carbonated beverage will change over time and at different temperatures in an open vessel. In our work we attempted to fill this gap in the research and followed the formation of gas bubbles on the surface of the vessel walls in different carbonated liquids, over different time intervals, at different temperatures and in vessels made of different materials. Our results made it possible to identify patterns affecting the process of formation and disappearance of carbon dioxide bubbles. Visual determination of the degree of carbonation of a beverage in an open vessel over time will allow more effective use of carbonated beverages to address swallowing in patients with this condition.

INTRODUCTION

The first carbonated soft drinks were invented in 1772 by the British scientist Joseph Priestley. In 1772, Priestley made a discovery by finding a method to enrich water with carbon dioxide, thereby creating the first artificial carbonated water (1). This discovery laid the foundation for the carbonation process used in the production of modern soft drinks. Carbonation not only enhances but also preserves the flavor, aroma, and nutritional value of beverages, making them more appealing to consumers (2). Priestley's research was instrumental in revealing the flavors and characteristics of these drinks in the field of carbonation. Plunging into the study of carbonated liquids, one should repeat the wisdom of the ancient physician Hippocrates: “the best (waters) are those which flow from elevated grounds, and hills of earth; these are sweet, clear, and can bear a little wine.”, which even at that time emphasized usefulness carbonated of mineral waters (3).

Bubbles require a catalytic center for growth consisting of a gas pocket on a solid surface, which can be glass or plastic. These gas pockets must have a radius above a critical value, which is usually between 0.1–0.2 μm for carbonated beverages. When the radius of the gas pockets is less than this critical value, the gas tends to dissolve. When its radius is equal to or greater than the critical value, it is able to take the form of bubbles. We analyzed the walls of a liquid container using image analysis to measure bubble nucleation and growth, and they determined the average bubble diameter.

We hypothesized that over time and with changing temperature, the degree of liquid carbonation will vary. We hypothesized that over time, liquids at room temperature remain more carbonated than liquids at other temperatures. We conducted experiments with three different carbonated liquids: Saryagash water, Borjomi water and Coca-Cola, which were poured into cups of different materials and changed the temperature of the carbonated liquids. We counted the number of bubbles as well as measured the size of bubbles. We noticed that bubbles disappeared at 60ºC if the carbonated liquid is poured into a glass or reusable plastic container, but they continued to form in the disposable plastic cup. These study results may have an impact on swallowing problems in patients, especially those who consume carbonated drinks, and further studies should be conducted on electrophysiological parameters of the throat and esophagus when drinking carbonated drinks may provide information on the effect on electrical activity of muscles and nerve signals during swallowing.

RESULTS

To determine the size of the gas bubbles in the liquid, we poured carbonated liquids into containers of different materials and measured the size of the bubbles using the series method (4). A cut-glass cup, reusable plastic cup with thick walls and a disposable plastic cup with thin walls were used in the experiment. Within each cup, the gas bubbles on the walls appeared to be approximately all the same size, regardless of their position in the cup.

Most bubbles formed on the walls of the cup during the first

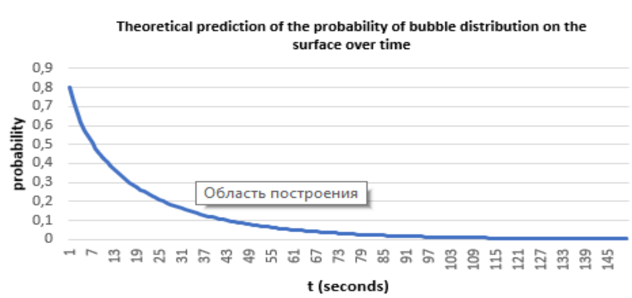

Figure 1: Theoretical prediction of the probability of bubble distribution on the surface over time. The figure illustrates the theoretical prediction of bubble distribution on the liquid surface as a function of time. We employed function W(t)=1-erf(x0/(2√Dt)) to simulate the dynamic evolution of bubbles. The x-axis represents time in seconds, while the y-axis depicts the probability of bubble occurrence. Notably, a high probability of bubble adhesion is observable within the first minute, after which the likelihood decreases, ultimately approaching zero.

