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Laboratory Experiment

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Creating and Experimenting with a Low-Cost, Rugged System to Visually Demonstrate the Vapor Pressure of Liquids as a Function of Temperature

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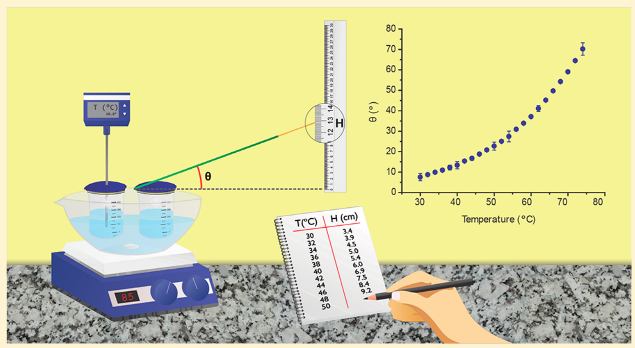
Supporting Information



ABSTRACT: A creative apparatus for use in a hands-on laboratory experiment that allows the visualization of the vapor pressure as a function of temperature is described in this paper. Inspired by homemade barometers and using simple materials that are easily accessible for teaching laboratories, a low-cost system for the establishment of the vapor-pressure curve was constructed and applied in deionized water and in car-radiator-additive samples (based on ethane-1,2-diol) at different concentrations. The system constructed proved to be efficient, simple, and quite robust and is applicable in teaching activities for comparing and visualizing vapor-pressure curves of different liquids. It can also be used to estimate the molar enthalpy of water vaporization. The main advantages and drawbacks of the apparatus created, the results obtained for liquid samples, and the evaluation of the ruggedness of this experiment are described throughout the text. The establishment of this system is the result of a project developed by first-year-undergraduate students along with postgraduate students and professors from the Bachelor's Program of Science and Technology, hosted by the Universidade Federal do ABC, as part of the innovative course the Experimental Basis of Natural Sciences, a practical course which seeks to build knowledge through experimentation.

KEYWORDS: *General Public, First-Year Undergraduate/General, Laboratory Instruction, Physical Chemistry, Hands-On Learning/Manipulatives, Misconceptions/Discrepant Events, Laboratory Equipment/Apparatus, Phases/Phase Transitions/Diagrams, Equilibrium, Gases*

■ INTRODUCTION

Vapor pressure is a concept addressed when learning chemistry that helps in the understanding of some phenomena and processes (such as boiling, distillation, and bonding properties),[1] and it is taught in secondary school and higher education. When teaching about vapor pressure, the approach is predominantly theoretical, as there is an overall shortage of simple and accessible experiments for this topic.

Most experiments demonstrating the behavior of the vapor pressure of liquids as a function of temperature are based on the isoteniscope.[2−5] Designed specifically for this purpose, the isoteniscope provides a standard method widely used for accurate and precise establishment of the vapor-pressure curves of different liquids.[6] Usually, experiments to measure vapor pressure use complex experimental arrangements with several different connections between glass elements[7,8] or materials of restricted access, such as a mercury manometers,[9−15] vacuum pumps[16] or other similar devices,[17−19] containers cooled with liquid nitrogen,[20] and gas chromatographs.[21] These factors make it difficult to reproduce these experiments for educational purposes, and they make the experiments costly and non-interactive.

In this context, some advances were reached regarding the dissemination of low-cost activities that promote contact between students and experimentation, either through the use of computational resources that simulate laboratory conditions and allow the student to carry out virtual experiments;[22−24] through the creation of real experiments with a lower cost

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apparatus;[20,25−31] or through experiments that are simpler to execute,[32−42] are miniaturized,[43] or are environmentally friendly.[35,44] Aligned with this trend and motivated to improve students' current understanding of liquid−vapor equilibrium[45−47] and properties of solutions,[48,49] the aim of this work was the creation of a low-cost alternative apparatus to study the vapor pressures of different liquids as functions of temperature.

The creation of the system was inspired by a homemade barometer,[50−52] a device consisting of a rigid container sealed off with a flexible membrane so that the internal pressure of the container is kept constant. As the external pressure (atmospheric pressure) varies freely, a deformation of the membrane occurs, which can be confirmed with the aid of a thin rod supported by the membrane. A correlation can also be established between the atmospheric pressure and the likelihood of rain or of a sunny day. The core idea here is adding a liquid sample inside the homemade barometer and then varying the surrounding temperature in such a way as to make the internal pressure of the container vary, while the external pressure is kept almost constant.

