The development of a multi-skill laboratory of gas laws for engineering freshmen

Punsiri Dam-O, Suwaphat Boonphasuk & Rasimate Maungchang

Walailak University
Nakhon Si Thammarat, Thailand

ABSTRACT: In this article, the authors present a newly developed laboratory experiment on gas laws for engineering and non-engineering students in a Thai university that replaced the previous experiment. The new experiment allows students to practise multi-skills through the investigation of three gases: air (mix gas), oxygen (diatomic gas) and argon (mono-atomic gas). To measure the pressure and volume, students utilised an instrument that was built from available tools, such as a syringe machine and a pressure sensor connected to a laptop for real-time and accurate measurement. To record and analyse the data, an MS Excel spreadsheet was created and provided to students. In this experiment, students were able to prepare oxygen using the skill learned in a chemistry course, examine Boyle's law and the universal gas constant, as well as learn to analyse data using MS Excel. By the ease of set up, the designed experiment is appropriate for use as a simple protocol for undergraduate teaching in basic physics or chemistry laboratory courses. The learning outcomes of engineering and non-engineering students were also compared, with the engineering students performing slightly better.

INTRODUCTION

A typical experiment associated with the verification of Boyle's law or Charles's law in studies of the ideal gas law often uses dry air [1-3]. In Thai universities, freshman engineering students have to complete a physics laboratory course as part of their studies. In one of those universities, a physics laboratory I course for freshmen in engineering programmes, involved the investigation of Boyle's law as one of the conducted experiments. In that experiment, students measured the pressure (P) and volume (V) of gas using a simple Boyle's law apparatus syringe containing the surrounding air. Even though the result of the experiment agreed with Boyle's law, the students seemed dissatisfied with the laboratory. The feedback showed that many students had wished they could investigate more types of gases, and thought that the experiment was too simple and did not fit the allocated three hours of group work.

The negative student feedback highlighted the need for revision, whereby the experiment was changed and implemented in the same course the following year, i.e. in 2021. To improve the experiment, more types of gases and related activities were added to the study. After the changes, students were assigned to make an investigation on three gas species, air, oxygen (O_2) and argon (Ar) representing mixed gases, diatomic gas and mono-atomic gas, respectively [4]. For oxygen, students had an opportunity to prepare the experiment themselves by using the skill acquired in a chemistry course.

In addition to Boyle's law, students needed to determine the universal gas constant (R) of the three gases. An instrument equipped with a pressure sensor and connected to a laptop was used to obtain a real-time and accurate result [2][5]. The students also learned to use an MS Excel spreadsheet to record and analyse the data by plotting graphs and making necessary calculations [6]. The feedback at the end of this course showed that they were satisfied with the experience gained in the experiment and the number of tasks was appropriate for the three-hour period.

In this article, the authors report on the details of the developed experiment including the laboratory set up, the result of the experiment, and the performance of engineering and non-engineering students. The simplicity of the set up and the experience gained by students in this experiment make it appropriate for a physics or chemistry laboratory course for first-year students in engineering programmes and other related programmes in science.

LABORATORY EXPERIMENT FOR FRESHMEN

The experiment presented in this article is a part of a physics laboratory course serving as a basic course for first-year engineering students majoring in computer engineering and artificial intelligence, chemical engineering, petrochemical and polymer engineering, civil engineering and electrical engineering, and also for first-year science and health science students majoring in physical therapy and medical technology. The experiment consists of three parts: Part I. Preparation of oxygen gas; Part II. Calculation of gas moles; and Part III. Verification of Boyle's law. The students were assigned to work in groups of three. Course materials were provided to students two weeks prior to the activity day consisting of conduct regulations in the laboratory, a laboratory report file in an MS Excel spreadsheet form, and a brief of the experiment and explanation on how to plot graphs and perform simple calculations in MS Excel. On the activity day, the class began with a pre-test, followed by an introduction to the laboratory, then the three parts of the experiment were carried out, the laboratory report file was completed next, and the session ended with a post-test. The three parts of the experiment are described in following paragraphs.

