Abstract

The two interconnected rubber balloons system is a demonstration widely used to show the effect of surface tension; however, the nature of the rubber skin, sizes of the balloons limit the ability of this demonstration. In this research, I measured the circumference and pressure of balloons for the calculation of surface tension. It was found that the demonstration can be done between circumferences of 30 cm to 50 cm for the party balloons to show the effect of surface tension as explained by the Laplace-Young equation.

Introduction

We have all had experience with blowing up balloons. Have you ever thought about why it requires force to blow the balloons? And why would you get tired after blowing it? Here we introduce you to surface tension, which is an attraction provided by a surface at the interface between two phases [1]. Because of the surface tension, a balloon has a difference between internal and external pressure [2] due to the attraction between rubber molecules at both the internal and external surface. The surface tension in the stretched rubber tends to contract the balloon; meanwhile, the greater internal pressure in the balloon exerts a force to expand the balloon. These factors balance and therefore result in an equilibrium state [3] of the balloon.

Consider the case of two interconnected balloons model [4] which includes two identical rubber balloons filled to different sizes with a closed valve in between. If the valve is opened, without previous knowledge, most people would intuitively assume the air would flow from the big balloon to the small one; nonetheless, we can set up the demonstration to let the air flow from the small one to the big one. In this case, we know from the Laplace-Young equation [1] that the larger the radius the smaller the pressure difference across the bubble. Assuming the balloons are spherical, we have a simplified equation with $\Delta p$ as pressure across the surface, $R$ as the radius of the balloon, and $\gamma$ as surface tension

$$\Delta p = 4 \frac{\gamma}{R} \quad \text{(spherical balloons)} \quad (1)$$

The demonstration intends to show the properties of surface tension, with unit of N/m, on the rubber balloon; however, the small balloon does not always inflate the big one. Nonetheless, it is always true only if the balloons were bubbles [4]. Due to this reason, I realized that there are
limitations using balloons to simulate the effect of surface tension in bubbles. Other than surface tension of the rubber surface, there are other elements that are in play in the system. In this research, we will study the real balloons in the two balloons model instead of assuming ideal balloons. Also, other factors influencing the system are assessed through the measurements of the surface tension.

Methods

In order to explain a real balloon system, we need to discard some assumptions made in the previous model in Eq. (1). Noted that Eq. (1) only accounts for spherical balloons, we then need to go back to the general result of Laplace-Young Equation, written in terms of mean curvature $H$

\[ \Delta p = 2 \gamma H \] (on a droplet) \hspace{1cm} (2)

It is the equation used for calculation of the pressure difference across an interface of two phases on a droplet. A droplet only has the external surface while bubbles and balloons have surfaces, both inside and outside. We therefore time the curvature by two to account for this difference [1]. Further, the mean curvature, $H$, describes the properties of the curvature at a point on the surface. Therefore, to rewrite the equation in terms of $R_1$ and $R_2$, the two principal radii of curvature, we have the Laplace-Young Equation at any point on the curved surface of the balloon

\[ \Delta p = 2 \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \] (a space enclosed) \hspace{1cm} (3)

As suggested by equation 3, I can find the surface tension of a balloon by measuring the curvature on any given points on the surface. Considering the curvature at different points on the balloon’s surface, we can tell from Figure 1 that the horizontal circumference is where the balloons have minimum curvature, thus maximum surface tension. Every point on the horizontal circumference has the same surface tension because the $R_1$ and $R_2$ are the same at all points.

In this research, I measured the horizontal circumference using measuring tape and took photo shots at the shape of the balloon for each stage of the balloon expansion. Using the photo shots, I estimated the ratio of $R_1$ to $R_2$. Then, $R_2$ could be calculated from $R_1$, which could be directly determined by measuring the horizontal circumference. Once the principal radii were recorded, the pressure difference across the rubber surface was the only element left to find.
In order to measure the pressure difference, I made a water manometer as a pressure gauge. By measuring the difference in height between the water surfaces at the two connected tubes, we can determine the gauge pressure in the balloon. The water manometer used here is of similar designed as in Calza et al.’s study.

As shown in Figure 2, each end of a T-connector was linked to clear tubes connecting to a balloon, a bike pump, and a water manometer. Using this pressure measuring apparatus, the pressure difference can be found while inflating the balloon. This experimental setup is shown in figure 3.

For comparison and more general results, the experiment is done on two different types of party balloons, 12” green and 14” red party balloons. The 12” green party balloons are imported by Canasia Toys & Gifts INC and the 14” red party balloons are imported by Siu & Sons Int’l Trading Corp.

In this research, I have made several assumptions which would cause some experimental errors in our measurements. Firstly, I assumed the rubber skin to be sufficiently thin enough that its thickness is negligible so inner and outer radii are regarded as the same. Also, new balloons are inflated and deflated a few times before the measurements are conducted because measurements done on new balloons are found to be hard to determine. The pressure difference fluctuates abnormally and does not give an unchanging value for the measurement when the balloon is maintained at a certain size; therefore, I “warmed up” the balloon before doing the measurements to prevent the “initial rigidity” as suggested in Osborne and Sutherland’s study.

After the data for each measurement was recorded, the data was processed in Excel for the calculation of surface tension at different sizes of balloons. Scatter plots of pressure difference versus circumferences and surface tension versus circumferences were created for analysis.
Results and Discussion

In this experiment, I measured the pressure difference in cm H\textsubscript{2}O and the horizontal circumference in cm. The uncertainty in measuring pressure difference was relatively constant throughout each trial. Small fluctuations were observed in the height of the water monometer. The uncertainty was estimated by observing the maximum and minimum in the fluctuations. When I measured the circumference, the measurements done on small size of balloon would give a larger degree of uncertainty because the same volume of air leaking caused a larger change in circumference when the balloons were small. The uncertainties of circumference were therefore estimated by assessing the speed of circumference decreasing.

