

Burning a Candle in a Vessel, a Simple Experiment with a Long History

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Abstract The experiment in which a candle is burned inside an inverted vessel partially immersed in water has a history of more than 2,200 years, but even nowadays it is common that students and teachers relate the change in volume of the enclosed air to its oxygen content. Contrary to what many people think, Lavoisier concluded that any change in volume in this experiment is negligible; moreover, the explanation relating oxygen consumption in the air with its change in volume is known to be wrong. In this work we briefly review the history behind the candle experiment and its relationship with some typical erroneous explanations. One of the key factors behind Lavoisier's success was the use of experiments carefully designed to test different hypotheses. Following these steps, we performed several closed volume experiments where the candle wick was replaced by a capillary stainless steel cylinder supported and heated by a nichrome filament connected to an external power supply. Our recorded experiments are displayed as web pages, designed with the purpose that the reader can easily visualize and analyze modern versions of Lavoisier's experiments. These experiments clearly show an initial phase of complete combustion, followed by a phase of incomplete combustion with elemental carbon or soot rising to the top of the vessel, and a final phase where the hot artificial wick only evaporates a white steam of wax that cannot ignite because no oxygen is left in the closed atmosphere. After either a complete or incomplete combustion of the oxygen, our experiments show that the final gas volume is nearly equal to the initial air volume.

1 Introduction

In the third century BC, the Greek engineer and scientific writer Philo of Byzantium was probably the first to report on the experiment of burning a candle inside an inverted vessel partially immersed in water; the well known result is that after the flame goes out, the water level inside the vessel increases. Philo described this experiment in his work *Pneumatica*,

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and was referenced by Heron of Alexandria in the first century AD (see Jastrow 1936, p. 171 and the end of the second paragraph of *Treatise on Pneumatics* in Woodcroft's (1851) translation of the *Pneumatics* of Hero of Alexandria). Philo's wrong explanation for the change in volume of the air inside the vessel was that corpuscles of air were converted into small particles of fire and escaped from the vessel producing a partial vacuum that drove water to ascend. Although this explanation is wrong and it can appear naive in modern days it was a reasonable explanation in Philo's time, based on the four classical elements of ancient Greece. Philo and Heron also knew and mastered the effects of temperature on the expansion of gases as demonstrated by their detailed explanations on the workings of many machines. In particular, in their works they discussed a machine closely related to the candle experiment called the thermoscope. Nowadays devices similar to the thermoscope are commercialized as a toy called hand boilers, which corresponds essentially to the thermoscope made popular by Galileo. Consider, for example, the following extract of a letter written by Benedetto Castelli to Ferdinando Cesarini in 1638.

an experiment shown me by our Signor Galileo more than 35 years ago. He took a small glass flask, about as large as a small hen's egg, with a neck about two spans long and as fine as a wheat straw, and warmed the flask well in his hands, then turned its mouth upside down into a vessel placed underneath, in which there was a little water. When he took away the heat of his hands from the flask, the water at once began to rise in the neck, and mounted to more than a span above the level of the water in the vessel. The same Sig. Galileo had then made use of this effect in order to construct an instrument for examining the degrees of heat and cold. (Knowles 1966, p. 8).

The thermoscope consists of a hollow glass sphere that is connected to a thin glass cylinder, whose free end is put inside water in a lower vessel, as shown in the left of Fig. 1. If the temperature of the glass sphere is first increased and afterwards the end of the cylinder is immersed in the water, then the water rises inside the cylinder as the temperature of the sphere decreases. The thermoscope works due to the thermal contraction of the hot air trapped in the upper vessel, causing a pressure difference which drives water to ascend through the narrow glass tube. The same principle explains the working of an old toy called the "drinking bird" and of the hand boilers. Modern versions of both toys can be ordered, for example, from <http://scientificsonline.com/> (search for hand boilers and drinking bird).

The working principle behind the candle experiment is also the thermal change of volume of a gas that produces noticeable changes in the level of a water column. Important