On the basis of a previous challenge of the postgraduate students, the first-year undergraduates were encouraged to idealize this experiment as part of the course the Experimental Basis of Natural Sciences hosted by our university. This course provides students with their first contact with scientific research, focusing on the development of essential skills, such as observing, formulating, interpreting, speculating, experimenting, and deducing.[53] In this paper, we described the results of this project, which was performed in 6 weeks, encompassing the assembly of the system; its operation; its characteristics, including its competitive advantages and limitations; and the results obtained with the system.[54]

■ EXPERIMENT

System Setup

Inspired by the homemade barometer, a beaker containing the liquid sample was used as a rigid container that was then sealed with a stretched latex balloon, which operated as a flexible membrane. A drinking straw supported by the latex balloon was used to get the internal pressure of the beaker. A thin wooden toothpick was added to the tip of the straw to increase the precision of the visual readings obtained with a millimeter-marked ruler. This structure was affixed in a ring stand and then partly immersed in a water bath.

For a temperature control, a second beaker with the same quantity of sample as the first and sealed with a latex balloon was also partially submerged in water. During the experiment, it was assumed that the temperature of the liquid in both beakers was the same. A magnetic stir bar was used with constant shaking to promote a homogeneous distribution of temperature within the water bath. The temperature of the sample, T (°C), and the corresponding position of the straw, P_T (cm), were recorded at intervals of 2 °C. The temperature of the sample was varied from room temperature (~25 °C) to 75 °C by electric heating in the water bath, and a thermocouple was used for measurement. Figure 1 shows the main steps used to set up the system. Further details are available in the Supporting Information.

Liquid Samples

An additive for an automotive-car radiator based on ethane-1,2-diol (a mixture containing monoethylene glycol, glycerol, and sodium 2-ethylhexanoate) was acquired at a local market, and

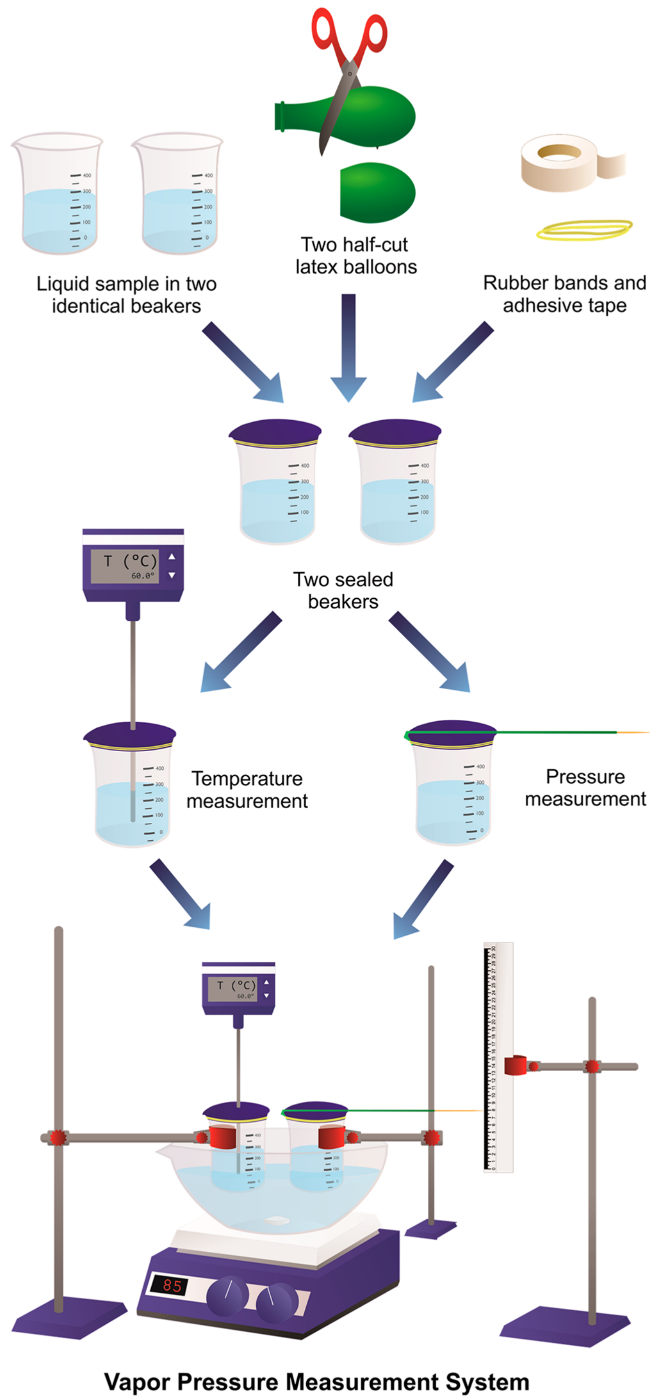

Figure 1. Main steps and materials involved in the apparatus setup.

deionized water was obtained in our laboratory. To prove that the volume of liquid does not affect the vapor pressure, three different volumes (50, 100, and 150 mL) of water were applied to the system. The additive sample was used in concentrated form and also in water-diluted solutions containing 25, 50, and 75% (v/v).