Part I preparation of oxygen gas: the instructor arranged materials and tools consisting of 2 - 3 g of manganese dioxide (MnO_2), 5 - 10 ml of hydrogen peroxide (H_2O_2), a transparent bottle with a hole toward the bottom and a 3-way valve on top, a conical flask with a double-hole stopper, a gas pipe, a syringe, water and a basin. The setup is illustrated in Figure 1.

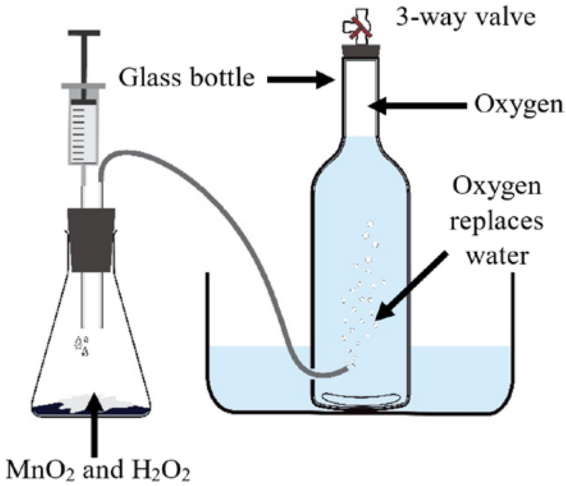

Figure 1: Oxygen preparation tool set consists of a conical flask where the oxygen is generated, a gas pipe through which it is conveyed and a bottle where the oxygen replaces water.

Before starting the experiment, students were briefly informed about the properties and hazards of the chemical substances and gases. To produce the oxygen gas, hydrogen peroxide is dropped into manganese dioxide through a syringe. The manganese dioxide catalyses the decomposition of the hydrogen peroxide to oxygen and water [7]. This chemical equation is shown in Equation 1.

$$2H_2O_{2(aq)} \rightarrow O_{2(g)} + 2H_2O_{(l)} \qquad (1)$$

The oxygen flows through the pipe, replaces the water and floats to the upper part of the plastic bottle. This bottle is connected with the 3-way valve for oxygen transfer to use with the Boyle’s law tool set in Part III, see Figure 1 above.

The students had to pay particular attention in the preparation of oxygen, and carefully perform the experiment to avoid any contamination in oxygen. For example, they had to inspect the whole tool for any leaks and expel existing air out of the bottle, gas pipe and the flask before mixing the substances to produce oxygen, and after oxygen had appeared, they had to use it as soon as possible to prevent any loss because the gas can dissolve in water. In regard to the other two gases, students obtained air from their surroundings and argon from a provided gas tank.

Part II calculation of gas moles: after the preparation of gases, students calculated the moles of air, oxygen and argon. The gas moles were subsequently used for the calculation of the universal gas constant *R*. To calculate moles (n) of gases, the mass of a specific volume gas (m) is weighed by using a 4 decimal scale, and then divided with its molar mass (M), see Equation 2.

$$n = \frac{m}{M} \qquad (2)$$

The air used in this experiment is considered to be dry air. So, the molecular masses are 28.9655, 31.9988 and 4.0026 g/mol, for dry air, oxygen and argon, respectively [8].

To verify Boyle’s law in Part III, each gas had to be pushed into the syringe. The mass of that gas was the mass of the syringe filled with the gas less the vacuum syringe. The method of measuring the mass of a gas was brought from the Flinn Scientific Web site [7].

Part III verification of Boyle’s law: the syringe filled with a gas from Part II was placed on a holder as shown in Figure 2. The tip of the syringe was connected to a 3-way valve and a pressure sensor. The PARTPORT dual pressure sensor was used in this experiment for accurate results. It measures absolute pressure in the range of 0 to 200 kPa with the resolution of 0.01 kPa. Alternative to using a pressure sensor, a straightforward way of calculating the pressure is by dividing force (F) exerted on the syringe piston rod over the cross-sectional area (A) of the syringe cylinder (P = F/A).

