INCREASING THE "POP" IN POPCORN

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ABSTRACT

Popcorn is one of the most widely consumed snack foods in America. On average, Americans eat 17 billion quarts of popcorn annually. In this experiment, it is shown that by reducing the pressure surrounding the kernel at the time of popping, the flake size or volume of the popped corn is increased. Pressures close to 30 inches of mercury (Hg) below atmospheric pressure were tested in a movie popper, a pot, and a microwave. The parameters commonly used in industry to measure the quality of popcorn are ω (percentage waste), σ (total volume per mass), and π (average flake size). The results show that as the pressure decreases, σ and π increase and ω decreases. This research can benefit the food industry because popcorn is often bought by weight and sold by volume, so larger popped kernels equal larger profits.

INTRODUCTION

Popcorn is a type of sweet corn that differs from other types of edible corn. It generally has a smaller kernel, is planted earlier, germinates at a slower pace, and matures faster than other types of corn [1]. Popcorn is a food that has spanned the course of American history. From the time of the Mayan, Incan and Aztec civilizations to the present, corn has been popped and enjoyed both as food and as a part of ceremonial proceedings. The oldest ears of popping corn were discovered in New Mexico in the year 1948 and these ears are believed to be about 4,000 years old [2]. Numerous accounts of early 16th century Aztec ceremonies describe the use of popcorn. Christopher Columbus noted in his memoirs that he observed the native Aztec women wearing corsages and garlands of popcorn for ceremonial dances. He also noted that the popcorn was used to decorate the statue of Tialoc, the god of maize (corn), fertility and rain [2]. Popcorn seemed to be a symbol for peace and goodwill, and was called *momchitl* [3]. One of the clearest and earliest accounts of popcorn was made by Father Bernardino de Sahagun (1499-1590), a Franciscan priest with deep interest in Mexican culture [3]. In his description of an Aztec ritual in honor of the Aztec god of fishes, Bernardino states, "They scattered before him parched corn, called *momchitl*, a kind of corn that bursts when parched and discloses its contents and makes itself look like a very white flower; they said these were hailstones given to the god of water" [3].

In 1612 French explorers in North America and the Great Lakes Region encountered the Iroquois tribe. In their writings, the French explorers mention drinking popcorn beer and popcorn soup as well as eating regular popcorn with the tribe [3]. The Iroquois tribe was not the only tribe to have this remarkable food. Most of the tribes in North and South America used popcorn by the time the pilgrims arrived in 1620. The American Indians related popcorn to peace and so utilized the food to trade with the pilgrims and settlers, symbolizing a peace offering. In fact, it was documented that Quadequina, the brother of Chief Massasoit of the

Wampanoag tribe brought popcorn to the first Thanksgiving dinner [3]. As a result of direct contact with American Indian tribes, popcorn became very popular among the settlers, thus implanting itself in the emerging American culture.

Methods of popping corn have changed over the years, being affected by culture and technology. In 1612, explorers observed the Iroquois' method for cooking popcorn: heating sand in a fire then toasting a corn cob in the fully heated sand [4]. In the 18th century people began to boil popcorn in oil or fat inside of mesh containers. In 1893 Charles Cretor invented the first mobile popcorn machine, showcasing it at the World's Columbian Exposition in Chicago [4]. Although the device weighed between 400 and 500 pounds and had to be drawn by a cart and pony, the invention was seen as revolutionary. The machine allowed a decent day's wages to be earned selling popcorn at any nearby park, busy corner, fair, or rally. The popcorn industry thrived, even during the Great Depression. During this period, sugar was rationed and the average American was very poor. Popcorn was the cheapest snack food available and was consumed three times as much as in previous years [2]. Then, in the late half of the 20th century, the invention of the microwave created an even greater increase in the consumption of popcorn [2, 4]. In 1945, Percy Spencer created the microwave by determining how to mass produce magnetrons. Incidentally, Spencer used popcorn as the main subject in many of his tests and thus the idea of the microwave oven evolved [4]. Popcorn could now be heated in a microwave within a bag, rather than in a pot, for convenient consumer use at home [4]. This invention caused the massive trend in consumption of popcorn that is evident in America today.

Popcorn has become a vital part of the American food industry. According to a study on the popularity of popcorn in America, Americans consume 17 billion quarts of popped popcorn annually, that is, 54 quarts per person per year [5]. In addition, popcorn is a low-calorie, high-nutrient source of dietary fiber [6]. With the modern health craze, popcorn has a new appeal. The volume and flake size of popcorn are variables of interest to the popcorn industry. Since most vendors of popcorn buy it by mass, but sell it by volume, larger popped corn would increase profits. The industry is specifically concerned with 3 parameters: expansion volume (σ), flake size (π), and waste (ω) [7]. These parameters are defined as:

$$\sigma = \frac{\text{total popped volume}\,(\text{cm}^3)}{\text{original mass}\,(\text{g})}$$

$$\pi = \frac{\text{total popped volume}\,(\text{cm}^3)}{\text{original mass}\,(\text{g})}$$

$$\omega = \frac{\text{number of un-popped kernels}}{\text{original number of kernels}} \times 100\%$$

The industry's highest values for these three parameters obtained under ideal conditions are $\sigma = 45$ cm^3/g, $\pi = 8$ cm^3/kernel, and $\omega = 6.89\%$ [7]. The average consumer using a standard microwave oven attains σ values of 36-40 cm^3/g, π values of 5-7 cm^3/kernel, and ω values of 10-12% [7]. This waste value demonstrates that if a consumer spends ten dollars on a box of popcorn, one dollar was wasted in un-popped popcorn. Popcorn undoubtedly has a thriving market. Hence a more efficient method of producing it would certainly be in the industry's best interest. This experiment will attempt to not only prove that lowering the pressure around a kernel increases the expansion volume and flake size, but will also attempt to solidify a new method of more efficiently popping popcorn.

THE THEORY BEHIND POPCORN

How Popcorn "Pops"

To understand the method of increasing flake volume one must first understand how a kernel pops. A popcorn kernel has two layers. The pericarp is the hard external shell of the kernel. Gelatinous starch and water form the main components contained within the pericarp as seen in Figure 1. When a kernel is heated, the water inside is vaporized and the gelatinous starch becomes liquefied. One basic concept of thermodynamics states that a gas expands when it is heated. Hence, as the water vapor is further heated, it expands within the pericarp. When the internal pressure increases, the pericarp can no longer withstand the pressure and the popcorn pops. The pressure point at which the pericarp fails is known as the yield pressure [8]. When the pericarp breaks, the water vapor rapidly expands and causes the starch to disperse outwards and to solidify, creating the popcorn we eat [8].