■ HAZARDS AND SAFETY PRECAUTIONS

The car-radiator-additive sample contains a significant quantity of ethane-1,2-diol, which is toxic when either ingested or inhaled. Therefore, we recommend that the instructor responsible for carrying out this experiment give a strict warning not to ingest and to avoid breathing this compound. Good

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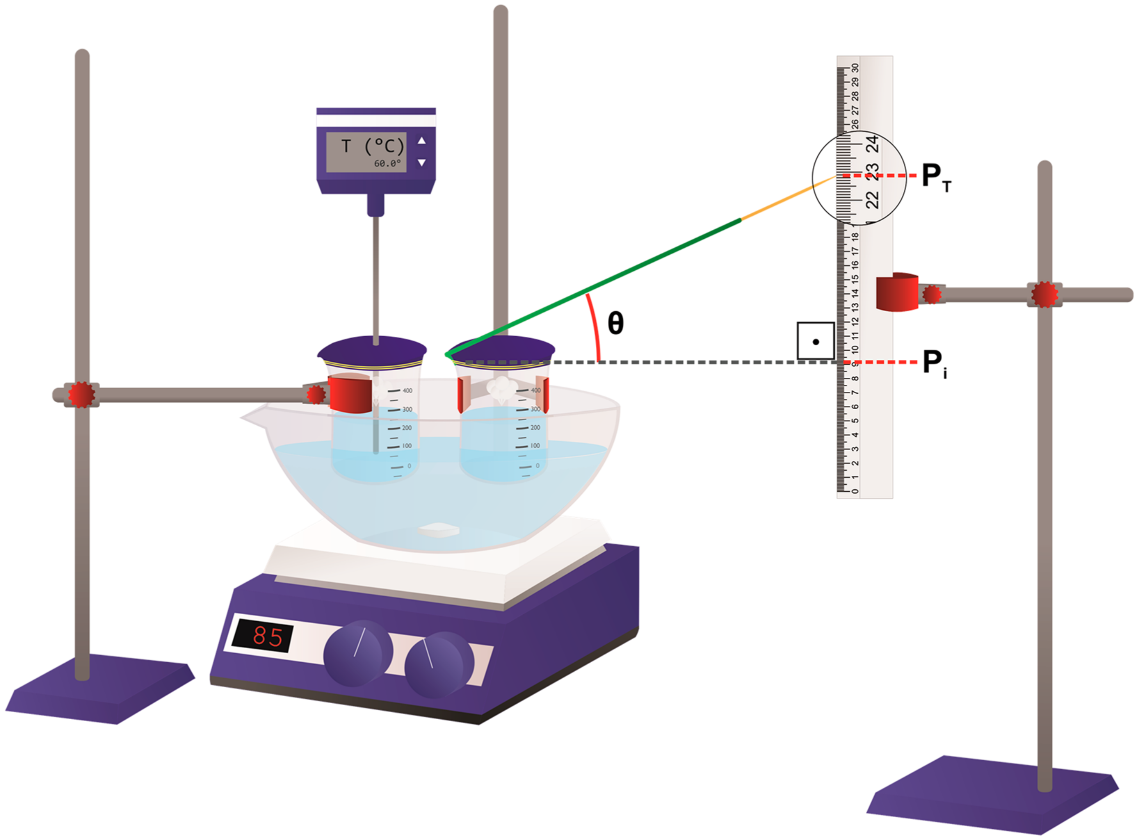

Figure 2. Illustration of the assembled system and simulation of the experiment running. The angle measured in the system is shown in detail and is formed because the latex balloon becomes semi-inflated with the pressure exerted by the vapor of the substance in its respective liquid−vapor equilibrium.

laboratory practices are also recommended. The safety conditions for this experiment and the risks associated with the use of chemical products are also included as part of the Supporting Information.