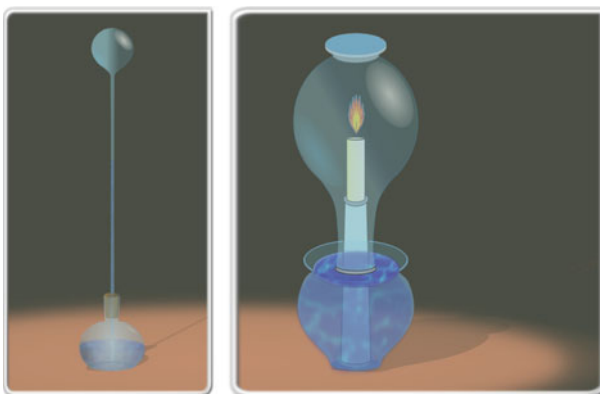


Fig. 1 Galileo's thermoscope (*left*), Philo of Byzantium candle experiment (*right*)

names that worked in the underlying principles behind the candle experiment, in chronological order, are: Philo of Byzantium, Heron of Alexandria, Galileo Galilei, Joseph Priestley, and Antoine Lavoisier. The initial part of this line of time is also shared by the thermoscope made popular by Galileo, device that is very important in the history of science because it gave birth to the development of the thermometer by several scientists. The similarities of this apparatus with Philo's candle experiment are evident in Fig. 1. A good starting point to read about this topic is the Wikipedia section on the history of the thermometer: <http://en.wikipedia.org/wiki/Thermometer>.

A common wrong explanation for the change of volume in the candle experiment is the following: oxygen from the air and carbon from the candle wax combine to produce carbon dioxide and water. After the combustion all the oxygen disappears from the gas, and since the oxygen content in the atmosphere is 21% (Benedict 2010),¹ a 21% decrease in the initial gas volume is produced.

The origins of some misconceptions for the candle experiment and several variants of the typical setup have been discussed in the literature (Birk and Lawson 1999; Krnel and Glazar 2001; New Scientist 1998; Peckham 1993) and the current status is that the chemical reaction only plays a minor role. The correct explanation for this experiment is that the observed change in volume is caused by the thermal expansion of air, by the trapping of hot air inside the vessel, and/or by air bubbling out of the vessel. This bubbling can be easily seen in the companion video that we recorded for the typical candle and vessel experiment.²

A common element found in the works that give the wrong explanation is their failure to design new experiments to test or falsify their hypotheses, or the use of a non strictly closed system. Most experimental scientists adhere to the idea that the only mechanism to accept or reject an explanation for any observed phenomena is to carefully design an experimental test for it. This is the essence of the scientific method of Galileo Galilei, but whose origins can be traced back to the works of Philo of Byzantium and others³ (Russo 2004; Jastrow 1936, p. 172).

In this work we report some new experiments that are based on Lavoisier's closed volume candle experiments, designed to test if a change in the gas volume really exists. Our simple closed system convincingly demonstrates the effects that thermal expansion plays in the classic candle demonstration. Our setup includes a candle where the wick was replaced by a thin stainless steel cylinder that is heated using an electric current. This setup allows us to light the candle even in the presence of low concentrations of oxygen as we provide the necessary heating to reach the ignition temperature of wax independently of the heat produced by the exothermic combustion. In the typical experiments the candle remains lit for about 10 s and extinguishes because of a low concentration of oxygen that cannot provide the necessary heat to maintain the ignition temperature necessary to sustain

¹ This is a reproduction of a book published before 1923, a copy of the 1912 edition is available online at <http://www.archive.org/details/compositionofatm00benerich>.

² The experiment can be visualized in the web page http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/Candle_demonstration/movimiento.html. After all the images are loaded you must press the Play button or advance to the next or previous frame using the arrow keys. It is also possible to move the mouse over the boxes of the navigation bar located below the central image to advance forwards or backwards. This experiment was recorded at 10 frames per second (fps).

³ Lucio Russo in his book *The Forgotten Revolution* traced the origins of the modern scientific method back to the Hellenistic Scientists. He quotes for example a revealing phrase from Philo: "That everything cannot be accomplished through pure thought and the methods of mechanics, but much is found also by experiment...."

the reaction. In our experiments we can make the candle flame to last up to 30 s, and three phases can be easily observed: first there is a phase of complete combustion, then there is a phase of incomplete combustion characterized by the presence of black smoke and finally there is a phase where only a hot white wax steam is evaporated by the artificial wick. We repeated our experiments stopping in any of the mentioned phases, with some experiments lasting for more than 60 s. In all of these experiments we obtain a final gas volume nearly of the same magnitude as the initial air volume. Because the first two phases require a different balance of the elements in the chemical reaction, our results show that the observed transitory change in volume is only a consequence of the thermal expansion and contraction of the gas volume. The final negligible change in volume was observed by Lavoisier in his closed volume experiments (Lavoisier 1777) and has been also reported in an experiment where a piece of paper was burned inside a rigid closed combustion chamber (Vitz 2000).