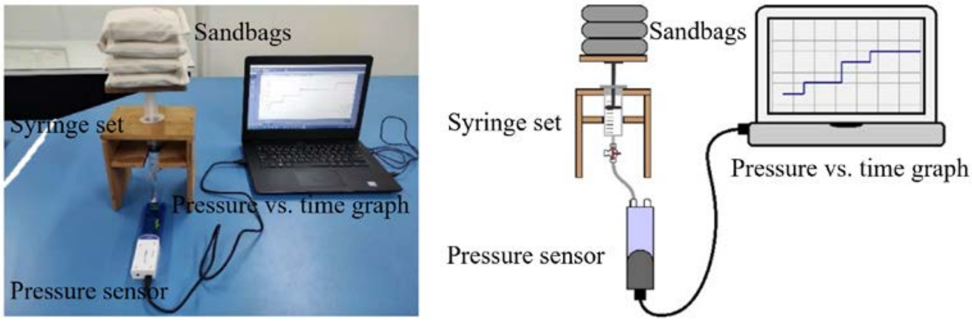

Figure 2: Experimental setup for the exploration of Boyle's law (left) and its diagram (right): the weight of sandbags exerting pressure on the syringe piston rod presses the gas in the syringe connected to the pressure sensor - the real-time graph was observed by students on the monitor.

Students performed this experiment by placing a sandbag on the syringe piston rod, measuring the volume of gas, and reading the pressure from the graph on the monitor. This process was repeated by adding more sandbags and switching to different gas species. Students needed to take into account the leakage of gas at high pressure. The leakage could be observed directly from the syringe or from the pressure versus the time graph on the monitor.

EXPERIMENTAL OUTCOME AND DISCUSSION

In exploration of Boyle's law, Table 1 contains the average numbers of the three gases' moles from Part II, and the average values of pressure and volume from Part III obtained by some groups of students in the class.

Table 1: Moles and pressure times of gases at six varied volumes in a piston area 1.06×10^{-5} m^3, at 298.15 K.

Gases	PV (N m)						
Air (0.0013 mol)	5.01	5.02	5.03	5.02	5.01	4.97	5.09
Oxygen (0.0019 mol)	5.35	4.83	4.94	5.02	4.89	4.95	4.9
Argon (0.0019 mol)	5.03	5.03	4.93	5.02	5.00	4.96	4.93

According to Table 1, the values of density for air, oxygen and argon were 2.6×10^{-4}, $3.8\times10^{-4}$and 3.8×10^{-4} mol/m^3, respectively. The data demonstrate that the values of pressure are in inverse proportion to the values of volume with a constant product of 5.00 ± 0.02 N m. Every gas in this experiment behaved in agreement with Boyle's law.

The graph of P and 1/V depicted in Figure 3 shows a linear relationship between them. To compute the ideal gas constant *R*, the slope (PV) of each graph was divided by its mole and the room temperature of 298.15 K. The obtained *R* values yielded degrees of error of 57.56% for air, 10.12% for oxygen and 1.14% for argon. The errors for oxygen and argon were in agreement with the findings by Rebillot [9]. While air, as a mixture of gases, gave a quite large error, argon, whose particles have almost no interaction, gave a very small error. The *R* constant from the experiment with air, oxygen and argon are 13.091, 7.472 and 8.219 of the error 57.46, 10.12 and 1.14, respectively.

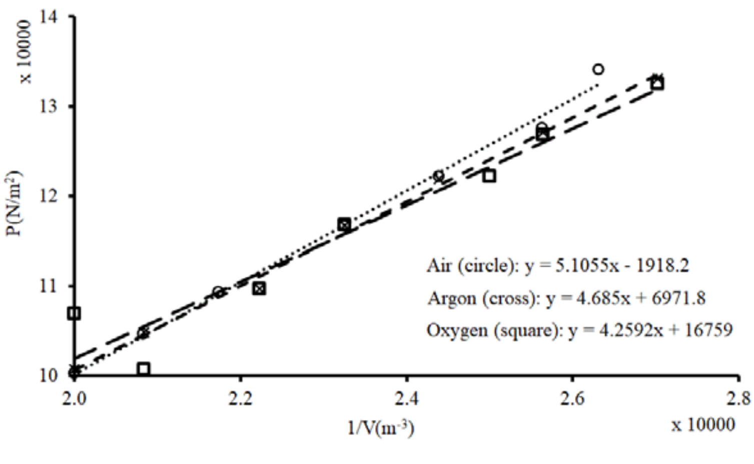

Figure 3: Graphical illustration of pressure versus the volume of the three gases.