■ RESULTS AND DISCUSSION

The following two values were recorded simultaneously: the temperature of the liquid T (°C), measured by a thermocouple, and the position of the straw in the ruler P_T (cm). Using these records, a third variable was used as a response proportional to the vapor pressure: the angle (θ) formed between the initial position of the straw (P_i) and the position as verified for each measurement (P_T). Figure 2 shows the assembled apparatus and illustrates the experiment running with the angle measured in the system.

Two-dimensional graphs with θ values (°) on the y-axes and T values (°C) on the x-axes, where θ represents the angle measured by the system, and T is the temperature of the liquid, were plotted with the data obtained for the liquid samples that used in the system. Figure 3 shows the results for the water sample. A clear ascending trend for the angle as the temperature increased was observed, following a typical exponential profile. This pattern is very similar to the vapor-pressure curve for water, as referenced in the literature.[55]

To confirm this correlation between the angle measured and the water vapor pressure, the results were analyzed on the basis of the Clausius−Clapeyron equation,[56] which connects the vapor pressure that a substance presents within liquid−vapor equilibrium with its temperature.[57] This equation can be written in a summarized form as follows:[58]

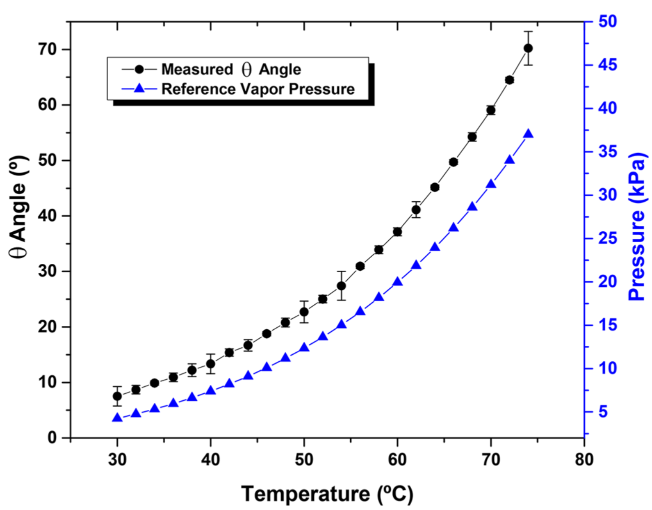

Figure 3. Double-y multicurve. The left-hand y-axis showing the angle as measured by the system, expressed in degrees, for deionized water as a function of temperature (°C), which is shown on the x-axis. Vertical error bars refer to ±1 standard deviation ($n = 3$). The right-hand y-axis shows the reference values for the vapor pressure of water (kPa) as obtained from the data tabulated in the *CRC Handbook of Chemistry and Physics*.[55]

$$\ln P_v = -\frac{\Delta H_{vap}}{R}\frac{1}{T} + C \qquad (1)$$

where T is the absolute temperature, R is the gas constant (8.314 J mol^{-1} K^{-1}), ΔH_{vap} is the molar enthalpy of vaporization of the

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substance, and C is a constant. This equation indicates that a graph of ln P_v versus $1/T$ should give a straight line with a slope of $-\Delta H_{vap}/R$.

Instead of inserting the vapor pressure into the equation, the angle obtained by the system was inserted. The graph of the natural logarithm of the angle, ln(θ), as a function of the inverse of the temperature $1/T$ (in K) resulted in Figure 4.

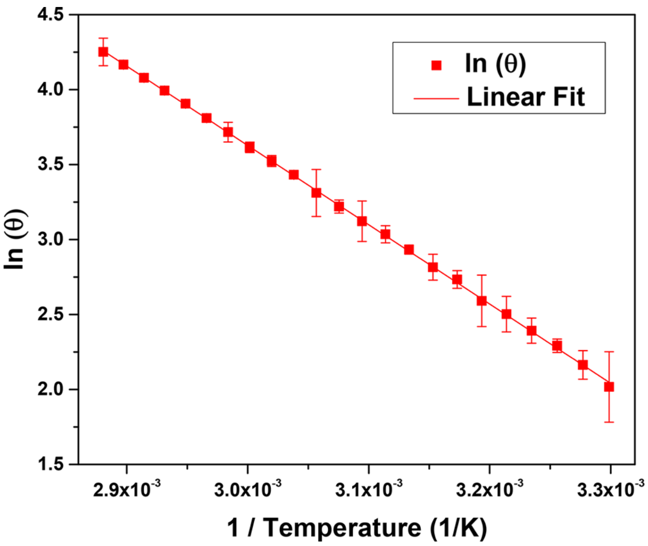

Figure 4. Bidimensional graph showing the natural logarithm of the angle, θ, on the y-axis and the inverse of the temperature, expressed in Kelvin, on the x-axis. The data for this linearization were obtained from the experiment with deionized water. The original data used (measured angles) are the same as those plotted in Figure 3. The solid line connecting the points represents the straight line obtained by the linear regression using the least-squares method. Vertical error bars refer to ± 1 standard deviation (n = 3).