After the results obtained in closed volume experiments, it is clear that in the typical candle and glass experiment the observed change in gas volume must be a consequence of trapping hot air and or air bubbling out of the system. A Gas Chromatography (GC) analysis for the atmosphere of the experiment of burning a piece of paper (Vitz 2000), shows a consumption of a 56% of the initial amount of oxygen. Although the chemical reaction for the candle experiment is different, the previous GC result shows that the amount of oxygen that reacts in the burning of paper experiment is not a small quantity, giving us some indirect evidence of the percentage of oxygen reacting in the candle experiments. As we will see below, our experiments show that the gas volume does not change, independently of the percentage of oxygen participating in the chemical reaction.

2 Lavoisier's Experiments

Joseph Priestley and Antoine Lavoisier played a leading role in the emergence of modern chemistry. In a series of experiments on chemical reactions and combustion, Lavoisier was able to measure properties of things invisible to him (gases), discovering the law of conservation of mass. This law is one of the most important achievements of science and is the basis to understand chemical reactions. Lavoisier systematically conducted Philo's candle experiment (Lavoisier 1777, p. 195), concluding that any change in volume is well below 1%. Lavoisier concluded correctly that the change of volume in the typical candle experiment was due to the thermal expansion of air. In a simple experiment, he placed an inclined inverted glass bell partially submerged in mercury, ignited the candle and quickly moved the candle inside the bell. The bell was quickly submerged and the column of mercury prevented air to bubble out, but strictly speaking this is not a closed system because initially air can enter or leave the bell. In contrast, his contemporary and scientific adversary Joseph Priestley in his experiments on combustion used sunlight and a lens to ignite different substances inside a closed volume. Lavoisier also designed a closed volume variation of the candle experiment: he put phosphorous near the candle wick, and closed the volume with a mercury bath, extracting some air to get a column of mercury that sealed the volume and allowed the gas to expand without bubbling out of the vessel. He then introduced a heated piece of iron through the column of mercury to ignite the phosphorous and light the candle.⁴

⁴ Lavoisier (1777): j'ai donc résolu de prendre toutes les précautions possibles pour obtenir un résultat plus certain, plus indépendant de toute erreur, et voici l'expérience qui m'a paru devoir être la plus décisive. J'ai

therefore, I decided to take all the precautions needed to obtain a more precise result, whose validity is not affected by errors, and the experience I think is the best for this purpose is the following: I held in place a small candle in the middle of a glass container; I attached to the top of the wick a little piece of Kunckel's phosphorus, of approximately one-sixth of a grain in weight; after which I put in the glass container a bath of mercury and covered it with a crystal bell. Finally, using a glass siphon that connected the interior of the bell to the outside, I made raise the level of mercury, by sucking, to a certain height that I marked very precisely using a band of sticky paper. After making all these preparations, I heated a piece of iron in the form of a rod, which I had bent for this purpose, until it become red, and introduced it under the bell, passing it through the mercury in order to touch the upper part of the candle and light the little piece of phosphorous.

After taking into account the known volume of oxygen that reacts with a known amount of phosphorous, he concluded that the change in volume due to the burning of the candle was negligible.⁵

which can be regarded as being absolutely zero, especially if one pays attention to the fact that this difference could be produced by a very small change in the ambient temperature.

It is interesting that people pretend to demonstrate Lavoisier's ideas of chemical reactions, measuring typical volume changes near 21% in an experiment where Lavoisier measured values below 1%. The negligible change of volume in Lavoisier's experiments has not been noted in the typical references of the candle experiment. Nowadays it is well known that after the flame goes out there is enough oxygen in the enclosed volume to allow a mouse to breathe without difficulties (Birk and Lawson 1999), an experiment also reported in the times of Lavoisier by Priestley. The candle experiment cannot be used to demonstrate that the oxygen content of air is 21%. To demonstrate the oxygen content of air, the simple experiment of rusting steel wool in a closed atmosphere is typically used (Gordon and Chancey 2005; JCE staff 2001). In this experiment, the oxygen combines with solid iron to produce a solid oxide, disappearing from the gas atmosphere. Depending on the setup, the oxygen content of the gas atmosphere can be obtained measuring changes in the gas volume or changes in the gas pressure. Lavoisier in 1779 also measured the oxygen content of the atmosphere in his classic twelve-day experiment where mercury is heated inside a closed air volume, resulting in a solid red powder of oxide of mercury and a 16% of the air used up (Lavoisier 1789, p. 35).

3 The Typical Candle and Vessel Experiment

Figure 2 shows a demonstration of the candle experiment, in which a glass is put over a burning candle partially immersed in water.