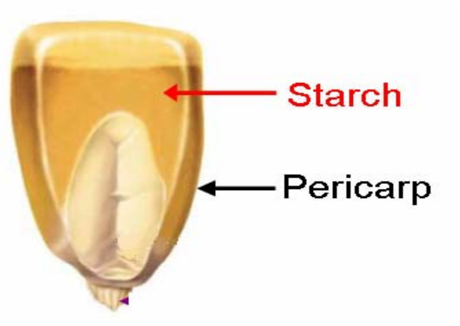

Fig. 1. This diagram depicts a view of the inside of a typical popcorn kernel.

The Thermodynamics of Popping Popcorn

The objective of this experiment was to determine whether decreasing the pressure surrounding the pericarp would increase the final expansion volume. The volume of the final kernel can be calculated using

$$P_f V_f^{\gamma} = P_i V_i^{\gamma} \tag{1}$$

where P_f is the pressure surrounding the kernel, V_f is the final popped volume of the kernel, P_i is the yield pressure, V_i is the volume of the kernel, and γ is equal to the specific heat of water at constant pressure divided by the specific heat of water at constant volume. The value of γ is about 1.3 for water vapor. (See Appendix A for the derivation of Equation 1)

Our goal is to measure V_f. Solving for V_f in Equation 1 yields

$$V_f = \left(\frac{P_i}{P_f}\right)^{\frac{1}{\gamma}} V_i . \tag{2}$$

Since we cannot change the yield pressure or the initial volume of the kernel, the only variable that can be modified to increase V_f is the external pressure P_i directly outside the kernel. Therefore, popping corn in systems with lower pressure should increase the volume of the finished product.

Theoretical Modeling of Final Volume Versus Pressure

While industry sets its benchmarks for popcorn size empirically as discussed in the introduction, we have developed a theoretical model that can predict the average volume per kernel π as a function of pressure. The model was based upon the properties of an adiabatic expansion, which assumes that the pop occurs quickly enough that there is no heat exchange and Equation 1 is valid. This relationship can then be compared to our experimental results.

Individual flake size, π, is equal to the total popped volume divided by the number of popped kernels. This value of π,

$$\pi = \frac{V_{total}}{k} \tag{3}$$

is the same as V_f, the individual volume of a popped kernel. Therefore, we can state that

$$\pi = \left(\frac{1}{\mathrm{P}_f}\right)^{\frac{1}{\gamma}} \mathrm{P}_i^{\frac{1}{\gamma}} V_i . \tag{4}$$

Since experimental pressure values were measured in inches of Hg below atmospheric pressure, Equation 4 was adjusted so that the variable P_f was in these units. Moreover, we accounted for the imperfection of laboratory pumps and the day-to-day variability of atmospheric pressure by assigning a number above 30 inches of Hg to represent atmospheric pressure. Although the pressure gauge displayed 30 inches of Hg below atmosphere, some air always remains within the popping chambers. Setting atmospheric pressure to 30 inches of Hg would theoretically produce a perfect vacuum yielding an infinite volume of popcorn, which cannot realistically be achieved. Thus, in order to attain meaningful results, atmospheric pressure was assigned a slightly higher value than the standard 29.92 inches of Hg. So the equation was altered using $P_f = 30.1 - P$ to obtain

$$\pi = \left(\frac{1}{30.1\text{-}\mathrm{P}}\right)^{\frac{1}{\gamma}} \mathrm{P}_i^{\frac{1}{\gamma}} V_i \tag{5}$$

where P is the pressure below atmosphere. The constants are $P_i = 274.74$ inches of Hg [9], $\gamma = 1.3$ [10], and $V_i = 0.178$ for yellow corn and 0.156 for white corn. Initial volumes for yellow and white corn were determined by measuring 80mL of corn in a beaker and counting the number of kernels to calculate the average volume per kernel. This process was repeated 5 times with different samples of corn for each instance and the complete average was then calculated.

Theoretical Modeling of σ and ω Versus Pressure

In the previous section, a theoretical model for π was derived from the laws of thermodynamics. However, in the cases of σ and ω no direct relationship between these variables and the pressure or volume could be derived. The value of σ is directly related to the number of popped kernels. There is no thermodynamic theory to predict the number of popped kernels. The number of popped kernels varies with sample size, corn type, and weight. Although it depended upon P_o, no direct relationship is derivable between the number of popped kernels and the pressure. As a result, no theoretical model could be derived for σ versus pressure. Similarly, the waste, ω, depends directly on the number of popped and un-popped kernels so no theoretical model could be derived for this variable.

METHODS AND PROCEDURES

The experiment involved the use of three separate devices: a movie popper, a microwave apparatus, and a pot apparatus. Though these devices varied widely in their respective methods, some procedural elements were common to all. The popcorn kernels used in the experiment were Orville Redenbacher's Original un-popped and Orville Redenbacher's White Corn. Each apparatus was assigned a type of corn that was constant throughout the trials. We wanted to simulate the method that industry employs to test popcorn, so each type of popcorn had to be sorted to determine the "good" and "bad" kernels. "Bad" kernels were determined through comparison of size and shape. The kernels that were about 2-3 millimeters smaller than the larger kernels were immediately thrown away. Kernels with cracks and breaks in the pericarp were also discarded. Smaller kernels would not be conducive to the experimental results because they have a smaller starch content compared to the larger kernels. Overall, the objective of sorting the kernels was to control variation and obtain a reasonably uniform source of kernels. Industry uses a similar process.

Movie Popper

The movie popper apparatus shown in Figure 2 is used most widely and successfully by industry. For this apparatus, 100 gram (g) samples of white popcorn were used. Each sample was counted and coated with enough vegetable oil to completely cover all of the kernels. After a uniform mixture was obtained, we poured the oil-kernel mixture into the pot inside the popper. The lid was then brought down and securely closed on top of the pot. Metal bars were placed horizontally across the width of the inside of the apparatus so as to prevent the force of the external atmosphere from crushing the movie popper. After the pot and bars were secured, the door was closed and latched shut.

For all trials below atmospheric pressure, the vacuum pump was used to lower the internal pressure of the machine. Once the pump was turned on, the position of the release valve was adjusted to observe the desired internal pressure. Once a stable pressure was obtained, the movie popper was turned on. After about 5 to 6 minutes the popcorn finished popping. The pump was then turned off, and the release valve was opened to raise the internal pressure back to one atmosphere so that the door could be opened. The popcorn in the pot was taken out immediately so it would not burn. After all of the popcorn was carefully removed from the machine, its volume was measured and the number of un-popped kernels was counted. When the trial was completed, the apparatus was cleaned. This process was repeated five times at each of the following pressures: 5, 10, 15, and 20 inches Hg below atmospheric pressure. The pumps were not strong enough to obtain any lower values of pressure.

