The use of concrete materials contributed to the understanding of chemistry concepts, which oftentimes are abstract. Socialization of more meaningful learning to elaborate conceptual maps showed that the proposed actions allowed for a wealthier conceptual construction. The chosen referential, i.e., planning of activities, strategies and resources employed assisted for the success of this educational process. This differentiated teaching methodology is positive for Youngster and Adult Education by providing for meaningful learning.

We believe that Chemistry teaching through 'food topics', as presented in chart 1, could be a possibility to promote Scientific Literacy of Youngster and Adult Education. Results showed that there was an increase in motivation and interest of students during the course, as well as the knowledge construction for solving practical problem situations. This way of action is to bet on Chemistry teaching not as a fragmented subject, but as teaching that seeks for solutions to the problems of this natural world.

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Falling temperatures: a simple estimation of the absolute zero

Bajando las temperaturas: una estimación simple del cero absoluto

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Abstract

When teaching an introductory course on thermal physics, one of the important challenges that a college physics teacher faces is to introduce to his/her students to the idea of an absolute minimum for the temperature, the so called 'absolute zero'. Indeed, given that the experiments used to determine the absolute zero temperature are usually performed in advanced thermodynamics courses, the usual procedure in introductory levels consists of passing on the notion based on the authority of a textbook. The aim of this article is to present a straightforward and low-cost experiment that allows introducing the notion of an absolute minimum temperature. The values obtained for the minimum temperature are in excellent agreement with the actual value of -273.15°C.

Key words*: absolute zero, school-level experiment, ideal gas.*

Resumen

Uno de los grandes desafíos que enfrenta un profesor de física de pregrado que imparte un primer curso de física térmica, es introducir a sus estudiantes en la idea que existe un valor mínimo para la temperatura, el denominado cero absoluto. En efecto, dado que los experimentos para determinar el cero absoluto suelen realizarse en cursos avanzados de termodinámica, el procedimiento habitual en los niveles introductorios consiste en transmitir la noción de temperatura mínima apelando a la autoridad de un texto. El objetivo de este artículo es presentar un experimento simple y de bajo costo que permite introducir la noción de temperatura mínima. Los valores encontrados para esta temperatura se encuentran en excelente acuerdo con el valor aceptado de -273.15 °C.

Palabras clave*: cero absoluto, experimentos de nivel escolar, gas ideal.*

INTRODUCTION

One of the important challenges for a college physics teacher, when teaching an introduction to the topics of heat and temperature, is to present to the students the idea of an absolute minimum temperature. This is the so-called *absolute zero*, which corresponds to the temperature of -273.15°*C* (0 *K*). Indeed, given that the experiments used to determine the absolute zero temperature are usually performed in advanced thermodynamics courses, the usual procedure in introductory levels consists of passing on the notion based on the authority of a textbook. Unlike other laboratory experiments about heat and temperature, the empirical estimation of the absolute zero typically requires expensive equipment and/or convoluted mathematical calculations. This difficulty is evident when reviewing the available experiments for teaching on this topic (Strange & Lang, 1989; Kim, et al., 2001; Amrani, 2007; Bogacz & Pedziwiatr, 2013).

The aim of this article is to present an original experiment that allows introducing the notion of absolute zero via three different albeit complementary procedures. The first procedure is a simple graphical estimation, which can be performed by both undergraduate and secondary school students. The other two procedures are slightly more complex compared with the first but are still relatively simple, and are designed for undergraduate students of science and engineering. The values we found using the three procedures are: -292.2°*C*, -275.90 ± 15°*C* and -275.74 ± 5°*C*, in excellent agreement with the actual value of -273.15°*C*. The experimental protocol is simple, and it only requires low-cost materials and equipment.

The article is organized as follows. First, we derive an equation that relates pressure with temperature, using the equation of state of ideal gases. Next, we describe the experimental setup, detailing the instruments and materials needed. We then present the results obtained and our estimation of the absolute zero through the procedures mentioned earlier. Finally, we discuss these results, comparing them with other experiments and highlighting key issues to address in a discussion with the students.