Presented in Figure 4, a total number of 129 measurements were done in four trials on 12” green party balloons. In addition, Figure 5 shows a total number of 195 measurements in four trials on 14” red party balloons. Graphs were created to show the dependence of pressure difference on surface tension and how the internal pressure was changing as the balloon size increasing.

When the balloon was initially inflated within a small increment of circumference (10 cm), the pressure was found to rise very quickly. As shown in Figure 4 and 5 on both green balloons and red balloons, the ascending segment of the graph signified the rapid increase of pressure. The increase in pressure confirmed the nature of surface tension. Initially, the surface of the balloons was wrinkle and not

![Figure 4](image-url)  
*Figure 4. The measured pressure difference across the rubber surface as a function of green balloons’ circumference.*

![Figure 5](image-url)  
*Figure 5. The measured pressure difference across the rubber surface as a function of red balloons’ circumference.*
fully extended. The effect of the surface tension quickly came in play as the circumference increased from 20 cm to 30 cm.

Following the rapid increase in pressure, the slowly descending segment was suggested by Equation 3, which stated that the pressure and radius is inversely proportional if the surface tension stays constant. It is also illustrated in Figure 6 and 7 where we can see the surface tension stays fairly constant for a long increment of circumference.

When the circumference increased, we can observed from Figure 6 and 7 that both kinds of balloons first had surface tension increasing rapidly, then the surface tension stays fairly constant between 30 cm to 50 cm for both balloons. Finally, the rate of surface tension increasing became higher as the balloon got close to burst. Consider the physical appearances of the balloons throughout expansion, the shape of the balloons are almost a perfect sphere between 30 cm to 50 cm. The balloons were elongated after 50 cm and approached an egg shape as the size increased. It can be explained that the balloons tried to approach a minimum, constant surface tension when the size increased but surface tension only increased slightly between 30 cm to 50 cm.

However, the rubber did not expand uniformly. The rubber skin was spread out unevenly. For a substance to have a constant surface tension, the substance needs to stay in a same state
where it has constant density. In the case of a balloon, the density of rubber skin decreases as the balloon inflated because the rubber molecules are further apart as the rubber skin expands. As a result, the surface tension is not constant. Nevertheless, the density of rubber skin does not decrease linearly. Osborne and Sutherland [6] suggested in their study that rubber has non-linear elasticity. The rubber skin does not give the same increase in force for each same increment in circumference. Consider that the surface tension stayed constant between 30 cm to 50 cm, I could then infer that the density of the balloons did not have a great change between 30 cm to 50 cm. As a result, the change in $\Delta p$ depended more on the effect of surface tension instead of the chemical nature of rubber (how much the rubber was stretched) between 30 cm to 50 cm. Therefore, we can then conclude that both kinds of rubber balloons performed more like bubbles between the circumferences of 30 cm to 50 cm.

The surface tension is most commonly referred to a property of a liquid. In the case of liquid formed bubbles, for example, a sample of soap water at a given state has a certain value of surface tension. As a result, the surface tension of bubbles formed using the sample would have a uniform surface tension at all points on the bubbles. Therefore, unlike balloons, the surface film possesses no elasticity [3]. This indicates that the stretching of the surface is impossible without using more soap water to create new surface. On the other hand, rubber has great extensibility. We can expect the surface tension to be changing with size of balloons because rubber does not have a constant density as it contracts and extends. In this experiment, we found out that the stretching was minimum between the circumferences of 30 cm to 50 cm for both kinds of balloons. One possible reason for this phenomenon is that between 30 cm to 50 cm, I observed that the non-stretched rubber near the opening is beginning to stretch and “create” new surface. The rest of the balloon skin was not further stretched and therefore the density remained unchanged.

As shown in the model of interconnected bubbles or ideal balloons [1] when the system reaches equilibrium, the volume of the smaller balloon or bubble would become zero while the larger one would be inflated with the air coming from the deflated one. The air will flow from the small one to big one because the surface tension is providing a greater internal pressure in the smaller one. In the case of real balloons, we have found out that this statement is only true for party balloons of circumferences between 30 cm to 50 cm. In this range, the surface tension is almost constant, for which is always constant for ideal balloons or bubbles. For circumferences less than 30 cm, the balloons could have a smaller internal pressure than bigger balloons, or vise versa for circumferences greater than 50 cm. This result is supported by Levin and da Silveira’s research, which studied this phenomenon in terms of thermodynamics. The effect of surface tension is best shown by the two interconnected balloons model between 30 cm to 50 cm for the party balloons.
Conclusion

In this research, I measured the circumferences of two kinds of party balloons and the pressure difference across the surface of balloons. From these two elements, I calculated for the surface tension at different sizes of balloons. As a result, I found out that the surface tension first increased quickly to a value between 40 N/m to 50 N/m as circumference changing from deflated to 30 cm. Between 30 cm to 50 cm, the surface tension stayed relatively constant within a value of 40 N/m to 50 N/m. After the circumference passed 50 cm, the rate of surface tension increasing became faster as the rubber skin approached its limit before burst. According to this behavior, it can be concluded that the two interconnected balloons demonstration needs to be done in between 30 cm to 50 cm to simulate the effect of surface tension in bubbles models.

Reference