Through the use of linear regression using the least-squares method, we arrived at the equation $\ln \theta = -(5287 \pm 390)/T + (19 \pm 4)$ with a high coefficient of determination, $R^2 = 0.9996$, which shows that the angle measured with the system is closely connected to the vapor pressure. The angular property can be used as an indirect measurement of vapor pressure, at least under the same conditions investigated in this experiment.

The slope obtained in Figure 4 was used to estimate the enthalpy of vaporization (ΔH_{vap}) of the water sample submitted to the system,[59] resulting in a value of 43.9 ± 3.2 kJ mol^{-1}. This value is quite close to the ΔH_{vap} value calculated for the same temperature range when the reference data regarding the vapor pressure of water was used (43.0 kJ mol^{-1}).[55] With a bias[60] of +2.1%, these two values are not significantly different when subjected to a two-tailed Student's t-test with 2 degrees of freedom at a confidence level of 90%.[61,62] The agreement between these values shows the accuracy achieved with the proposed apparatus.

The system was also evaluated by applying three different volumes of water (50, 100, and 150 mL), obtaining almost identical results, showing that the variation of the volume of liquid does not in any way change the vapor-pressure curve, as theoretically expected. To prove this with greater mathematical rigor, the results were compared using analysis of variance (ANOVA) with a unique factor at a confidence level of 95%.[62] This comparison proved that the results are not significantly different. The ability to change the volume of liquid inside the container is a major advantage of this experiment because some studies mention that a very common conceptual error is thinking that vapor pressure depends on the quantity of liquid and vapor present in the system.[1,63−65]

Figure 5a shows the vapor-pressure curves obtained for the car-additive samples at different concentrations (25, 50, 75, and 100%, v/v). The higher the ethane-1,2-diol concentration, the lower the pressure measured.

This reduction in the vapor pressure allows the use of this system in teaching activities for thoughts and discussions regarding the intermolecular forces of liquids. In this case, the inference of stronger intermolecular interactions on ethane-1,2-diol than on water can be assumed by comparing its structures. Compared with the molecular structure of water, ethane-1,2-diol has the presence of an extra oxygen atom (−OH group); thus, it is predicted that ethane-1,2-diol has a greater ability to make

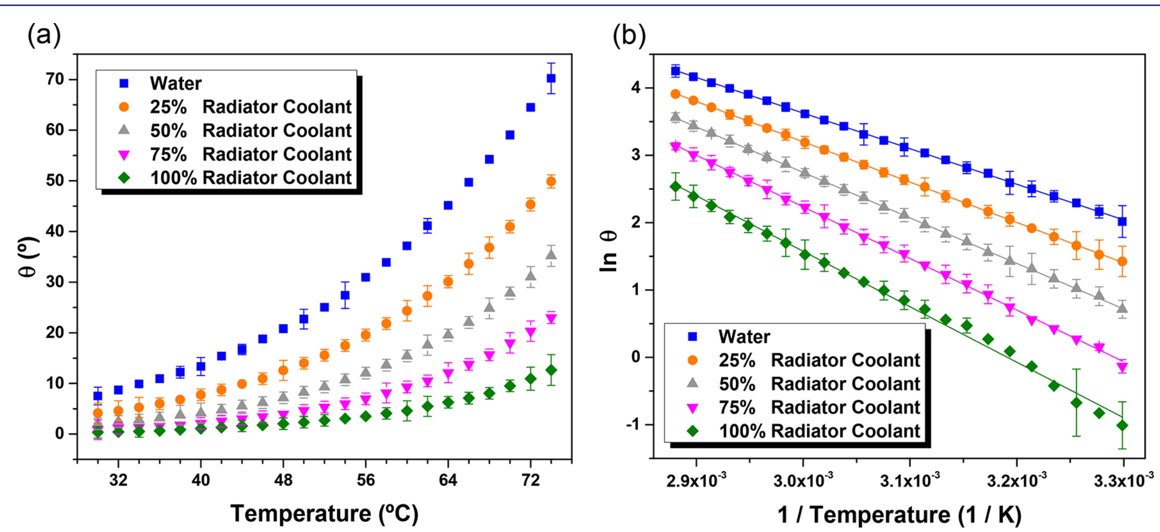

Figure 5. (a) Graph showing the angle obtained through the system (y-axis) versus the temperature (x-axis) for deionized water and for additives for car radiators at different concentrations (25, 50, 75, and 100%, v/v). (b) Graph showing the natural logarithm of the angle measured in degrees (y-axis) versus the inverse of the temperature on the Kelvin scale (x-axis), showing in a solid line the segments obtained through linear adjustment. Vertical error bars refer to ± 1 standard deviations (n = 3).