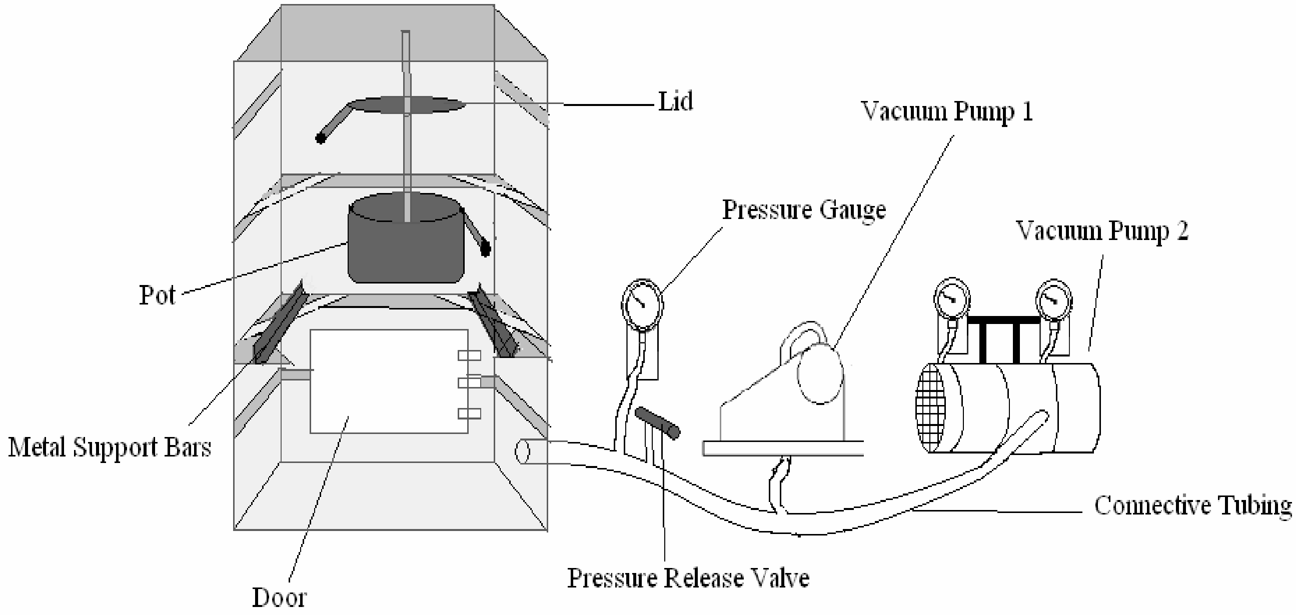

Fig. 2. Movie Apparatus. This diagram depicts the setup of the movie popper.

Pot Apparatus

The pot apparatus was actually a pressure cooker attached to a vacuum pump as seen in Figure 3. The pot was placed on a heating element and contained a digital thermometer so the internal temperature of the pot could be monitored. The thermometer was secured to the lid of the pot and was lowered approximately an inch into the pot. This ensured that only the layer of air under the metal lid was measured, not the metal. Between every trial, the temperature of the air inside the pot was brought to 75°C.

For this apparatus, 20 gram samples of yellow popcorn were used. Once the desired temperature of the pot was reached, we unlocked and lifted the lid, poured the sample of popcorn kernels into the pot, replaced and secured the lid, turned on the vacuum, adjusted the release valve to obtain the desired internal pressure, and started the stopwatch. The popcorn was then cooked for four minutes. Approximately five seconds before the four minute cooking time ended, we turned off the pump and released the pressure valve before opening the lid. After cooking, the popcorn was transferred from the pot to the beaker, where its volume was then measured. We noted the temperature flux between the original 75°C and the final temperature after the four minute cooking period. After each trial, we recorded the volume of the popped corn and counted the number of un-popped kernels. We repeated this method for five trials at each of the following pressures: 5, 7, 10, 12, 15, 17, 20, 25, and 30 in Hg below atmospheric pressure.

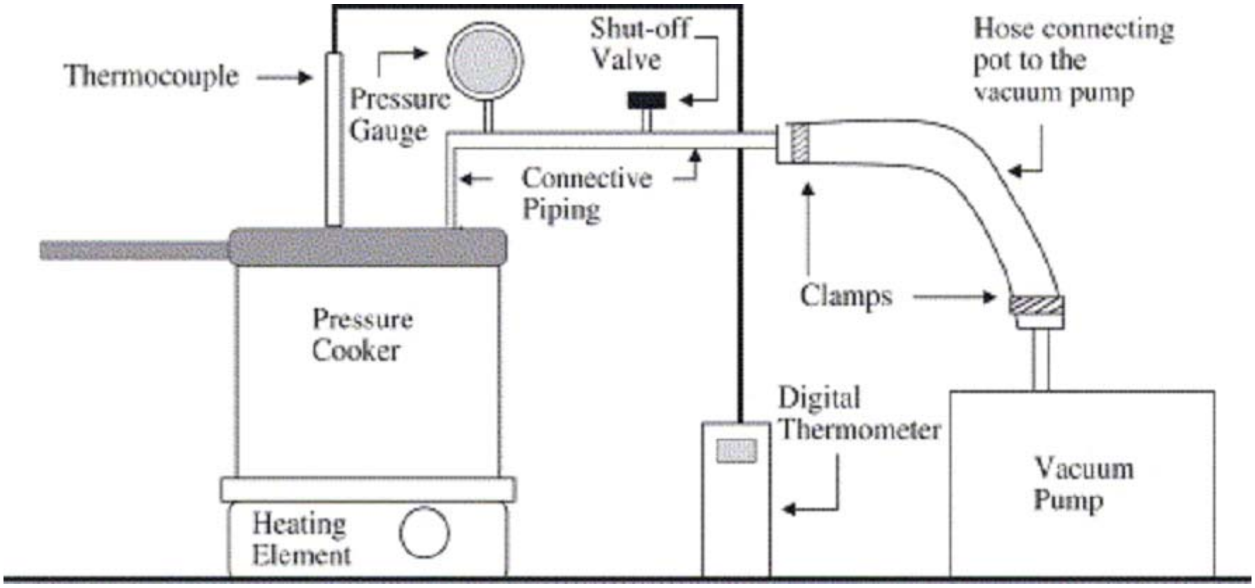

Fig 3. Pot Apparatus. This diagram depicts the setup of the pot apparatus.