THEORETICAL FRAMEWORK: THE RELATION BETWEEN PRESSURE AND TEMPERATURE OF AN IDEAL GAS

According to the equation of state of ideal gases, if we have n moles of gas in a container of constant volume V, the absolute pressure P and the absolute temperature T_K (in Kelvin) of the gas are related by the following equation (Petrucci, et al., 2011; Serway & Jewett, 2008):

$$P = \frac{nR}{V} T_K \tag{1}$$

where $R = 62.32\ mm\ Hg{\bullet}L{\bullet}mole^{-1}{\bullet}K^{-1}$ is the universal gas constant. We know that T_K is related to the temperature in Celsius degrees T through the following relation:

$$T_K = T + T_{\min} \tag{2}$$

In this equation, Tmin is the minimum theoretical temperature that can be reached, which has been estimated to be Tmin= -273.15°C (Petrucci, et al., 2011). Replacing equation (2) on equation (1) we have:

$$P_K = sT + sT_{\min} \tag{3}$$

where $s = nR/V$. This equation represents a line with slope s and intercept on the abscissa equal to $T_{\min}$, as shown in figure 1. It is easy to note that decreasing P implies decreasing T. However, given that P can only take positive values (it is an absolute pressure, not a difference in pressure), there is a point below which T cannot decrease further (i.e., the temperature T corresponding to a pressure $P = 0$). This point corresponds to the minimum possible temperature, or absolute zero.

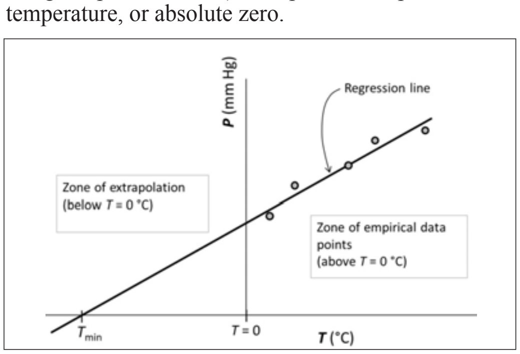

Figure 1. A plot illustrating the theoretically-guided procedure to estimate the absolute zero. If we empirically obtain P, T data points in the range of temperature above 0°C, we can calculate a linear regression on these points. For an ideal gas, we expect a linear relationship between P and T. We then use the regression line to extrapolate values below 0°C, which makes it possible to obtain the intercept of the line on the abscissa (where the pressure of the gas is expected to become zero).

Let us assume we have n moles of air at a temperature $T = 0$°C and we measure its absolute pressure P. Then we raise the temperature to a new known value and measure P again. By repeating this procedure, we obtain a set of (P, T) value pairs that can be plotted. Let us also assume we perform only measurements above 0°C, to avoid experimental complications. If we assume that air is an ideal gas, then within experimental error the measured values should lie on a straight line as the one depicted in figure 1. Such a line can be estimated by simple linear regression, and then compared with the theoretical line given by equation (3). If $T_{\min}$ is an unknown value to estimate, then by extrapolating (P, T) to values below 0°C (see figure 1), it is possible to estimate $T_{\min}$ by comparing the expected intercept $sT_{\min}$ with the empirical intercept given by the regression equation. This is the basic idea underlying the experiment that we describe in the following section.

INSTRUMENTS AND MATERIALS

In this section, we describe the instruments and materials used in our experiment. Note that there are alternative materials that could perform the same functions, and, therefore, we are only suggesting what we used. Instruments:

- An arterial pressure manometer
- A thermometer to measure liquid water temperature.

Materials:

- A small, heat-resistant glass flask (approximate volume 50 cm^3).
- A short piece of flexible plastic tubing (to connect the flask and the manometer)
- A few containers with water (to serve as water baths)
- A kitchen-type water boiler (to raise water temperature)

Figure 2 shows a diagram of the experimental setup. The manometer is tightly connected to the flask through the piece of tubing. The manometer allows measuring the air pressure inside the flask, which is placed in the water bath. After a few minutes, the air inside the flask will attain thermal equilibrium with the surrounding water. The thermometer is used to measure the water temperature, providing an indirect measure of the air temperature. Figure 3 show different views of the experimental setup.

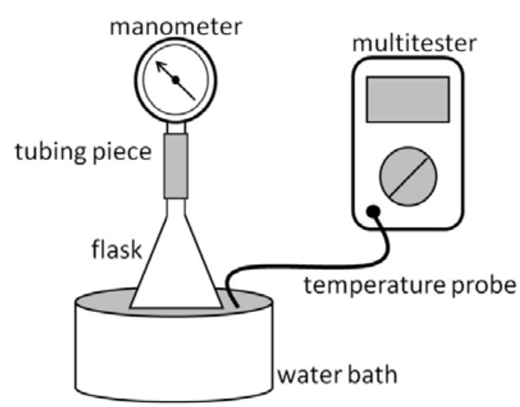

Figure 2. Diagram of the experimental setup.