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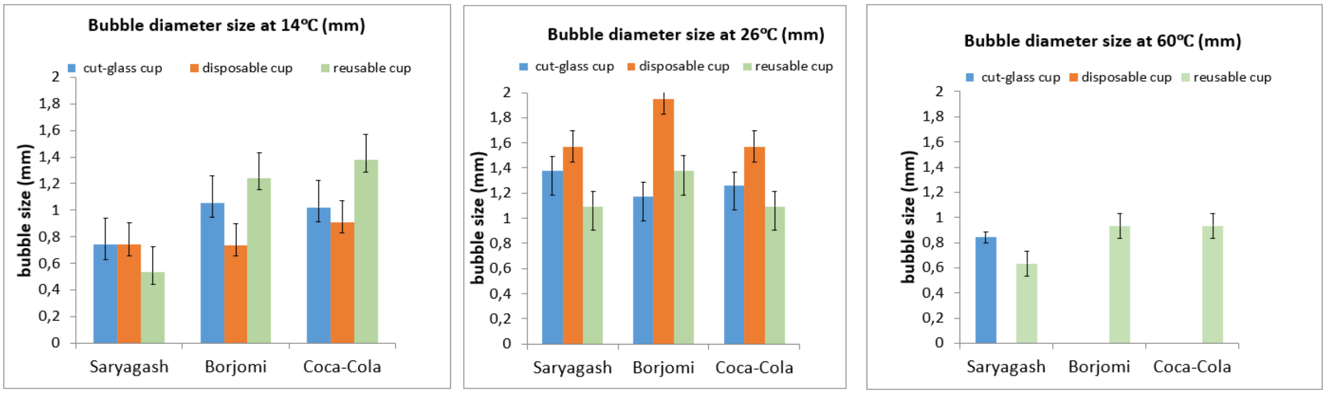

Figure 2: The analysis of bubble size across different carbonated drinks. The table presents the results of an Analysis of Variance (ANOVA) statistical test conducted to assess the impact of different factors on gas bubble sizes in various carbonated liquids. The independent variables examined include temperature (14°C, 23°C, 60°C) and the type of carbonated liquid. The dependent variable is the size of gas bubbles, measured in millimeters. Different types of carbonated beverages (Saryagash, Borjomi, Coca-Cola) significantly affected bubble size ($p < 0.0002$). Bubble size was significantly influenced by temperature, with bigger bubbles at 26°C compared to 14°C ($p < 2e\text{-}16$). There was a marginally significant interaction between liquid and temperature ($p = 0.0295$). This suggests that the effect of temperature on bubble size may not be the same for all liquids.

30 seconds after filling the cup with carbonated liquid. After the initial minute, the number of bubbles stabilized, allowing us to focus our observations primarily on the behavior of bubbles during this period. Factors such as environmental temperature, pressure, and impurities can influence the longevity of bubbles in an open container of carbonated liquid, which we will consider in our analysis.

For the theoretical estimation of the time interval during which it makes sense to consider the adhesion of carbon dioxide bubbles to the walls of the vessel, the problem from Landau's textbook was studied (5). The process of gas bubble formation on the walls of a vessel is caused by Brownian motion of carbon dioxide molecules in the liquid (6). Gas bubbles move chaotically in a liquid bounded on one side by a flat vessel wall. When the gas bubbles hit the wall, they "stick" to it. The probability that a gas bubble originally at distance x_0 from the wall will reach the wall within 2.5 minutes can be described by the function $W(t)=1-\text{erf}(x_0/(2\sqrt{Dt}))$ **(Figure 1)**. In this formula, the diffusion coefficient of carbon dioxide in water at room temperature is 191 nm/s (7).

The three-factor ANOVA with interaction revealed significant main effects of liquid type, temperature, and container material on both bubble size and number, alongside a significant interaction between liquid and temperature for bubble size (all $p < 0.05$) **(Figure 2)**. These findings point to the complex interplay of these factors in influencing gas bubble characteristics in carbonated beverages.

Tukey's HSD post-hoc comparisons provided the following key insights:

Liquid: Differences in bubble size were observed between all three liquids, with Coca-Cola generally forming larger bubbles compared to Saryagash and Borjomi **(Figure 2)**.