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hydrogen bonds, likely with more intense intermolecular interactions, than water. This reasoning explains the difficulty of ethane-1,2-diol to form a vapor in relation to the ability of water. Figure 5b shows the linear regression obtained after mathematical treatment using the Clausius−Clapeyron equation.

■ RUGGEDNESS

The ruggedness of the experiment was assessed in order to check the possibility of reproducing the experiment under different conditions. Reproducibility, regarding the precision of the results obtained when there were changes to the days of the execution of the experiment and to the water samples, latex balloon, ruler, beaker, straw, thermocouple, heating plates, and operators, was estimated using the highest coefficient of variation (CV) used among the 10 executions of the experiment, obtaining a result of 7.9%. This value shows that the experiment can be applied for teaching activities with an appropriate level of precision. In this estimation of reproducibility, only latex balloons of the same colors, sizes, and brand were evaluated, because in previous tests we noticed that these factors had a strong influence on the variation of the results. Thus, we recommend that these parameters should be constant during the execution of the experiment. More observations for the ruggedness of the experiment are described in the Supporting Information.

■ ADVANTAGES AND DIFFICULTIES

The main advantages of the experiment are the following:

(i) The first is the simplicity of the setup and the ease of execution, particularly in regards to the cheap and accessible materials involved.

(ii) The second advantage is the versatility of the system, which can be assembled in different versions and adapted to different laboratory situations with the replacement of the heating source used (in this case, a heating plate), such as with a Bunsen burner, gas lamp, or electric pitcher that heats water, or with the replacement of the thermocouple with a mercury thermometer or other temperature gauge.

(iii) Another is the allowance for volume variation inside the system, which allows for confrontation between experimental results and a common conceptual error, favoring correct learning based on experimentation.

(iv) The use of nonvolatile liquids is another distinguishing factor for the system; many of the systems used for the establishment of vapor pressure are only sensitive in the case of volatile liquids.

(v) The final advantage is the possibility of estimating the molar enthalpy of vaporization using this system.

The drawbacks of the experiment are as follows:

(i) Measurements oscillate because of intense elastic resistance at low pressures and because of vapor leakage at high pressures. Leakage is due to the not-so-efficient seal and gas diffusion through the latex, which makes investigations unfeasible when the temperature of the water is above 75 °C.

(ii) The experiment does not involve any direct measurement of pressure, but rather the measurement of a property related to it.

(iii) The elasticities of the balloons can differ among the different brands, sizes, and colors; the change in elasticity is reduced if these parameters are kept constant using the same band, the same size, and the same color of balloon. Extended use of the balloon also promotes a significant change in its elasticity.

■ CONCLUSIONS AND OUTLOOK

This experiment allows for the visualization of the behavior of vapor pressure as a function of temperature. The relationship between these variables (vapor pressure and temperature) can be exploited in qualitative and even quantitative ways. The great advantages of this system are its versatility and low cost. The system can be used with other liquid samples and in different laboratory conditions, covering the needs of different laboratory courses.

In addition, we believe that this course model encourages the development of projects that combine the creative abilities of freshmen students with the experience of postgraduate students and the strategic guidance of a professor, creating a space conducive to the development of activities and experiments that bring new educational and creative solutions to facilitate the teaching−learning process, especially with regard to concepts that are traditionally abstract and difficult to understand. In other words, in this model, it is possible to create innovative teaching activities and to provide new approaches for other students.

We hope to contribute a new approach to vapor-pressure studies with this experiment.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00381.

Instructions for teachers (presentation and hazards and safety precautions), student laboratory instructions (student handout, worksheet, and report sheet), and more details about the experiment (additional ruggedness observations and measurements and mathematical treatment) (PDF, DOCX)

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Notes

The authors declare no competing financial interest.
A video showing experimental procedures is available at https://youtu.be/cwgPKQy-vVU.

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