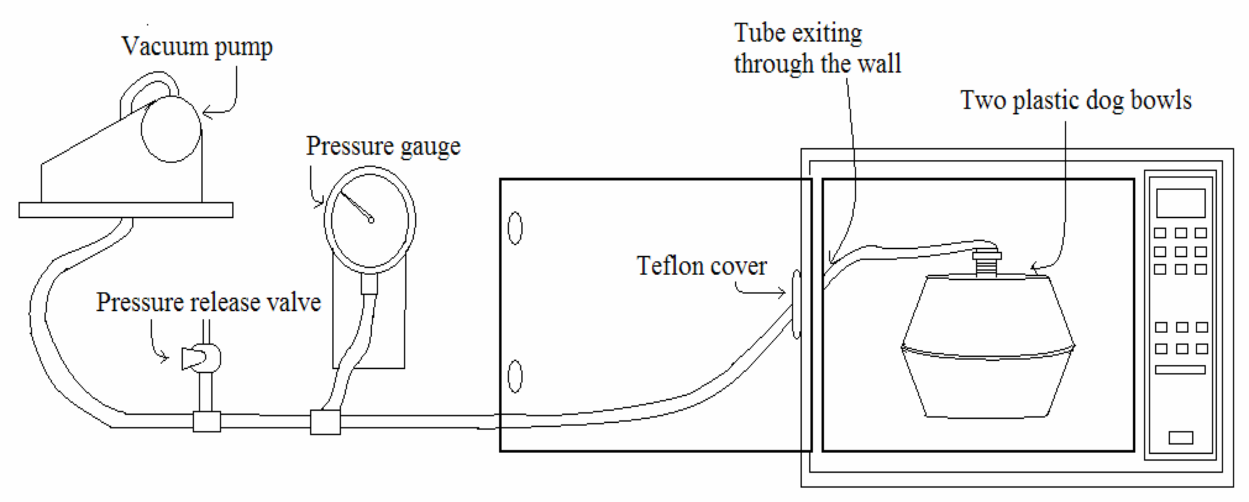

Fig. 4. Microwave Apparatus. This diagram depicts the external and internal setup of the microwave apparatus during the running of a trial. The rectangle with the dashed lines represents the bag of popcorn inside of the two bowls.

Microwave Apparatus

The microwave oven is the device most commonly used by consumers to pop popcorn in their homes. A vacuum pump was connected to the microwave oven with a tube that ran through the left wall as seen in Figure 4. The hole in the side of the microwave was fit with a Teflon sleeve, so that microwave rays would not leak out. A pressure gauge and a release valve were connected to the pump so that we could measure and control the pressure of the container inside the microwave.

Ten gram samples of Orville Redenbacher's Original yellow popcorn kernels were used for this apparatus. Each sample was placed inside a brown lunch bag that had been cut in half.

Approximately 2 cm of the top of the bag was folded over in a pattern to seal the bag. No adhesive was applied because it often burned. The bag was placed in one of the bowls, and the second bowl was placed on top (See Figure 4). The bottom of the bag faced upward so that the kernels were evenly exposed to the microwave rays. The vacuum pump was turned on to reduce the internal pressure within the bowls, and the release valve was adjusted to stabilize the pressure at the desired value. Then the microwave oven was turned on for 3 minutes to pop the kernels. Note that the amount of time required to pop the kernels was determined by running 10 trials under normal atmospheric pressure to find the ideal time that produced the most popped popcorn. After the popcorn was removed from the microwave, the popcorn flakes were placed in a beaker, the un-popped kernels were counted, and the volume was measured.

Five trials were performed each at atmospheric pressure and at values of 5, 10, 15, 20, 25, and 30 in Hg below atmospheric pressure. Note however, that the trials at 30 in Hg below atmosphere only had 2 runs because the plastic bowls imploded and could not be replaced. After each trial, minutes were permitted to pass to allow the microwave bowls and glass plate to cool. Furthermore, the bowls and plate were run under cool water. We also removed the light bulb from the microwave to prevent excess heat from being emitted during the trials.

EXPERIMENTAL RESULTS

The results validate the hypothesis that as pressure is lowered, the quality of popcorn as measured by industry standards improves. The variable σ (cm^3/g) which is a measure of the total volume divided by the mass increased for all three apparatuses as can be seen in Figures 5 and 6. For the microwave and the pot σ nearly doubles as pressure is decreased from atmospheric pressure to 30 inches of Hg below atmosphere. For the movie popper, however, σ only underwent a slight change as the pressure was reduced, though the value was higher overall in comparison to the pot and microwave. The σ values found with the movie popper began at a higher point and thus, did not have as much capacity to increase. The industry maximum for σ is 45 cm^3/g and an average consumer can get a maximum σ of 40 cm^3/g. The pot and the microwave achieved maximum σ values of 39.38 cm^3/g and 45.00 cm^3/g, respectively as seen in Figure 6. These values are smaller than the industry maximum but larger than the average consumers' maximum. As seen in Table 1, the movie popper neither exceeded the industry maximum nor consumer maximum for σ.

The waste, ω, decreased significantly for the microwave and pot apparatus as the pressure was lowered as seen in Figures 7 and 8. The movie popper had consistently low ω values at all pressures which is why a downward trend was not observed. The movie popper and pot apparatus attained ω values that were significantly below the industry and consumer lows while the microwave was only slightly below the industry value. The industry low is 6.89% compared to 3.15% for the pot, 2.18% for the movie popper and 6.18% for the microwave (Tables 1, 2, 3). As shown in Figure 8, the waste found with the microwave and pot apparatuses were significantly affected by lowering the pressure while the movie popper was not as affected.

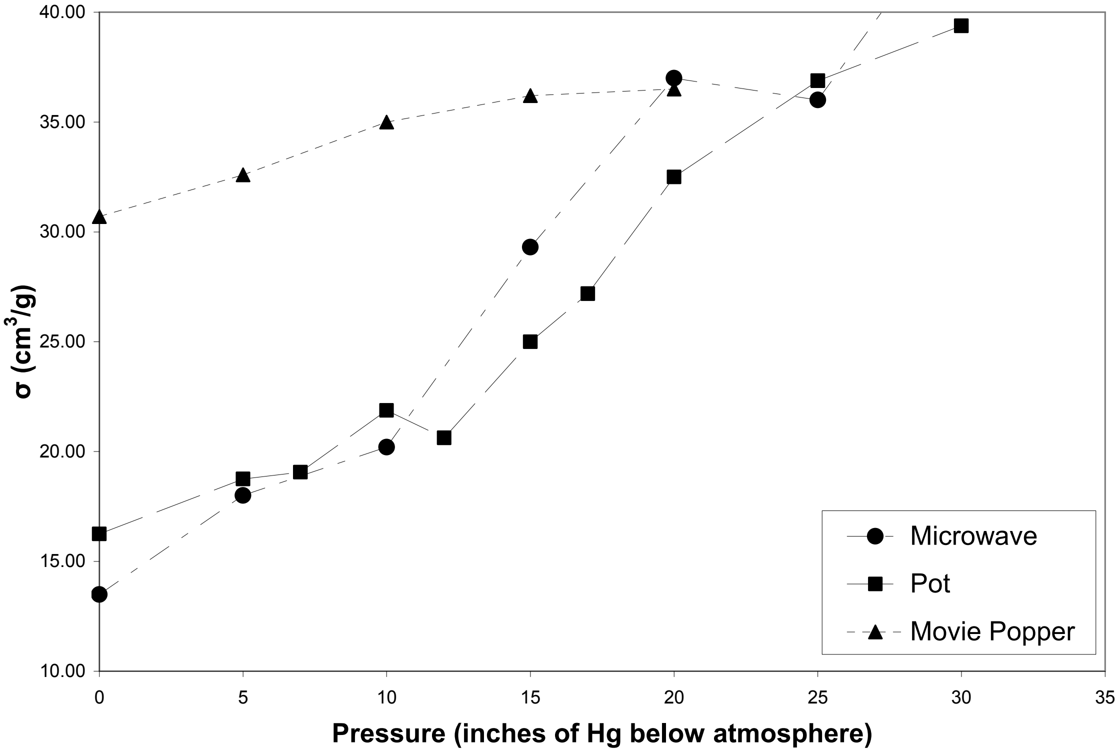

Fig. 5. The relationship between σ and pressure, the total popped volume divided by the un-popped mass, for the three apparatuses.