We recorded a video of this typical candle and vessel experiment where the change in the air volume is clearly observed and the bubbling of hot air can be easily seen at the

Footnote 4 continued

assujetti, au milieu d'une capsule de verre, une petite bougie; j'ai fixé à la partie supérieure de la mèche un petit morceau de phosphore de Kunckel, du poids d'un sixième de grain environ; après quoi j'ai placé la capsule sur un bain de mercure, et je l'ai recouverte avec une cloche de cristal; enfin, avec un siphon de verre qui communiquait de l'intérieur de la cloche à l'extérieur, j'ai élevé, en suçant, le mercure jusqu'à une certaine hauteur; que j'ai marquée très-exactement avec une bande de papier collée. Lorsque tout a été ainsi disposé, j'ai fait rougir une petite tringle de fer que j'avais recourbée pour cet objet, puis je l'ai passée pardessus la cloche à travers le mercure pour aller toucher le haut de la bougie et enflammer le petit morceau de phosphore.

⁵ Lavoisier (1777): ce qui peut être regardé comme absolument nul, surtout si l'on fait attention qu'un très-léger changement de la température du lieu où se faisait l'expérience a pu produire cette différence.

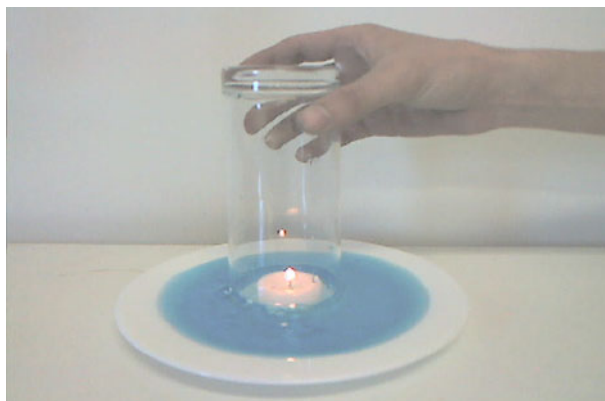


Fig. 2 Typical setup for the candle and vessel experiment

beginning (see footnote 2) of the experiment. A correct analysis of this simple experiment, performed to discover the relationship between the change in volume of the enclosed air and the underlying chemical reaction, can be a challenging task. Wrong conclusions are typical in this experiment and in any experiment that uses a volume of gas that is not strictly closed. The origins of typical misconceptions and the correct explanation for this experiment have been reported in several works (Birk and Lawson 1999; Peckham 1993; New Scientist 1998), although some of these works mention results that do not agree with the negligible change in volume reported in the original works of Lavoisier.

The typical chemical reaction considered in the analysis of this experiment is (Birk and Lawson 1999) $C_{25}H_{52} + 38O_2 \rightarrow 25CO_2 + 26H_2O$. Taking into account that initially the O_2 constitutes a 21% of the initial gas volume and assuming that all the oxygen takes part in the combustion, 38 O_2 molecules corresponds to a 21% of the initial atmosphere. If 38 molecules corresponds to a 21%, then 25 CO_2 molecules corresponds to a 13.8% and 26 H_2O molecules corresponds to 14.4%. The chemical reaction shows that the initial 21% of oxygen transforms to a 13.8% of volume of CO_2 and a 14.4% of volume of H_2O , resulting in a possible change of volume of the enclosed gas between +7.2 and -21%, depending on how much of the products from the reaction are left in the gaseous, liquid or solid phase, or dissolved in water.

For example, if O_2 , CO_2 and H_2O are in the gas phase, the initial 38 molecules transform to 51 molecules and the final volume grows in 7.2% (13.8 + 14.4 - 21%). If CO_2 is not considered in the final volume or it is supposed to be dissolved in the water that seals the volume, and if the H_2O molecules are supposed to condense in the liquid phase, then the initial 38 O_2 molecules disappear from the gas volume producing a final gas volume 21% smaller than the initial air volume. If there is not enough oxygen to sustain the reaction, the change in volume should be less than these values because only a fraction of the oxygen is consumed.

After a series of papers that appeared in the *Journal of Chemical Education* (Birk and Lawson 1999; Glantz 1963; Krnel and Glazar 2001; Peckham 1993), the oxygen consumption explanation for the candle experiment was demonstrated to be wrong. But the wrong naive explanation that a partial vacuum is produced because of the consumption of all the oxygen in the enclosed air continues being disseminated.