The plan of class activities is shown in Table 2. The pre-test aimed to encourage the students to study before class and to attend it on time. The questions asked students to demonstrate their understanding of the concept of constant value of PV under a fixed temperature and mole by plotting the PV versus the V graph. However, most of the students (over 85%) failed to plot an acceptable graph. Three examples of students' responses are shown in Figure 4. Only the left figure was acceptable as a correct answer. This question was discussed with students when they obtained their results (Table 1).

Table 2: The amount of time spent on individual activities of this experiment (the whole experiment lasted for three hours).

Activity	Minute	Material
Pre-test	5	Pre-test paper
Laboratory introduction	40	Laboratory direction and VDO clip
Oxygen preparation	30	Oxygen preparation tool set shown in Figure 1
Boyle's law experiment	30	Boyle-experimental set up shown in Figure 2
Graph plotting and data analysis	50	Spreadsheet form
Post-test	5	On-line post-test
Class discussion	20	Students' report

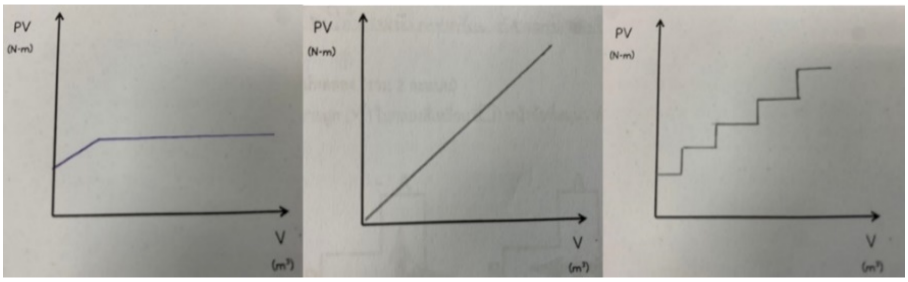

Figure 4: Examples of students' responses to a pre-test question: *Sketch a graph on the given axes under the condition of fixed temperature and mole.*

In an introduction to the laboratory at the beginning of the class, the instructor briefly explained to students how to use the pressure sensor and its working principle, all experimental set up and how to use the 3-way valve. Then, students were asked to conduct the experiment. The preparation of the oxygen gas and the Boyle's law experiment took about an hour. These activities allowed students to work collaboratively as a group. They performed different tasks within the group, letting two members prepare oxygen, while the rest of the team carried out experiments on Boyle's law with air and argon. Students' feedback indicated that they thought the amount of work in this experiment was appropriate. Some of them said that *This lab was not so boring, we had a variety of tasks to complete;* and *I enjoyed preparing oxygen and felt excited when seeing big oxygen bubbles floated and were stored in the bottle*.

During the activities, students conducted the experiment, recorded data, plotted graphs, analysed the data, as well as discussed their results in the prepared MS Excel spreadsheet. The instructor demonstrated how to plot graphs to some students who had little experience with using MS Excel. In this activity, students gained experience learning to store, analyse and visualise large chunks of data. Interestingly to note that one semester after the course some students who had first learned to use MS Excel in the class mentioned that they had to use MS Excel intensively in their sophomore year.

In the post-test, there were two questions asking students to briefly describe how to calculate pressure without using the pressure sensor and give another approach to determine the constant *R*. More than 80% of the students were able to numerically compute gas pressure by multiplying the force exerted on the syringe with its cross-sectional area. However, only about 10% of them were able to answer the second question, while the rest did not answer the question. The solutions to all the questions were discussed with students at the end of the class.