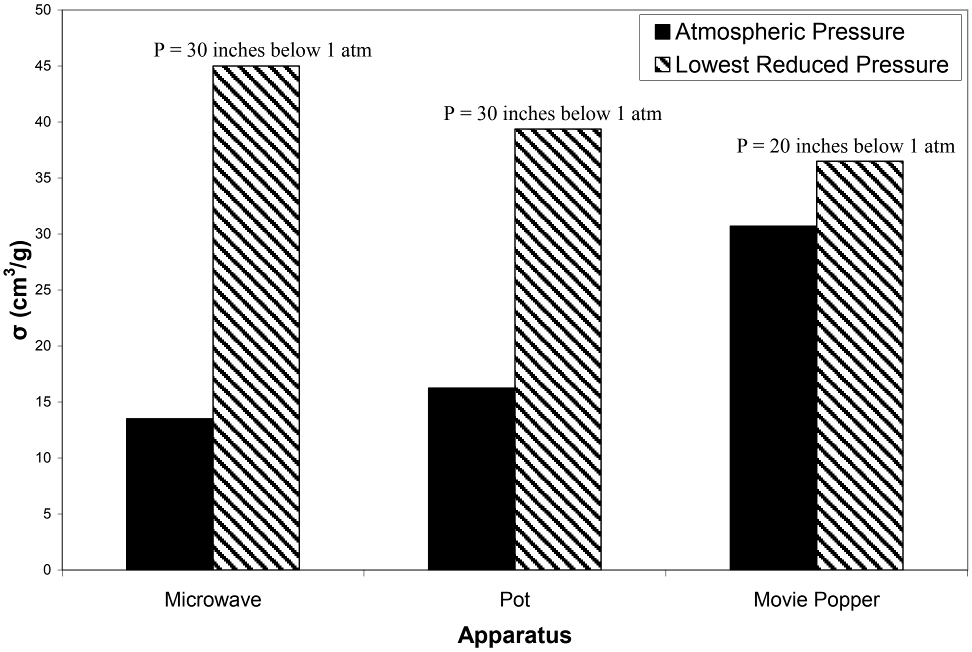

Fig. 6. The maximum and minimum σ values attained by the three apparatuses.

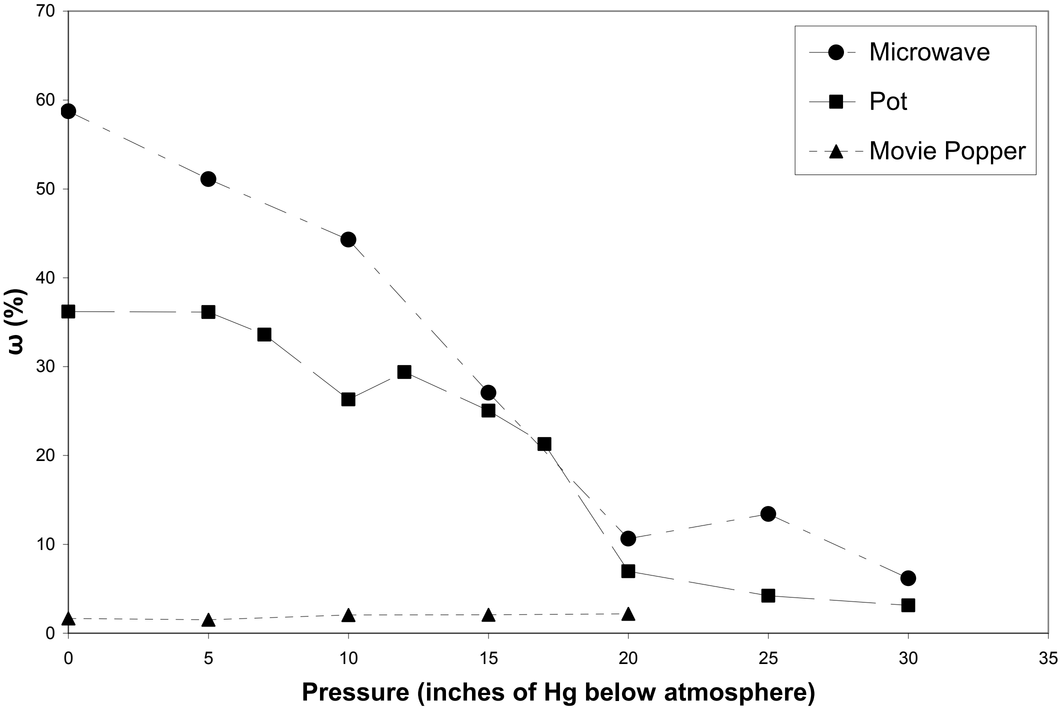

Fig. 7. This graph models the relationship between lowering pressure and waste for the microwave, the pot, and the movie popper apparatuses.

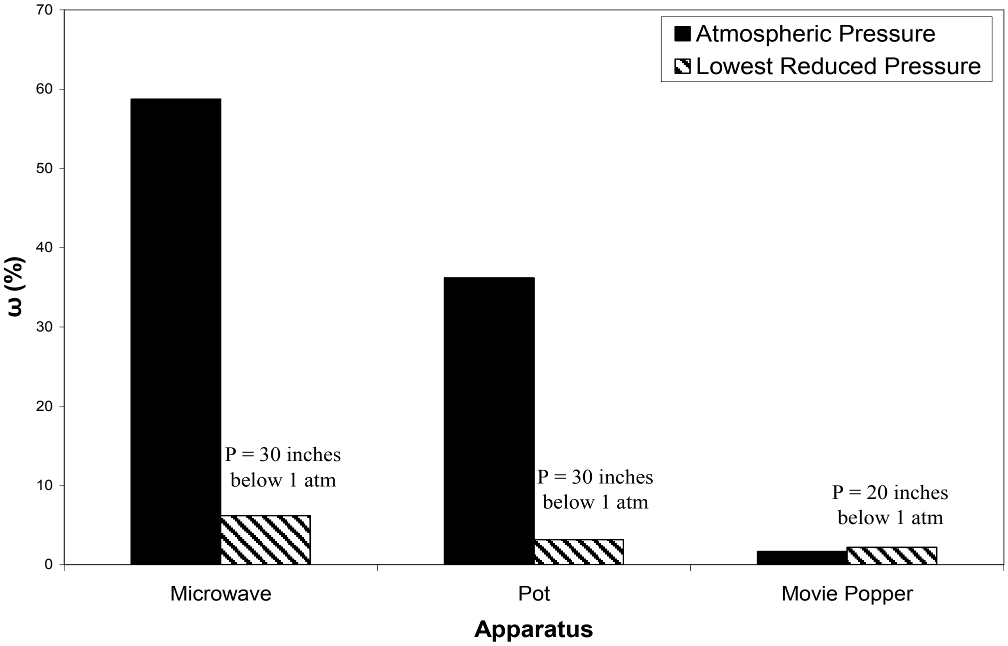

Fig. 8. This graph represents the maximum and minimum values for ω attained by the pot, microwave, and movie popper apparatuses.