For a recent example, search for the Lifting Lemon Physics Trick in the site <http://www.einsteinyear.org>. This new version of the candle experiment consists in a circular lemon slice with some matches inserted forming a pyramid with its heads put together and pointing upwards. The system is let to float in a dish of water, the matches are lighted and the system is covered using a glass. This is supposed to be a bar trick that it is simple to setup and where people is puzzled by the lemon being levitated magically inside the glass. This lemon trick was one of the activities developed by the Institute of Physics as part of the celebration of the Einstein Year in 2005. The Institute of Physics in Europe and the American Physical Society in the US are the most important institutions with a worldwide basis of members providing scientific news and information to physicists from universities from all over the world. The Einstein year was a worldwide celebration of the physics community; it was a big, serious and high quality activity. But the lifting lemon trick proposed to engage non scientists with science, appears explained using both the right and the wrong explanations. Our experiments clearly show that the chemical reaction is not responsible for the change in volume observed in a typical candle experiment or in this Lifting Lemon Physics Trick.

Today, there are particular cases of use of the wrong explanation in the candle experiment that reach a large audience that can be not aware of the current status of the candle experiment. The Levitating Lemon Trick belongs to this class but can be argued that it was not noticed because it was disseminated by the physics community. To mention another example of this class that is being disseminated by a company providing lab equipment for teaching chemistry, search for 'Dalton's Law of Partial Pressure' at www.pasco.com. This company sells an interface and a pressure sensor bundled with an activity to measure the oxygen content of the air using Dalton's law and the candle experiment. This is a modern experimental setup where it is provided a mean to eliminate the CO_2 from the gas atmosphere, and it is clear that they intend to measure the oxygen content in the air to be 21%.

Besides these dramatic examples, many published papers (with either the right or the wrong explanation) share the error of not using a strictly-closed system and therefore the reported experimental results cannot be trusted. For example, (Caplan et al. 1994) recognizes the importance of not letting hot air escape in the form of bubbles, but to solve this problem a partially submerged tilted beaker is placed over the floating candle after it has been lit. This setup is thus trapping hot air and it is a non closed system.

A classic discussion of the candle experiment is given in Fowles's book (Fowles 1960), a classic book that even today is a great source of demonstrations for the teaching of basic chemistry. In page 62 (Expt. 64.—A Candle burnt under a Bell-jar) a closed version of the candle experiment is explained and it is noted that it is better to conduct this experiment in a closed atmosphere rather than in the typical demonstration setup. It is also mentioned that the candle experiment appears to show that only a small fraction of the air will support combustion. Notwithstanding this, several works in the literature during the twentieth century continued to use non closed systems, thus helping to propagate the wrong explanation for the candle experiment.

4 Our Closed Volume Experiments Using an Artificial Wick

To help our students to understand the origins of the wrong explanation of this experiment, we have recorded our own closed volume experiments, which can be visualised as web pages in our web site (<http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/>). The

reader can easily visualize and analyze images from each experiment, obtaining values for the time and the volume (level of the water) directly from the web page by clicking on a point of an image (Vera and Romanque 2009).

Figure 3 shows our setup to conduct a closed volume candle experiment where the candle wick was replaced by a thin metallic cylinder heated using an electric current. Lavoisier used mercury to seal the air volume but in typical simple modern versions of the experiment it is replaced by a water seal. It is also possible to use a rigid container to perform closed volume combustion experiments (Vitz 2000) and measure changes in the gas pressure to obtain using Dalton's law the equivalent change in volume at atmospheric pressure. As mentioned by Vitz (2000), big pressures appear in a combustion experiment and some care must be taken to maintain a perfect seal in these experiments. Because we wanted to record an experiment where the change in gas volume is clearly observed, we designed a setup that uses a water seal to maintain a closed gas volume for the combustion. We used an acrylic container to hold the water seal and an inverted 500 ml graduated cylinder was positioned leaving a small aperture between its submerged end and the bottom of the container to allow the water to flow. Two electric wires were installed passing through two holes in the lower part of the container. The wires outer insulation layer was removed inside the holes, which were sealed using a hot silicone gun. The upper part of the outer insulation layer was also removed and a thin nichrome wire was wrapped around the copper wires. We used a regulated 30 V power supply to pass an electric current through the nichrome wire and the voltage was adjusted to heat the filament until a brilliant red color was obtained. A support was attached to the upper part of the electric wires to hold a small candle in place. The cotton wick was replaced by a small stainless steel hollow cylinder that was obtained from a syringe needle 0.5 mm in diameter. A 1 cm cylinder was cut using a file tool to mark a circular groove and afterwards the needle was broken using pliers. The cylinder was partially inserted in the candle and was hold in place by wrapping the nichrome wire around it. To prepare the experiment a hose is used to suction some air and make the water to rise inside the inverted graduated cylinder.