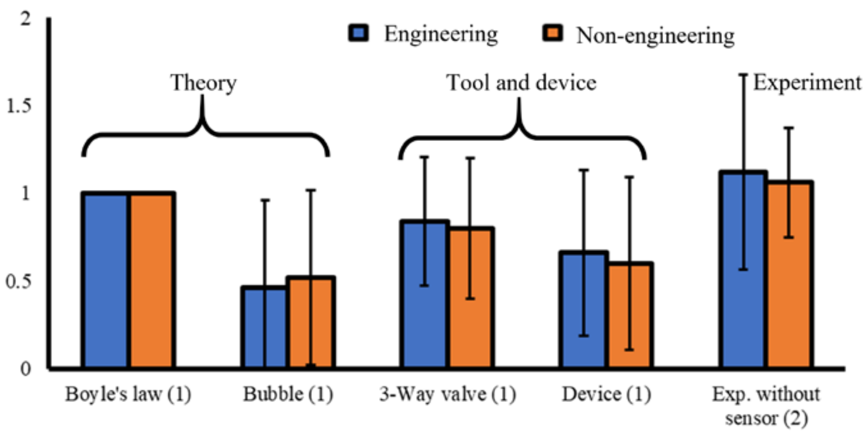

Figure 5: Students' average scores on the knowledge of Boyle's law, use of tools and devices, and ability to perform the experiment (engineering students: N = 50 and non-engineering students: N = 50).

In the final examination, each student drew lots to take a set of examination questions corresponding to one out of the eight laboratories they completed in this course. They had 45 minutes to complete three parts consisting of theory, the use of tools and devices and a short actual experiment. The result of the test is shown in Figure 5.

Learning achievement of the engineering students was on par with that of non-engineering students. However, some differences between the two groups were observed as follows:

- Theoretical part: Question 1 (1 point). The question asked students about the statement of Boyle's law. All students answered the question correctly.
- Theoretical part: Question 2 (1 point). The question checked the students' comprehension of Boyle's law from a given scenario, *compare the sizes of bubbles floating from the bottom to the top of the glass*. The average score of the non-engineering students was just 0.06 points higher than that of the engineering students.
- The use of tools and devices: Question 1 (1 point). The question asked students about the use of the 3-way valve, *adjust the handle to control water flow in the l-shape turn*. The engineering students performed the task better than the non-engineering ones with the margin of 0.04 points higher.
- The use of tools and devices: Question 2 (1 point). The question asked about the specification of the pressure sensor. The engineering students did slightly better on this question than the non-engineering students with a margin of 0.06 points.
- Short actual experiment (2 points): The students had to verify Boyle's law without using any pressure sensor. They had to measure the volume of a gas, calculate the pressure from the force exerted on the syringe rod, record data, plot a graph and determine the gas constant R in an MS Excel spreadsheet. The engineering students obtained the average mark of 0.02 higher than the non-engineering students. There were 14% of the engineering students and 6% of the non-engineering students who performed the task perfectly.

Based on the obtained results, it is evident that the engineering students had shown a better skill of using tools and devices compared to the non-engineering students. Consequently, they performed the experiment slightly better.

IMPACT ON ENGINEERING AND TECHNOLOGY EDUCATION

Physics laboratories play an important role in practical knowledge acquisition that is necessary for a complete understanding of physics. Without understanding physics principles and relevant practice, an engineer will not be competent to cope with existing and emerging problems of science and technology. This study has demonstrated an endeavour to change traditional physics lecturers and laboratory activity (cookbook laboratory) into more active and engaging student-centred laboratory activities.

To be specific, the complexity of experimental processes added to this laboratory was as high as in real life; the application of gas preparation was an good illustration of how different disciplines are interconnected [10]; the use of the sensor/computer interface for measurement helped students to become accustomed to a modern instrument based on fundamental physics; the use of the MS Excel software gave students an alternative tool for data visualisation and analysis; the laboratory assignment of working in groups could develop collaboration skills needed to properly interact, engage and synergise, while working towards a common goal. The practices of integrated skills in this laboratory contributed to students' experience essential for their professional practice in engineering.

CONCLUSIONS

This article demonstrates the development of an existing experiment to verify Boyle's law and to determine the ideal gas constant R. The laboratory experiment was implemented in a physics laboratory course for freshmen in an engineering programme at a Thai university. Three gas types including a noble gas (argon), a diatomic gas (oxygen) and a mixed gas (air) were used, allowing students to observe different behaviour among the three gases.