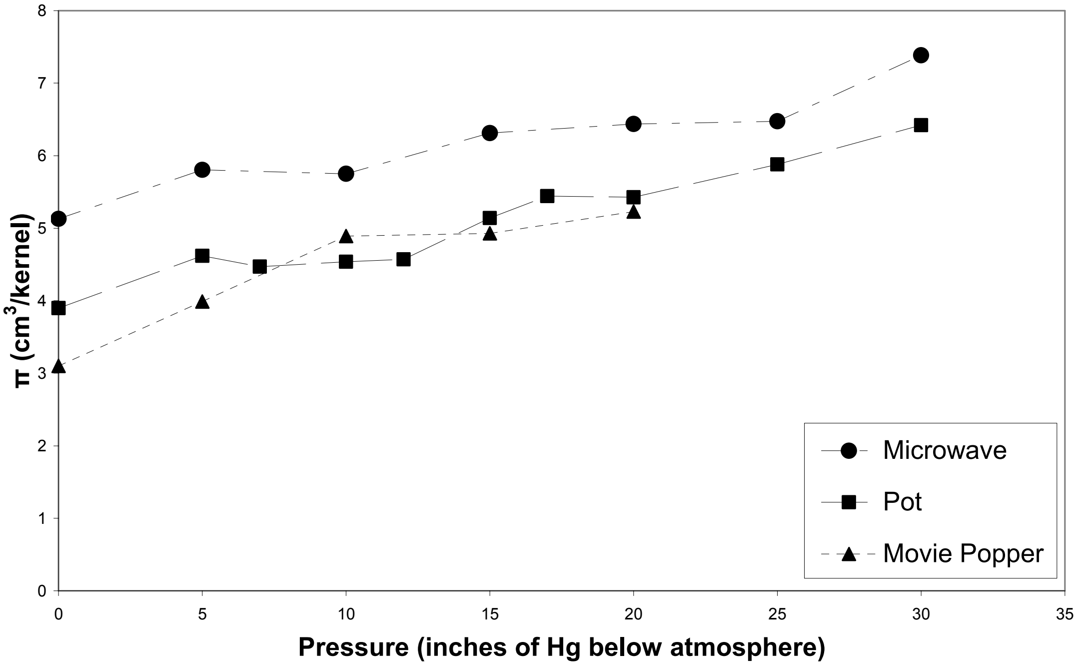

Fig. 9. Shows overall relationship between π and pressure.

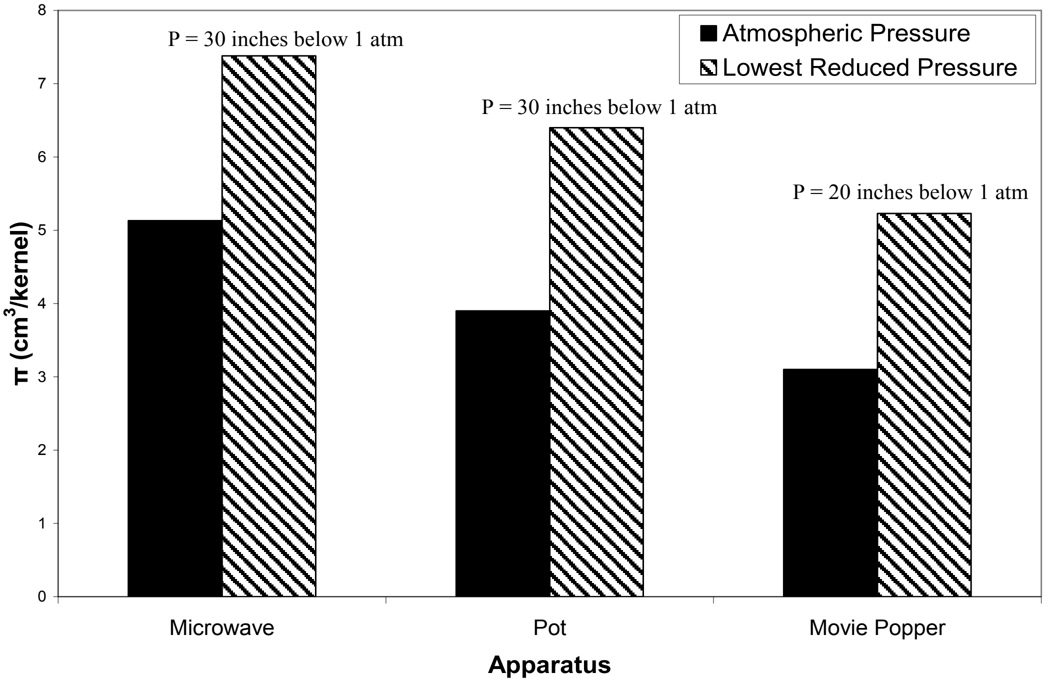

Fig. 10. This graph represents the maximum and minimum values for π attained by the three apparatuses.

