Vacuum: its meaning and its effects throughout experimental activities

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Abstract

The central subject of this didactic project is the vacuum, its meaning and its effects. The choice of this topic was suggested by the fact that the concepts involved are often explained from the theoretical point of view without an experimental verification. This exercise has been tested with a group of high school students, both in the university laboratory and by teachers in the classroom. In the first part we present some qualitative experiences concerning the balance of forces; before the experiment the students have been asked to make a prediction of the result and to give a physical motivation of their response. Using a bell inside a vacuum chamber we emphasize a difference between mechanical and electromagnetic waves: how the first one requires a medium for propagation. In the second part a quantitative measure relative to the phenomenon of the fall of a weight is treated. The experimental apparatus allows a measure of the acceleration of gravity in vacuum and at different pressure values. These measurements allow students to quantify the buoyant force and the force of viscous friction. In the third part it is foreseen to observe phase transitions; in particular it is required to measure the temperature of a boiling point. Using a solution of water and salt it is possible to compare the boiling point of distilled water and of this solution at the same pressure. The interdisciplinarity of physics and chemistry in this measurement is relevant. A fundamental educational part is the calibration phase. The removal of internal energy, by activating the vacuum pump, decreases the temperature of water with its subsequent freezing; this observation stimulates interesting discussions with students on the phenomena involved. This exercise enables students to understand some fundamental physical concepts; it is mainly intended for high school students.

Keywords

Secondary education: upper (15-19)
laboratory activities
teaching

Experimental activities

The didactic activity is focussed on the topic of vacuum (Hayn, 1975).The choice of vacuum is due to the fact that the concepts involved are often explained from the theoretical point of view without an experimental verification (Sassi & Vicentini, 2009). We present here some experiments both qualitative and quantitative. The main observation of the experiment is the effect of the presence of air and the measurements of physical phenomena varying the pressure. We performed this experimental work with students coming from three different secondary level schools (ages 14,16,17) and with attending the first year of bachelor in Physics.
The first part, qualitative experiments, is shown to the whole class while the second, quantitative experiments, is only conducted with small groups of students. In particular we present a study of the fall of a weight as a function of pressure.
Each part of this work has been mached with evaluations before and after the activities.
The important features of our tests are that they require only a few minutes and they come immediately after the activity in order to understand how and what the student comprehended in laboratory.

Observations on the qualitative experiments

For the experiments we used an experimental setup that is composed of: a trivac rotary vane vacuum pump, a vacuum bell jar, pointer manometer, Pirani heat-conducting manometer with display, baroscope, Magdeburgo hemispheres, a bell, a balloon and a lamp. At the beginning, some qualitative understanding of the balance of forces is examined (Ku & Chen, 2013); before the experiments, we ask students to make a prediction of the result and to give a physical motivation of their response (Nissani et al., 1994). Students discuss the forces involved and how these forces change with decreasing pressure.
The baroscope in particular allows to test the effect of air on the buoyant force observing that in a vacuum only gravity is involved: in fact, in air the baroscope is in equilibrium due to the buoyant force, but upon decreasing the pressure, the buoyant force becomes negligible and only gravity is relevant.
In the vacuum chamber it is also possible to show the difference in propagation between sound and light using a bell and a lamp. This experience underlines a difference between mechanical and electromagnetic waves and how the first one requires a medium for propagation.

Figure 1. Experimental setup for qualitative experiments

The fall of a weight

In the main part of the laboratory activity a quantitative measurement of the fall of a weight is shown, using a tube and six photocells**.**

Figure 2. Experimental setup for the fall of a weight

The experimental apparatus, shown in figure 2, allows the determination of the gravity acceleration in a vacuum and a measure of the speed of fall at different values of pressure. These measurements lead students to quantify the buoyant force and the force of viscous friction (Cross & Lindsey, 2014).

Experimental steps of the measure are:

- Evaluation of the ball falling without the tube
- Evaluation of the ball falling in the tube at atmospheric pressure, for the evaluation of the confining effect of the tube
- Evaluation of the ball falling in the tube in vacuum
- Measure of the fall speed at different pressure for evaluating the variation of acceleration according to the pressure.

The confining effect can be evaluated from the difference between values found for acceleration at the same atmospheric pressure with and without the tube.

The data analysis is carried out by fitting the distance between photocells versus time, at different values of pressure, thus obtaining several values of apparent acceleration due to gravity. Students could also evaluate theoretical corrections through the Reynolds number calculation, finding the value of the viscosity coefficient.

The mathematical formula that students use, are the following:

$R_e = UL/\nu = UL\rho_{air}/\mu$

where:
U = average speed
L = diameter tube (internal) = 0,08 m
ν = kinematic viscosity (20 °C) = 2,3 * 10^{-6} m^2/s
μ = dynamic viscosity
ρ_{air} = air density in function of pressure and temperature

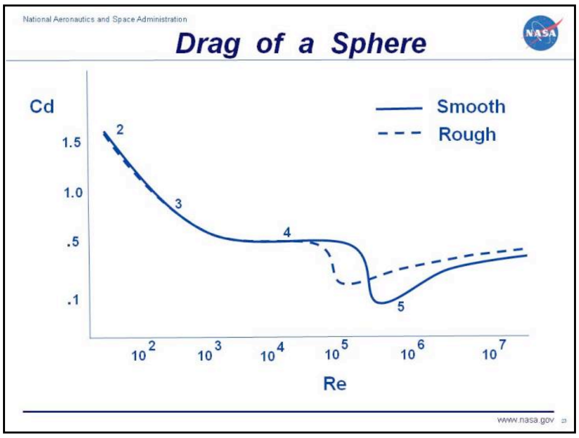

Figure 3. C_d value versus Reynolds number

By evaluating the Reynolds number, we could understand the air flow (laminar or turbulent) and obtain the coefficient C_d.
Then it's possible to calculate the friction force by:

$F_{fr} = ½ C_d\rho_{air}v^2A$

$\rho_{air} = p\,(1- 0.378p_v/p)/(R_a\,T)$

where R_a is the specific gas constant
p_v is the vapour pressure

The results of the measurements performed by students are the following:

- At pressure = (6.1 ± 0.1) mbar:
  $s(t) = s_0 + v_0t + 1/2gt^2 = 0.002+1.47t+ 4.90t^2$

  and the acceleration is $g = (9.80 \pm 0.07)\ m/s^2$

- At pressure = (993 ± 10) mbar:

$s(t) = s_0 + v_0t + 1/2gt^2 = 0.002 + 1.47t + 4.64t^2$

and the acceleration is $g = (9.29 \pm 0.07)\ m/s^2$
We underline the different sensibility of the pressure measurements because the experimental setup is composed by two barometers, used by the students in different pressure conditions; in particular the first one for pressure (0-200) mbar and the second one for (200-1000) mbar.

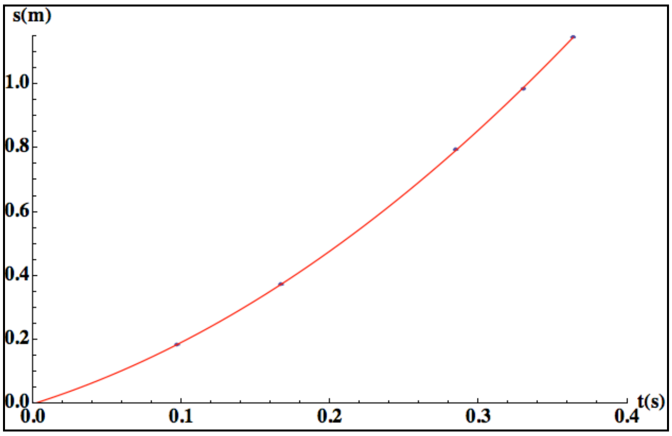

Figure 4. Parabolic fit s(t) at (993 ± 10) mbar

The difference between the two values of acceleration is due to forces that are relevant in air: the viscous friction, the edge effect of the tube and the buoyant force.

The phase transitions of water

Changing the pressure is possible to observe the phase transitions of water that occur at different temperatures; in particular it's possible to measure the temperature of the boiling point at different pressures.
A fundamental educational experience is the calibration phase in which the student evaluates the right time to read temperature and pressure at the beginning of the boiling phase.
The curve of the boiling temperature as a function of pressure can be plotted and compared with the theoretical curve for distilled water. Using a solution of water and salt it is possible to compare the boiling point of distilled water and of this solution at the same pressure. The interdisciplinarity of physics and chemistry in this measure is relevant. The removal of internal energy in the process decreases the temperature of water with its subsequent freezing; this observation allows an interesting discussion with the students on the phenomena involved.

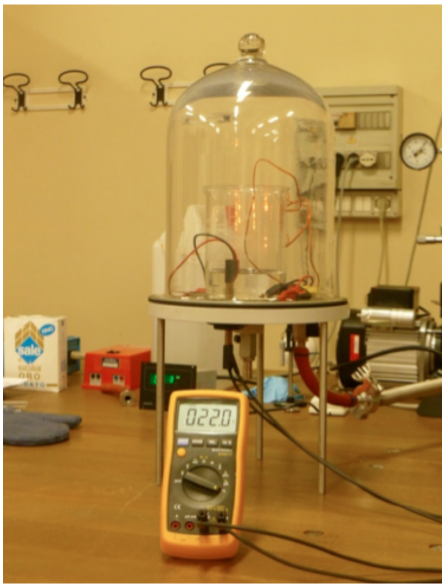

Figure 5. Experimental setup for the observation of phase transitions of water

Students and teachers

The teachers involved in the project have found rich benefits in using this approach; the idea to ask students their prediction before the experiment stimulates their interest. Through the strategy of task based oriented laboratory activity, problem solving and critical thinking are encouraged and higher-order cognitive skills (HOCS) are developed.

The students have shown interest in qualitative experiments; in particular they have been fascinated by the fact that water boils at room temperature and, after a few minutes, it freezes: this observation allows students to reason about thermodynamics and the relation between pressure, temperature and volume.

Also older students (16-18 years old) have found many difficulties in making prediction on the behavior of the baroscope in vacuum. They realized that the buoyant force depends on the presence of the air, and it is greater on the sphere; however, they haven't associated different buoyant forces to different volume.

A critical point for the students has been the discussion on the balance of forces, as was underlined in the experiments of balloon and Magdeburgo hemispheres.

When we asked to students a preference about qualitative experience, they chose the one related to the bell inside vacuum chamber, probably because the explanation was more immediate and simpler compared to balance of forces.

Conclusions

This exercise enables students to understand some fundamental physical concepts, important also in everyday life and is mainly intended for high school students.

Below we want to underline the didactic aim of this exercise:

- Interrogating qualitative expectations helps us to introduce the topic and the theory and is perceived by the student as useful to understand the experimental activity
- In qualitative experiments it is important to reflect on the balance of forces and on the buoyant force in air
- In the part about water, we examine the calibration to determine the temperature at the onset of boiling
- The student obtains the value of g, experimentally and reflects on additional forces present in nature and on their relevance; in particular the buoyant force and the viscous force.

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