Figure 4 shows a volume versus time plot for our experiment,⁶ visualized as a web page in Fig. 5. To gain control of the combustion process, the candle wick was replaced with the artificial wick as shown in Fig. 6. After applying a voltage, the filament warms up heating the wick. The bottom of the heated metal wick melts the candle wax, which rises inside the cylinder by the action of capillary forces. In the upper end of the cylinder the liquid wax ignites producing a flame. When the electric current is turned off the flame cannot remain lit by itself because of the heat conduction through the electric wiring. In this experiment, we used a 500 ml graduated cylinder and an initial air volume of 250 ml. During the heating process the air volume increases; after turning off the voltage the candle flame extinguishes and the air volume decreases to a final volume that is very close to the initial one. Collecting data for this experiment using the web page software⁷ (Vera and Romanque 2009), the plot shown in Fig. 4 was obtained, where the final volume ends about 1% larger than the initial volume.

⁶ Click on the `movimiento.html` web page in http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/Candle_artificial_wick_partial_combustion/. This experiment was recorded at 10 fps.

⁷ By clicking on a point of the image (for example the water level) the coordinates of that point will be stored by the web page software and the next image will be displayed to continue collecting data. Afterwards clicking on the 'VER DATOS' button a new window will be opened displaying the collected data.

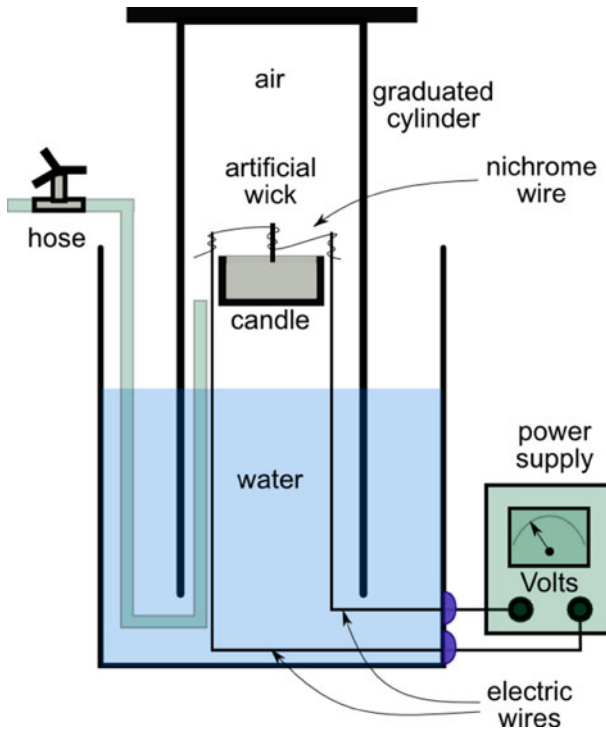


Fig. 3 Experimental setup used in our closed volume artificial wick candle experiments

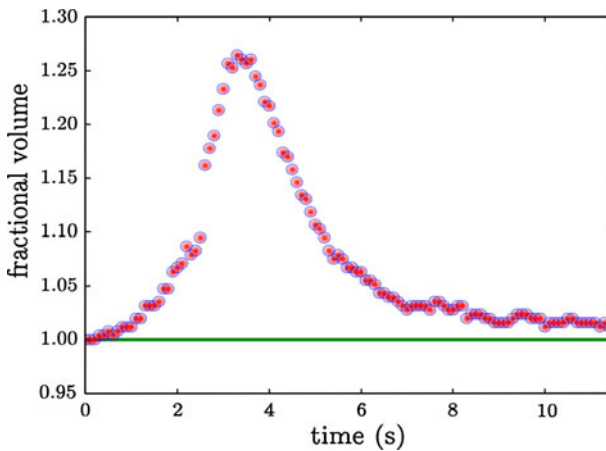


Fig. 4 Fractional volume versus time plot for a closed candle experiment

It is well known that in the candle experiment only a fraction of the oxygen reacts before the candle light extinguishes. This was demonstrated in the times of Lavoisier by putting a living mouse in the remaining atmosphere after the combustion had ended (a video of this experiment is mentioned in Birk and Lawson 1999). In a variation of the



Fig. 5 Candle experiment inserted in a web page for visualization and analysis



Fig. 6 A candle with a metallic artificial wick heated using an electric current

previous experiment,⁸ we turned off the electric current in the filament well after no signs of flame were observed. The final change in gas volume for this experiment was similar to the 1% increase of the initial volume for our previous partial oxygen combustion experiment. We are confident that after the combustion, no oxygen was left inside the closed volume, because in this experiment it is possible to distinguish an initial phase of complete combustion, followed by a phase of incomplete combustion with elemental carbon or soot rising to the top of the cylinder, and ending with a final phase where the hot artificial wick

⁸ Click on the movimiento.html web page in http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/Candle_artificial_wick_total_combustion_1/. This experiment was recorded at 5 fps.

only evaporates a white steam of wax. The presence of convective flows that pass near the hot artificial wick and the fact that our artificial wick can sustain the combustion for a longer period of time by maintaining the temperature above the ignition temperature, give support to our assumption that all the oxygen is consumed.