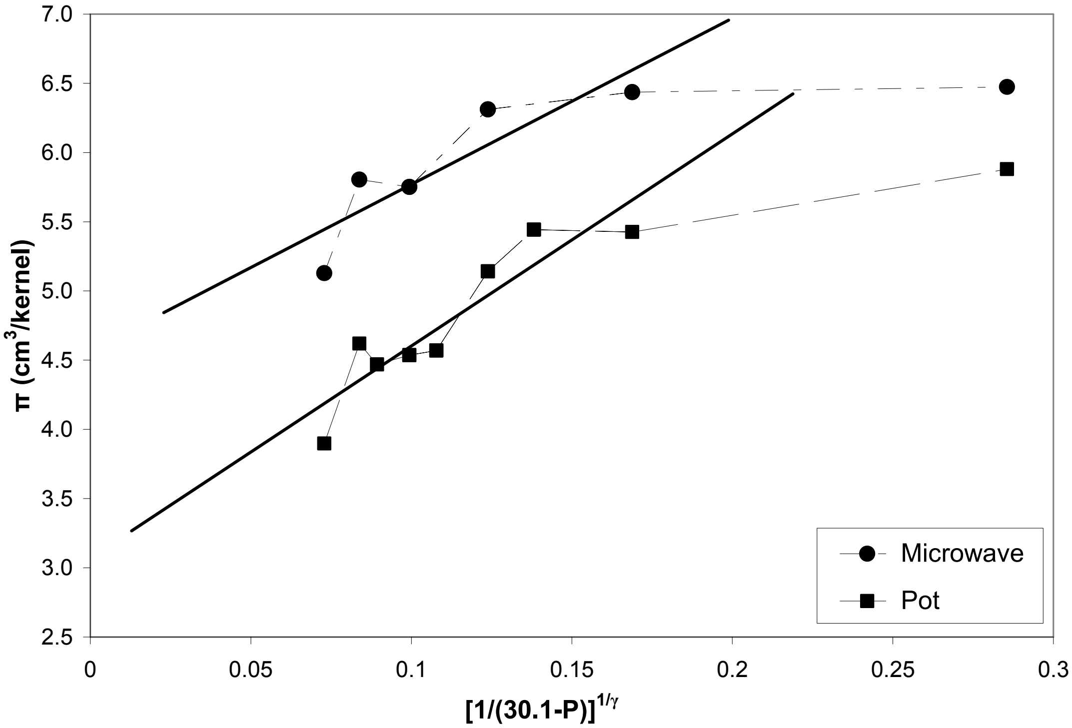

Fig. 11. The graphical model of the theoretical model of π vs. π. The linear regressions depict the theoretical prediction of infinite expansion. The dotted lines connect points and provide a visual displaying the actual limitations of expansion.

The variable π also increased for all three apparatuses. All three apparatuses failed to reach the industry standard of 8 cm^3/kernel. However, the microwave at 30 inches of Hg below atmosphere exceeded the consumer average of 5-7 cm^3/kernel with 7.38 cm^3/kernel. Figures 9 and 10 show the relationship between π and pressure as increasing for all three apparatuses.

The results for each apparatus show that while the movie popper was the most consistent apparatus, the pot and microwave were most impacted by the decrease of pressure. The values of σ and ω changed significantly enough to justify decreasing the pressure for the pot and microwave to 20 inches Hg below atmospheric. All three apparatuses resulted in increases in π as the pressure was lowered, with the microwave yielding the best overall π values. It was not necessary to decrease the pressure to see a change in ω for the movie popper since it stayed relatively constant at all pressures. For the microwave and pot apparatuses a decrease of 20 inches Hg below atmospheric was sufficient to decrease ω noticeably while further reducing the pressure produced minimal benefit. Therefore, evacuating the pressure to 20 inches Hg below atmospheric is the most beneficial for the microwave and the pot apparatuses since it is the lowest pressure that produces the most dramatic change.

Comparing Theoretical Models with Empirical Data

In the Theory Section, we derived a model of popped popcorn volume from thermodynamics principles which we can now compare to actual data from the experiment. We used a graphical approach by plotting Equation 5 which plots π as a function of pressure, as shown in Figure 11.

Using a linear regression model, the slopes of the fitted lines were compared with the coefficient derived from Equation 5, which was 13.38. When the connected points are analyzed, they appear to approach an asymptotic limit of expansion that can be attributed to the limitations of starch in a kernel, causing a logarithmic appearance. A percent error calculation was used to determine how much the empirical data varied from the model.

$$\frac{\left|Empirical - Theoretical\right|}{Theoretical} \times 100\% \qquad (6)$$

The microwave apparatus varied by 10.28% and the pot apparatus varied by14.57%. Since the movie apparatus could only be evacuated to 20 inches of Hg below atmosphere, the fit to the theory was not analyzed.

SOURCES OF ERROR

Several obstacles were faced during each experiment. Most obvious was the arbitrary nature of measuring the total volume of popcorn. In each trial we placed the flakes into a beaker and tapped it until they settled. However, since each flake was an irregular shape, measuring the exact volume was impossible as the gaps between the flakes made these measurements imprecise. In addition, the popping chamber was not entirely airtight. This was demonstrated when the pressure gauge would occasionally fluctuate during the popping process. Although the pressure never differed from the target by more than 1 inch of Hg below atmospheric, it still probably led to inconsistencies in the result. Other obstacles included human error arising from miscounted kernels and imprecise cooking times.

In initial trials with the movie popper, we left the popcorn inside the chamber for several minutes after popping. However, some of the popcorn continued to be heated and burned even after the apparatus was turned off. Due to this burning, the volume of the popped pieces decreased, varying the results. In some of the trials, especially the 10 inches Hg below atmosphere trial, the number of un-popped kernels was abnormally low. This occurred during sorting because the largest kernels fell to the bottom of the container. We used these kernels to conduct the 10 inches Hg below atmosphere trials. Thus, although 100g of popcorn was still popped, there were far fewer kernels, affecting sigma σ and omega ω.

For the pot apparatus, heating presented the greatest source of error. The results of the first trial of each day were dramatically different from each subsequent trial. This was most likely caused by the warming of a cool pot to 75°C. Moreover, the temperature within the pot fluctuated during popping because we could not control the amount of heat transfer from the hot plate to the pot. Other error may have resulted when pouring the kernels into the heated pot, because the lid demanded much effort to completely seal and often took more time than expected. We also occasionally didn’t pour the kernels in the pot at exactly 75°C, and the four minute optimal cooking time period was also sometimes exceeded accidentally.

In the case of the microwave apparatus, the major source of error was the microwave oven itself. Initially, we began with a new General Electric microwave and performed several preliminary trials to find the ideal popping time. However, the results were extremely inconsistent, ranging from trials with zero popped kernels to trials that resulted in a fused mass of burnt popcorn. The inconsistency most likely resulted from an overheated magnetron, the internal device that generates microwaves. Thus, we waited about 8 minutes after each trial to wipe the bowls and chamber with wet paper towels. However, we could not directly cool the magnetron so overheating was still a source of error.

After one trial in which the popcorn bag lit on fire, we decided to switch to an older Sears Kenmore microwave. The Sears Kenmore microwave had a weaker power rating, and we again attempted several unofficial trials to find an ideal popping time. In the end, the popping time was situated at 3 minutes. At first, the second microwave produced inconsistent results as well. However, we developed an improved way of cooling the microwave chamber by lining it with cold wet paper towels and waiting approximately 10 minutes between each trial. This finally improved the consistency of the results. We also reduced the temperature in the chamber by removing the light bulb inside.

Once we began popping at 20 inches of Hg below atmosphere, the popcorn started to burn. Believing that the low pressure created a higher temperature within the popping chamber, we lowered the popping time to 2.5 minutes. Although it did not produce burnt popcorn, the new time could not be reconciled with the previous trials since popping time was no longer a constant. We reverted back to a 3 minute popping time to observe if the popcorn would burn again. This time, the popcorn did not burn and actually produced data which fit the predicted trend. Thus, 3 minutes was decided to be the official popping time. This was all due to the inconsistent nature of how the microwave produced microwaves. The strength of the microwaves varied with each trial.