Figure 3. The left image shows the arterial pressure manometer connected to the flask via a piece of flexible tubing. The middle image shows the flask is partially submerged in the water. Pressure is measured with the manometer, and water temperature with a multi-tester. The right image shows the five containers with water at different temperature used in the experiment. Water is heated using the boiler shown at the right side.

A manometer is connected through plastic tubing to a glass flask containing air. The flask is introduced in the water, whose temperature is measured with a probe connected to a multi-tester. This temperature is the indicator of the air temperature inside the glass.

PROCEDURE AND RESULTS

To perform the measurements we start by submerging the glass container in the water bath containing a mixture of water and ice, to obtain a temperature close to 0°C. Once the flask is in thermal equilibrium with the bath, we connect the flask to the manometer using the piece of tubing. For the equilibrium temperature we calibrate the manometer at 0°C. We know that the pressure at the manometer P_m and the atmospheric pressure P_{atm} are related to the absolute pressure according to:

$$P = P_m + P_{at} \tag{4}$$

Let us assume that atmospheric pressure corresponds to standard conditions (P_{atm} = 760 *mm Hg*). Since the resolution of our manometer was 1 *mm Hg* and we observed values close to zero for the first measurement, we approximated the value of *P* for the first measurement to 760 *mm Hg*. Once we have the first pair of *P*, *T* values, we place the flask (the manometer must remain attached) successively to rest of the water baths, each with an approximate temperature of 10°*C* higher than the preceding one. On each case, we wait 1-2 minutes for the establishment of thermal equilibrium between the air and the water bath, and we measure again *T* and P_m. Then we calculate *P* using equation (4).

Table 1. Results of one experiment

T (°C)	Pm (mmHg)	P (mmHg)
2.2	0	760
15.9	40	800
45.3	112	872
69.3	178	938
95.5	244	1004
100.2	254	1014

Table 1 shows the experimental values we found for *P* and *T*. The first column contains the water bath temperature *T*(°*C*). The second column contains the manometer pressure P_m (*mm Hg*) and the third column contains the absolute pressure $P = P_m + 760$.

The first estimation of the absolute zero, which we will designate as T_{min1}, it is based on a simple graphical procedure illustrated in figure 4. This is a straightforward procedure that does not aim to be accurate, but only to provide a first approximation to the minimum temperature, without requiring statistics or algebra.

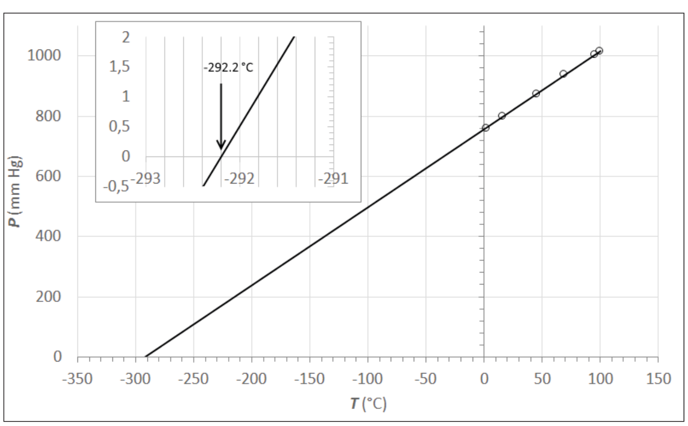

Figure 4. Scatter plot of values from Figure 4 (data in table 1), including an extrapolation of the best-fit line to graphically determine the value of the minimum temperature. The inset shows enlarged the area where the graphical estimation was performed.

The students can accomplish this procedure using graph paper and a rule to trace an eye-estimated line of best fit to the experimental points. The line should extend (extrapolate) until it intersects the abscissa axis (i.e., the temperature axis). The temperature value at the point of intersection between the best-fit line and the temperature axis, corresponds to the absolute zero temperature, in Celsius degrees (see Figure 4). In this example, the value obtained in the estimation was T_{min1} = -292.2 °C.