We also ran another variation of this experiment where the electric current was turned on and off several times,⁹ the total elapsed time of the experiment being larger than before. The different phases are clearly visible and the final result for the change of volume was similar to the results of our experiments discussed above. In this experiment it is easy to observe the movement of the hot wax steam. The wax evaporation observed in this version of the experiment is similar to what happens in a Molecular Beam Epitaxy (MBE) machine, where different kinds of molecules are evaporated and let to deposit on the sample. This white gas steam should not be confused with the steam seen after blowing out a candle, because in the later case the steam has not the necessary temperature to support combustion even in the presence of oxygen and in our experiment the heat provided by the artificial wick always maintain a steam temperature above the ignition temperature of wax. As discussed by Faraday in his *Chemical History of a Candle* of the year 1861 (Faraday 1978; see Fig. 2; p. 15), after gently blowing out a candle it is possible to relight the candle by approaching a match to the steam far from the candle. The steam ignites and propagates the combustion towards the candle wick. We remember that for the combustion of a piece of paper in a closed volume the percentage of oxygen that chemically reacts with the paper is around 56% and in our experiment we can sustain the combustion for up to 3 times the typical time of 10 s for the combustion in a typical closed volume experiment for a candle or for a piece of paper, which gives a strong support to our hypothesis that no oxygen has been left in the enclosed gas.

5 Discussion

In addition to our artificial wick experiments, we have recorded the typical candle and glass demonstration shown in Fig. 2 where air bubbling out of the system can be easily seen (see footnote 2). We have also recorded a closed volume experiment that uses a normal candle which is ignited putting a head match near the wick and focusing light on it.¹⁰ The final volume of enclosed air obtained in this last experiment was around 1 or 2% larger than the initial gas volume. This result is consistent with our artificial wick results; however, the chemical reaction for the oxidation of the head match should be taken into account in a quantitative analysis of the experiment.

In our experiments we use a closed air volume to prevent bubbling and since we use a stainless steel artificial wick, the chemical reaction involves only oxygen and the candle wax. We prefer our artificial wick and the electric ignition of the candle instead of the focused light method because our setup allows burning all the oxygen in the initial air volume. For example, when using a focused light beam to ignite the candle it is necessary to include a head match (or phosphorous as Lavoisier did) near the wick, so that the beam ignites the head match and the resulting flame lights the candle. A focused light beam from the sun or a high intensity lamp can hardly ignite the head match inside a glass container

⁹ Click on the [movimiento.html](http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/Candle_artificial_wick_total_combustion_2/) web page in http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/Candle_artificial_wick_total_combustion_2/. This experiment was recorded at 5 fps.

¹⁰ Click on the [movimiento.html](http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/Candle_closed_volume_focused_light/) web page in http://laplace.ucv.cl/TrackMovingObjects/Gallery/Candle/Candle_closed_volume_focused_light/.

and cannot (using normal lenses) directly light the candle or sustain the chemical reaction. This is very different from our artificial candle wick, where the heat produced using an external electric current can light the candle and sustain the chemical reaction in the presence of low quantities of oxygen or just evaporate a hot steam of white candle wax. This hot white steam is above the ignition temperature and can sustain an incomplete reaction which produces carbon monoxide and soot as shown in our experiments. The high temperature of the steam is enough to initiate the combustion and the observed gas convection inside the closed volume ensures that any oxygen that gets close to the initial part of the hot wax steam will eventually react.

In summary, after all our systematic experiments, we can conclude that the volume change in the typical candle demonstration can be explained by bubbling and the trapping of hot air, the same principle behind the fire cupping in traditional medicine. Our results confirm Lavoisier's results for an incomplete combustion and show that for either a total combustion of oxygen or for a partial combustion of the 21% of oxygen in the initial volume of air, the final gas volume ends very close to the initial volume. It is also clear from our experiments that when the atmosphere is poor in oxygen there is production of soot (C) that is accompanied by production of carbon monoxide (CO). These two kinds of molecules should be incorporated in the chemical reaction for a correct explanation of this experiment.