Despite eventually getting relatively stable data after improving our methods, several difficulties still arose. During a 30 inches of Hg below atmosphere trial, the top bowl of the popping chamber failed, creating a loud implosion during the middle of the popping process. We replaced the top bowl with a new identical one. Several trials later, the bottom bowl imploded in a similar fashion. These implosions were due to the fact that the bowls were 4 years old and over time developed weaknesses from relatively quick heating and cooling between trials. We further suspect that the bottom bowl was damaged when the first imploded which is why it failed only a few trials later. Due to the failure of the apparatus and the lack of replacement bowls, we could only complete two trials at 30 inches of Hg below atmosphere.

CONCLUSION

The goal of this experiment was to test the relationship between the pressure surrounding the un-popped kernels of popcorn and the final volume of the popped popcorn. The success of the experiments was measured by the three variables that the popcorn industry uses: σ (total volume per mass), π (average flake size), and ω (percentage waste). The results show that as surrounding pressure decreases, σ and π increase, and ω decreases. We developed a mathematical model that estimated individual flake size by using adiabatic principles and the ideal gas law. The differences between the model and the experiment can be accounted for when limiting factors such as the fixed amount of starch are analyzed. It is obvious that the amount of starch limits the final popped size. According to results, a pressure of 10 inches of Hg below atmospheric pressure causes an appreciable difference in popcorn volume for the movie popper. For the other two apparatuses the best results were obtained when the pressure reached 20 inches of Hg below atmospheric pressure. The movie popper was the most efficient device for obtaining ideal values of σ and ω whereas the microwave and pot apparatuses displayed the effects of decreased pressure more prominently.

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APPENDIX A

Derivations

In this section, Equation 1 will be derived starting with the Ideal Gas Law Law,

$$PV = nRT \tag{A.1}$$

where P is the pressure, V is the volume, n is the number of moles, T is the temperature, and R is the ideal gas constant. In any adiabatic process, no heat is exchanged between the system and its surroundings. We assume that the process of popping popcorn in adiabatic so no heat is exchanged and temperature remains constant.

In order to derive the equation making the adiabatic expansion of an ideal gas, one can start with the following basic assumptions of thermodynamics. We start with the definition of work,

$$W = -\int F ds \tag{A.2}$$

and the definition of internal energy,

$$U = \int_{T_o}^{T_f} C_v dT \tag{A.3}$$

where

$$C_v = \frac{dU}{dT}. \tag{A.4}$$

By the definition,

$$P = \frac{F}{A}. \tag{A.5}$$

This changes Equation A.2 to the form

$$W = -\int PAds \tag{A.6}$$

Substituting dV = Ads we obtain

$$W = -\int PdVc \tag{A.7}$$

In an adiabatic process, no heat transfer occurs. Thus, the work done is equal to the internal energy change, giving us the following relation,

$$-\int_{V_o}^{V_f} PdV = \int_{V_f}^{V_0} PdV = \int_{T_o}^{T_f} C_v dT \tag{A.8}$$

From the ideal gas law, we can write P as

$$P = \frac{nRT}{V}. \tag{A.9}$$

Substituting P into Equation A.8, we obtain

$$\int_{V_f}^{V_0} \frac{nRT}{V} dV = \int_{T_o}^{T_f} C_v dT \tag{A.10}$$

Dividing both sides of Equation A.10 by T yields

$$nR\int_{V_f}^{V_0}\frac{dV}{V}=C_v\int_{T_o}^{T_f}\frac{dT}{T}\,. \tag{A.11}$$

By integrating both sides we obtain

$$nR(\ln V_o-\ln V_f)=C_v(\ln T_f-\ln T_o) \tag{A.12}$$

Substituting for nR in Equation A.12 and simplifying gives

$$(C_p-C_v)\ln\left[\frac{V_o}{V_f}\right]=C_v\ln\left[\frac{T_f}{T_o}\right]. \tag{A.13}$$

Dividing by C_v, and using the definition $\gamma=\frac{C_p}{C_v}$, we find that

$$(\gamma-1)\ln\left[\frac{V_o}{V_f}\right]=\ln\left[\frac{T_f}{T_o}\right]. \tag{A.14}$$

Equating the argument of the natural logarithmic functions, we obtain

$$\frac{V_o^{\gamma-1}}{V_f^{\gamma-1}}=\frac{T_f}{T_o} \tag{A.15}$$

Using algebra and substituting in the following value for T,

$$T=\frac{PV}{nR} \tag{A.16}$$

we find that

$$\frac{\frac{P_fV_f}{nR}}{\frac{P_oV_o}{nR}}=\frac{P_fV_f}{P_oV_o}=\frac{V_o^{\gamma-1}}{V_f^{\gamma-1}}. \tag{A.17}$$

Finally, by cross multiplying, the final result is obtained below

$$P_oV_o^{\gamma}=P_fV_f^{\gamma}. \tag{A.18}$$

APPENDIX B: Tables

Pressure (inches Hg below atmospheric)	**Number of kernels**	**Popped Vol. (cm^3)**	**σ (cm^3/g)**	**π (cm^3/kernel)**	**ω (%)**
0	1009.4	3072	30.7	3.10	1.67
5	851.0	3264	32.6	3.99	1.52
10	732.2	3504	35.0	4.89	2.05
15	749.6	3624	36.2	4.93	2.08
20	716.0	3648	36.5	5.23	2.18

Table 1: Movie Popper Data. This table depicts the average values of five trials taken at each pressure.

Pressure (inches Hg below atmospheric pressure)	**Number of Kernels**	**Popped Volume (cm3)**	**σ (cm3/g)**	**π (cm3/popped)**	**ω (%)**
0	128.20	350.00	16.25	3.90	36.18
5	127.00	365.00	18.75	4.62	36.15
7	129.25	381.25	19.06	4.47	33.60
10	131.20	420.00	21.88	4.54	26.32
12	128.25	412.50	20.63	4.57	29.39
15	129.40	465.00	25.00	5.14	25.05
17	127.50	543.75	27.19	5.44	21.28
20	129.60	640.00	32.50	5.43	6.97
25	131.20	730.00	36.88	5.88	4.22
30	126.20	780.00	39.38	6.42	3.15

Table 2: Pot Apparatus Data. This table depicts the averages of the five trials taken at each pressure.

Pressure (inches Hg below atmospheric)	**Number of kernels**	**Popped Vol. (cm^3)**	**σ (cm^3/g)**	**π (cm^3/kernel)**	**ω (%)**
0	63.0	135	13.5	5.13	58.73
5	63.2	180	18.0	5.80	51.11
10	63.8	202	20.2	5.75	44.29
15	63.4	293	29.3	6.31	27.06
20	64.2	370	37.0	6.44	10.64
25	64.0	360	36.0	6.47	13.43
30	65.0	450	45.0	7.38	6.18

Table 3: Microwave Apparatus Data. This table depicts the averages of the five trials taken at each pressure.