Temperature: Across all liquids, significantly larger bubbles were present at 26°C compared to 14°C. At 60°C, bubble size varied by liquid: Saryagash and Borjomi exhibited substantial bubble disappearance, while Coca-Cola still maintained slightly larger bubbles compared to lower temperatures **(Figure 2)**.

Container material: No significant differences in bubble size were observed between the three container materials **(Figure 2)**.

Liquid-temperature interaction: The magnitude of temperature-induced changes in bubble size differed between liquids. Saryagash and Borjomi showed the most pronounced difference in bubble size between 14°C and 26°C, while Coca-Cola exhibited a smaller increase **(Figure 2)**.

DISCUSSION

Our investigation delved into the intricate dynamics governing the formation of bubbles in carbonated liquids, scrutinizing the impact of temperature, liquid type, and cup material on this phenomenon. Recognizing the nuanced interplay between the type of carbonated liquid and the vessel employed, we undertook a meticulous examination considering various factors. The selection of distinct carbonated drinks, each characterized by unique chemical compositions and carbonation levels, contributed to the recognition of the diverse outcomes attributable to specific brands or drink types. Rigorous attention to brand and composition variables bolstered the precision of our result interpretations. The measurement methods adopted, utilizing a systematic row method based on photos captured with a smartphone camera, introduced a consistent approach to bubble size determination, acknowledging the potential discrepancies associated with different measurement techniques across studies.

Additionally, we considered conditions such as temperature, humidity and pressure during our study. Since our research took place in Almaty Kazakhstan at an altitude of 785 meters above sea level, we acknowledged that atmospheric pressure could influence gas bubble formation. The variations in boiling temperature due, to altitude emphasized the importance of controlling these variables. By providing this context information our findings can be regarded as reliable and applicable while accounting for adjustments needed when conducting studies at different altitudes.

Beyond the confines of our immediate investigation, we recognize the broader implications of our findings, especially for individuals contending with specific health concerns, notably those prone to swallowing difficulties. The size of

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bubbles in carbonated drinks, influenced by factors like temperature and cup material, assumes significance in this context. For individuals grappling with swallowing challenges, the presence of large gas bubbles, particularly at room temperature, could pose additional hurdles, introducing resistance during the swallowing process and potentially causing discomfort.

We were interested to understanding of how the number of bubbles changes over time after filling a glass with liquid from a bottle. Our observations show that the number of bubbles actively changes in the first 2.5 minutes from the beginning of observation, which is confirmed by the graph (Figure 1). It is important to mention that two of the liquids are mineral water, and the third liquid is soda. It can be assumed that the presence of sugar also affects the degree of decarbonization of the drink.

In drawing parallels with the study exploring the effects of carbonated liquids on swallowing behavior in hospitalized patients without dysphagia, there emerges a common thread in our emphasis on individualized reactions (8). Both investigations acknowledge the inherent variability in responses among individuals, reinforcing the need for personalized guidance.

MATERIALS AND METHODS

We used three different carbonated liquids: strong carbonated water with a mass fraction of carbon dioxide over 0.4% (Coca-Cola classic drink), medium carbonated water from 0.3% to 0.4% (Borjomi mineral water), or weak carbonated water with a fraction from 0.2 to 0.3% (Saryagash mineral water) (9).

To clarify the influence of the vessel material on the bubble size, we poured the studied liquids into: a disposable polystyrene cup (height 9.2 cm, neck diameter 7.5 cm, bottom diameter 5 cm), a reusable polystyrene cup (height 8.5 cm, neck diameter 8.7 cm, bottom diameter 5.5 cm), or a cut-glass cup (height 16 cm, neck diameter 8 cm, bottom diameter 5