Our modern versions of Lavoisier's experiments were designed to help our science students to understand some of the basic principles of Chemistry by using multimedia materials to directly measure some physical variables. Additionally, they can learn the basics of combustion and chemical reactions using our particular set of experiments as a model to build their own versions of these simple experiments. Understanding the causes for a final volume of similar size to the initial volume, regardless of a complete or incomplete combustion of oxygen, is a complex task that is beyond the level of an introductory course and should be studied using gas chromatography (Vitz 2000; MacNeil and Volaric 2003) or other advanced techniques like laser spectroscopy (Wolfrum 2001).

Within the experimental errors for our simple setup, our results are consistent with Lavoisier's closed volume experiments and with other reported closed volume experiments. These results also coincide with Vitz's results for the burning of a piece of paper in a closed combustion chamber where a zero change of pressure is reported and a 56% of O₂ is consumed, as measured using GC. The wrong explanations for the candle experiment only appear when trying to explain the results of a candle experiment using a non strictly closed setup.

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References

- Benedict, F. G. (2010). *The composition of the atmosphere with special reference to its oxygen content*. Nabu Press. See also <http://www.archive.org/details/compositionofatm00benerich>, Accessed 30 July 2010.
- Birk, J. P., & Lawson, A. E. (1999). The persistence of the candle-and-cylinder misconception. *Journal of Chemical Education*, 76(9), 914–916.

- Caplan, J. B., Gerritsen, H. J., & LeDell, J. S. (1994). The hidden complexities of a “simple” experiment. *Physics Teacher*, 32(5), 310–314.
- Faraday, M. (1978). *The chemical history of a candle*. Atlanta, Georgia: Cherokee Pub. Co.
- Fowles, G. (1960). *Lecture experiments in chemistry*. New York: Basic Books.
- Glantz, J. (1963). Demonstration notes: Oxygen in air. *Journal of Chemical Education*, 40, A477.
- Gordon, J., & Chancey, K. (2005). The determination of the percent of oxygen in air using a gas pressure sensor. *Journal of Chemical Education*, 82(2), 286–287.
- Jastrow J. (Ed.) (1936). *The story of human error*. London: D. Appleton-Century Company. (A preview is available at <http://books.google.cl/books?id=tRUO45YfCHwC>, Accessed 30 July 2010).
- JCE staff. (2001). Just breathe: The oxygen content of air. *Journal of Chemical Education*, 78, 512A.
- Knowles, W. E. (1966). *A history of the thermometer and its use in meteorology*. Baltimore, Maryland: The Johns Hopkins Press, p. 8. (Translated from *Le opere di Galileo Galilei*, vol XVII, p. 377. See also: The Galileo Project. <http://galileo.rice.edu/sci/instruments/thermometer.html>). Accessed 30 July 2010.
- Krnel, D., & Glžar, S. (2001). Experiment with a candle without a candle. *Journal of Chemical Education*, 78(7), 914.
- Lavoisier, A. (1777). Mémoire sur la combustion des chandelles dans l’air atmosphérique, et dans l’air éminemment respirable. *Mémoires de l’Académie des sciences*, année 1777, 195. Available online at <http://www.lavoisier.cnrs.fr/memoires2.html>, Accessed 30 July 2010.
- Lavoisier, A. (1789). *Traité élémentaire de chimie*. Paris: Cuchet. Available online at <http://www.lavoisier.cnrs.fr/livres.html>, Accessed 29 Dec 2010.
- MacNeil, J., & Volaric, L. (2003). Incomplete combustion with candle flames: A guided-inquiry experiment in the first-year chemistry lab. *Journal of Chemical Education*, 80(3), 302–304.
- New Scientist. (1998). The last word, *New Scientist* (2136, May 30 1998) 105.
- Peckham, G. D. (1993). A new use for the candle and tumbler myth. *Journal of Chemical Education*, 70(12), 1008–1009.
- Russo, L. (2004). *The forgotten revolution: How science was born in 300 BC and why it had to be reborn*. Berlin: Springer.
- Vera, F., & Romanque, C. (2009). Another way of tracking moving objects using short video clips. *Physics Teacher*, 47(6), 370–373.
- Vitz, E. (2000). Paradoxes, puzzles, and pitfalls of incomplete combustion demonstrations. *Journal of Chemical Education*, 77(8), 1011–1013.
- Wolfum, J. (2001). Introductory lecture: Advanced laser spectroscopy in combustion chemistry: From elementary steps to practical devices. *Faraday Discussions*, 119(1), 1–26.
- Woodcroft, B. (Translator) (1851). *The pneumatics of Hero of Alexandria*. London: Taylor Walton and Maberly. Available online at <http://www.history.rochester.edu/steam/hero/>, Accessed 30 July 2010.