The obtained results confirmed that in a fixed mole and temperature environment, gasses behave in accordance with Boyle's law. The calculated values of R of different gases from P and 1/V were within 60% of error from the standard value of 8.314 J/mol·K. Argon, which is considered to behave closest to the ideal gas, yielded the least error followed by oxygen and air, respectively. As a consequence, the error of R can be used to differentiate the type of a given gas in this experiment.

The development of this laboratory had been carried out through the laboratory activities: the laboratory experiment, measurement with the sensor/computer interface instrument, data analysis in spreadsheet, students' assessment in accordance with the proposed activities. When learning through these laboratory activities, students demonstrated that they could acquire physics knowledge and various practical skills - as demonstrated by the collected statistics.

The physics knowledge allowed students to connect theoretical concepts with natural phenomena of gases through the conducted experiment. The practical skills that students acquired relate primarily to the use of tools and devices, which brought them to understand the working principle of the sensor and to be familiar with a technological instrument in scientific experimentation. The ability to perform the experiment without using the sensor would ensure the students' ability in applying their knowledge and experimental skills to different scenarios without the proper laboratory instrument. Another benefit for students is their development of soft skills, such as critical thinking, problem solving, teamwork and digital literacy that would be applicable in their future profession [11].

Lastly, essential fundamental knowledge and multi-skills should be acquired by engineering students from the early stages of education. In higher education, for the first-year students, the institution should arrange fundamental courses with class activities relevant to the curricula. The activities should be challenging, complex, practical and interdisciplinary, and they have to reflect the real world, where the graduate will have to practice their profession as an engineer.

ACKNOWLEDGEMENTS

The authors would like to thank their undergraduate students, Kamin Kanchanapradith and Sirawit Treepia, who helped them to prepare the laboratory equipment, carry it out and repeat it many times to confirm the results.

REFERENCES

1. Limpanuparb, T., Kanithasevi, S., Lojanarungsiri, M. and Pakwilaikiat, P., Teaching Boyle's law and Charles' law through experiments that use novel, inexpensive equipment yielding accurate results. *J. of Chemical Educ.*, 96, **1**, 169-174 (2018).
2. Davies, G.B., Discovering the gas laws and understanding the kinetic theory of gases with an iPad app. *Physics Educ.*, 52, **4**, 045005 (2017).
3. Ivanov, D.T., Experimental verification of Boyle's law and the ideal gas law. *Physics Educ.*, 42, **2**, 193-197 (2007).
4. Cornely, K. and Moss, D.B., Determination of the universal gas constant, R. A discovery laboratory. *J. of Chemical Educ.*, 78, **9**, 1260 (2001).
5. Iqbal, A., Qazi, S.M. and Anwar, M.S., Verifying gas laws. *Lums School of Science and Engineering* (2016).
6. Peterlin P., Data analysis and graphing in an introductory physics laboratory: spreadsheet versus statistics suite. *European J. of Physics*, 31, **4**, 919-931 (2010).
7. Flinn Scientific, Density of Gases (2017), 19 July 2022, www.flinnsci.ca/C/pub_91663
8. Picard, A., Davis, R.S., Gläser M. and Fujii K., Revised formula for the density of moist air (CIPM-2007). *Metrologia*, 45, **2**, 149-155 (2008).
9. Rebillot, P.F., Determining the ratio C_p/C_V using Rucchart's method. The College of Wooster, Ohio United States, *ratio*, 1-3 (1998).
10. Krosnicka, K.A., Lorens, P. and Moronowicz, I., Bridging theory and practice in postgraduate education on development and planning: Gdynia Urban Summer Schools 2016-2018. *World Trans. on Engng. and Technol. Educ.*, 17, **3**, 302-307 (2019).
11. Thanachawengsakul, N., Wannapiroon, P. and Nilsook, P., How a digital knowledge engineering learning process can enhance technical skills in software engineering. *World Trans. on Engng. and Technol. Educ.*, 16, **3**, 312-316 (2018).