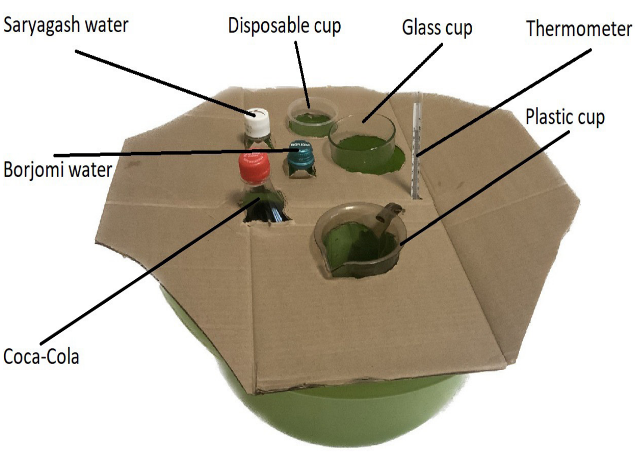

Figure 3: Experimental Setup for Temperature Control. A water-filled container featuring a strategically positioned sheet of cardboard with precision-cut apertures for instrument placement. This configuration ensures uniform temperature across devices during the experiment, optimizing experimental conditions.

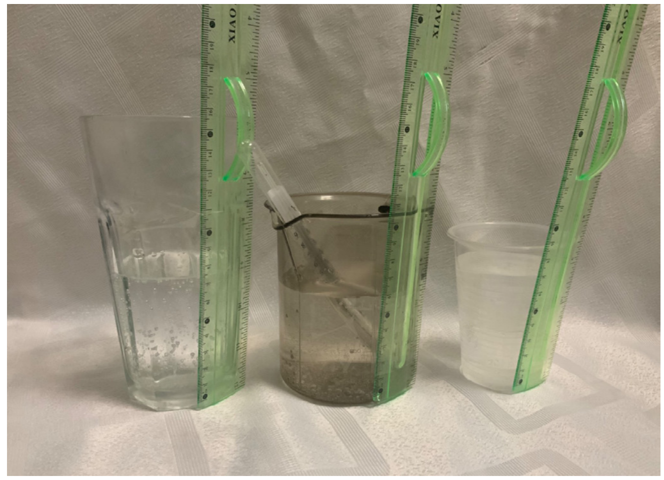

Figure 4: Representation of Experimental Vessels. The illustration depicts three distinct containers fabricated from diverse materials, each serving as a designated environment for our research investigations. The variances in container material, such as glass, reusable plastic, and disposable plastic, were integral to understanding the impact of material composition on the carbonation dynamics of Saryagash water, Borjomi water, and Coca-Cola. This controlled design allows for systematic exploration of the influence of container material on bubble formation and dissipation within the carbonated liquids under investigation.

cm).

At first, we placed all three closed bottles with carbonated liquid and empty glasses in a large vessel with water. We poured water of the desired temperature into the large vessel and kept the water temperature constant, monitoring its value with an alcohol immersion thermometer with a division value of 1ºC **(Figure 3)**. After reaching thermal equilibrium in the system (about 15 minutes), we removed the empty glasses and bottles with carbonated liquid from the cardboard fixtures. We poured 300 ml of carbonated water into each cup **(Figure 4)**. A ruler with a graduation value of 1 mm was taped to the outside of each cup.

For the next series of experiments, the vessels were thoroughly washed with water and dried in the air. Each experiment was carried out 5 times, the size and number of bubbles on the walls of the vessel were calculated. To find the dependence of degree of carbonation on temperature, we repeated measurements at temperatures of 14ºC, 26ºC, and 60ºC.

In our study, we aimed to assess potential variations in bubble sizes based on different carbonated liquids, temperatures, and container types. We employed an Analysis of Variance (ANOVA) test to statistically evaluate whether significant differences existed among these variables.

To statistically analyze the differences in bubble size and number across liquids, temperatures, and container materials, we employed a three-factor ANOVA with interaction using Python software.

The ANOVA model assessed the main effects of liquid type (Saryagash, Borjomi, Coca-Cola), temperature (14°C, 26°C, 60°C), and container material (disposable plastic, reusable plastic, glass) on both bubble size and number. Additionally, the analysis investigated the interaction term between liquid and temperature, considering their potential combined influence on bubble characteristics.

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Following the ANOVA, we performed post-hoc comparisons using Tukey's HSD test to identify statistically significant differences in bubble size and number between specific groups formed by the factors and their interaction. This allowed us to pinpoint which liquids, temperatures, and container materials differed significantly in terms of gas bubble formation and presence. Statistical significance thresholds were set at $p < 0.05$.

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