The other two procedures we present to estimate T_{min} are slightly more elaborated and complex and are based on simple linear regression. Indeed, Figure 5 shows a scatter plot of the *T* and *P* values of table 1, alongside the linear regression line. In the figure, the coefficient of determination R^2 is also shown, which in this case it corresponds to an almost perfect linear fit R^2 = 0.9996.

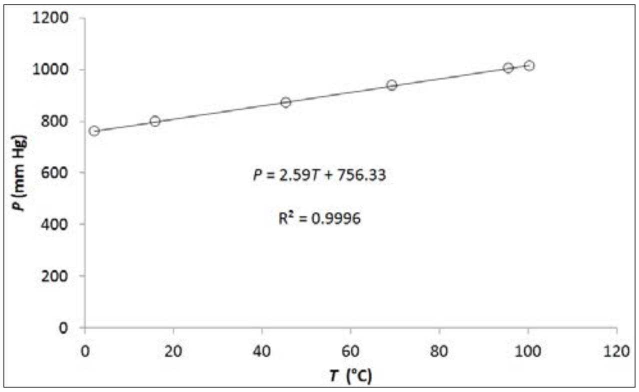

Figure 5. Scatter plot of T vs P values, obtained for one experiment (data in table 1). Regression line, equation and R2 value are also shown.

Therefore, within experimental error, the scatter plot corresponds to a line, in good agreement with the theoretical model introduced in section 2 (see and figure 2).

The second estimation of the absolute zero, which we will designate as T_{min2}, it is obtained directly from the regression line, taking *P* = 0 and solving for *T*:

$$T_{min\,2} = -\frac{756.33\ mmHg}{2.59\ mmHg \cdot {}^{\circ}C^{-1}} = -292{,}02\ {}^{\circ}C \tag{5}$$

This value only differs by 6.9% from the accepted value of -273.15°*C*, which constitutes an excellent estimation. The third estimation, which we will design as T_{min3}, leads to a much more accurate value, and results from a comparison among the regression line intercept on the abscissa with the theoretical intercept T_{min}, given by equation (3). To do this, we need to determine the value of *s*. As we saw in the previous section, it is given by:

$$S = \frac{nR}{V} \tag{6}$$

It has been shown empirically that the volume occupied by 1 mole of an ideal gas at standard conditions of pressure and temperature (760 *mm Hg* and 0°*C*) is 22.4 *L* (Petrucci, et al., 2011). This value is known as the *molar volume*. If we assume that the air behaves as an ideal gas, and since we know the flask volume 50 cm^3 = 50×10^{-3} *L*, then the flask contains approximately 2.23×10^{-3} *moles*. Using these values for *n* and *V*, and considering *R* = 62.32 $mm\ Hg \cdot L \cdot mole^{-1} \cdot K^{-1}$, we obtain:

$$s = 2.78\ mmHg \cdot {}^{\circ}C^{-1} \tag{7}$$

By comparing equation with the regression equation (see Figure 6), it is easy to see that the intercept of the regression line must be equal to sT_{min3}, that is:

$$sT_{min\,3} = 756.33\ mmHg \tag{8}$$

from which we solve for T_{min3} to obtain:

$$T_{min\,3} = \frac{756.33\ mmHg}{2.78\ mmHg \cdot {}^{\circ}C^{-1}} = 272{,}06\ {}^{\circ}C \tag{9}$$

In contrast with the second procedure, which produced a negative value, in this case we obtain an absolute (positive) value for the minimum temperature. This value differs in 20.09°*C* from T_{min2} but is much closer to the accepted value of -273.15°*C*. Therefore, within experimental error, we obtained a remarkable estimation, considering the experiment's simplicity.

Once we complete all the measurements, we suggest placing the flask again in a water bath with ice at a temperature close to 0°*C*. We should obtain a measurement of P_m close to zero. If we verify this, we have evidence to assume that the number of moles of air within the flask has remained constant, which is an essential requisite for a correct interpretation of the results.

By repeating the procedures 2 and 3 several times we can elaborate further and treat the obtained values statistically, obtaining means and standard deviations. We can interpret the latter as a measure of both variability and experimental error.

Table 2: Estimations of Tmin2 and Tmin3 values from four separate experiments

Experiment	Tmin2 (°C)	Tmin3 (°C)
1	-292.92	-272.06
2	-272,96	-270.99
3	-257.67	-279.91
4	-280.06	-279.99
Mean (± SD)	-275.90 (± 15)	-275.74 (± 5)

Table 2 summarizes the results we obtained in 4 repetitions of the experiment. The values of 'Experiment 1' correspond to the values presented previously for the procedures 2 and 3. The data in the table show that the mean value for T_{min3} is a bit more accurate than the mean value for T_{min2}. In addition, the variability (measured by the SD) of T_{min3} estimations is much smaller than that of T_{min2}. In the next section we refer to these discrepancies.

DISCUSSION AND CONCLUSIONS

The discussion that follows contains several ideas that can be used by teachers with the students in their analysis of results of the procedures 2 and 3.

A first issue is related to the difference in the mean values for T_{min2} and T_{min3} (see Table 2). As we have seen, these two values have a reasonable accuracy (they both differ by a couple of degrees from the actual value). Nevertheless, their precision (the variability in the data) is very different. To interpret this difference we must analyze the different procedures which led us to T_{min2} and T_{min3}. In the second procedure, we obtained T_{min2} directly from the regression line, which in turn had been obtained from empirical data. In contrast, to calculate T_{min3} we carried out a comparison among the theoretical and the regression lines. For this comparison, we estimated the value for the intercept on the abscissa using numbers from chemistry and physics textbooks. That is to say, unlike the case of T_{min2}, we used numbers with a large precision. This allows explaining the differences in precision between both estimations.

A second issue about the experiment that is worth examining refers to the assumption of an ideal gas. By comparing the regression and theoretical lines, we see an excellent agreement between them. If we compare the regression slope (2.59 mm Hg•°C^{-1}) with the theoretical slope (2.78 mm Hg•°C^{-1}), we see only a 6.8% difference. These results, therefore, allow a simple interpretation: as a first approximation, the air can be modelled as an ideal gas.

Finally, it is interesting to place our results in the context of previously reported experiments aimed at estimate empirically the absolute zero temperature. In the next paragraphs, we analyze some estimations of Tmin found in the literature of science education and we compare them with ours.

Bogacz and Pedziwiatr (2013) report a method in which they measure the pressure inside a glass bulb with air, at different temperatures. They use an electronic pressure sensor connected to a computer. The value they report is -267 ± 15°*C*, a number less accurate and precise than ours. And besides, the requirement of an electronic-computerized system implies a more sophisticated setup.

Kim et al. (2001) determined volumes of air with water vapor at different temperatures, and used these values to estimate the corresponding volumes of dry (pure) air. With these latter values, they build a *V* vs *T* curve that allows them to estimate, also by extrapolation, the absolute zero. The experimental method is fairly simple, although the calculations are more complicated than ours. The reported value by Kim et al. is -276.01 ± 8 °*C*. This number is not as exact as our values, and its precision surpasses that of T_{min2} but not that of T_{min3}.

Strange and Lang (1989) estimated the absolute zero from a *V* vs *T* line using an experimental setup with a flask, a syringe, a water bath, a thermometer and a manostat. The experimental procedure is fairly straightforward, although slightly more complex than ours, and it entails measuring both *V* and *T* for the air enclosed in the syringe. In this case, the obtained value is -276 ± 21 °*C*, which is less accurate and less precise than ours.

Amrani (2007) proposes a method of determination of absolute zero that requires a computer, specific software, an absolute zero apparatus (a hollow copper sphere), an absolute pressure sensor, a thermistor, and a water bath. In this case, several values of *P* and *T* are measured, and the author reports a value of -270 ± 4°*C*, whose accuracy and precision are better than our values. Nevertheless, the experiment requires sophisticated and expensive instruments.

As a general conclusion, we assert that our experiment is comparatively accurate, precise, simple, and cheap. We also proposed two approaches to the estimation of the temperature (T_{min2} and T_{min3}) which can be compared both in a single experiment and in separate repetitions. These procedures involve relatively simple calculations and can provide interesting discussion material for students, which can serve to improve the learning of the physical concepts.

In our experience as physics teachers, the idea of a minimum temperature is relatively difficult to grasp by the students. If we approach the subject on purely theoretical considerations, the concepts are usually harder to learn. We think that an empirical approach such as the one we presented can provide the required material for a more profound and significant understanding.

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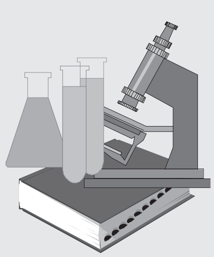

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