

PHYSICS 258 Lab Manual¹

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Lab 1

Ratio of Specific Heats of a Gas

Learning Objectives

- To determine the values of $\gamma = \frac{C_p}{C_v}$, the ratio of the specific heat at constant pressure (C_p) to the specific heat at constant volume (C_v), for air, a monatomic gas (argon), a diatomic gas (nitrogen), and a polyatomic gas (carbon dioxide), using the method of Clément and Desormes.
- To determine the value of γ for air using Rüchardt's method.

Introduction

When heat is supplied to a substance, provided there is no change of state such as from solid to liquid, the temperature of the substance rises. The **specific heat** is the quantity of heat required per unit mass per unit of temperature increase – a typical unit for specific heat is Joules per kg per K ($\text{J kg}^{-1}\text{K}^{-1}$). For example, if the substance is a gas, we have to consider whether or not the gas is permitted to expand while the heat is supplied. If the gas does not expand, we have a constant volume process and all the heat supplied goes to increasing the internal energy (U) of the gas.

This internal energy consists of kinetic energy of translation of the molecules and, in the case of diatomic and polyatomic gases, rotation of the molecules as well. At elevated temperatures, vibration of atoms in the molecules may occur as a further component of internal energy. The specific heat measured in a constant volume process is called the **specific heat at constant volume**, C_v .

If, as heat is supplied, the gas is allowed to expand at constant pressure, the gas must do work in this expansion. The amount of heat that is now required to bring about the same temperature change as before is greater because of the work that must be done in the expansion. Thus, for a gas, the specific heat at constant pressure is always greater than the specific heat of the same gas at constant volume: $C_p > C_v$.

The ratio of the specific heats is of considerable significance as it is related to the molecular structure of the gas. If n is the number of degrees of freedom of a molecule of the gas, γ can be expressed as

$$\gamma = \frac{C_p}{C_v} = \frac{n+2}{n}.$$

A monoatomic molecule has only the three degrees of translational freedom and consequently $n = 3$ and $\gamma = \frac{5}{3}$. For a diatomic molecule there are two additional rotational degrees

of freedom so that $n = 5$ and $\gamma = \frac{7}{5}$. A polyatomic molecule can absorb energy into three rotational motions as well as the three translational ones: hence $n = 6$ and $\gamma = \frac{4}{3}$.

The velocity v of propagation of a sound wave in a gas is also related to γ ; in fact

$$v^2 = \frac{\gamma P}{\rho}, \quad (1)$$

where ρ is the density of the gas and P its pressure.

Hence measurements of γ give information about both the molecular structure of the gas and an acoustic property.

Theory

Method of Clément and Desormes

In the method devised by Clément and Desormes for the measurement of γ , the physical procedures are remarkably simple but the reasoning is somewhat subtle. A flask is filled to slightly more than atmospheric pressure with the gas to be tested, and allowed to reach thermal equilibrium. If the atmospheric pressure is H cm of mercury (cmHg), then this initial pressure will be

$$P_0 = H + \frac{\rho h_0}{13.59} \text{ cmHg},$$

where ρ is the density of the fluid in the manometer in g/cm^3 and h_0 the manometer reading after it is steady.

The stopper is now removed for about 1 second allowing the pressure in the flask to drop to atmospheric pressure H . This sudden expansion is adiabatic and its effect is to cool the gas in the flask. The stopper is tightly closed and the gas in the flask is allowed to warm back to room temperature. Readings should be taken every time a pressure change is noticed, until equilibrium is reached. Calculate γ as these readings are taken. This should not take longer than 15 minutes and will be accompanied by an increase of pressure in the flask. This final pressure will be

$$P = H + \frac{\rho h_1}{13.59} \text{ cmHg}.$$

From three observations, namely the atmospheric pressure (H), the initial manometer height difference (h_0), and the final height difference (h_1), a value for γ may be found. Indeed, to a good approximation, only the initial and final readings of the manometer (h_0 and h_1) are needed.

It is important to note that we are dealing with the same constant quantity or mass of gas throughout the experiment. At the initial pressure P_0 (which is greater than atmospheric) let us imagine that a mass of gas occupies a volume V_0 shown as the shaded area in figure 1. There is, of course, an additional volume $V - V_0$ of gas in the flask.

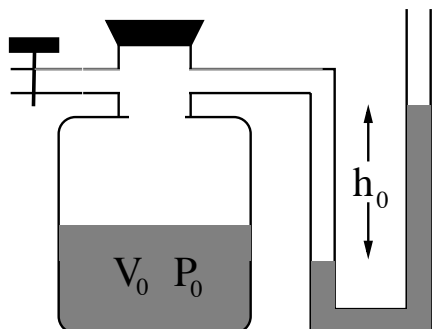


Figure 1: Initial State.

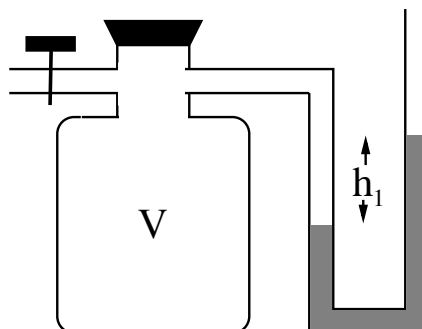


Figure 2: Final State.

When the stopper is opened briefly, the pressure is promptly reduced to atmospheric pressure H as $V - V_0$ escapes and V_0 expands adiabatically (no heat exchanged with the exterior during expansion) to the full volume V of the flask. In figure 2 the state of the gas represented by the shaded part of figure 1 has gone from state A (figure 3) to state B (stopper open and not drawn). The change is adiabatic, and hence

$$P_0 V_0^\gamma = H V^\gamma. \quad (2)$$

After the stopper is closed again the volume doesn't change any more, but the gas gradually warms up to room temperature. This change is indicated in figure 3 as a change from state B to state C .

Now points A and C are both at room temperature; hence

$$P_0 V_0 = P_1 V. \quad (3)$$

From equations 2 and 3 it is easy to see that

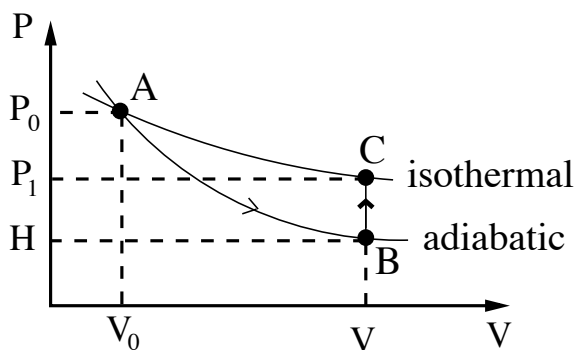


Figure 3: $P - V$ Diagrams for Isothermal and Adiabatic Processes. Note that the origin of this graph is not $(0, 0)$; in fact $P_0 - H \ll H$ and $V - V_0 \ll V$.

$$\frac{P_0}{H} = \left(\frac{P_0}{P_1} \right)^\gamma, \quad (4)$$

i.e.,

$$\gamma = \frac{\ln \left(\frac{P_0}{H} \right)}{\ln \left(\frac{P_0}{P_1} \right)}. \quad (5)$$

Experiment

This experiment will be, in part, performed as a class project. Instructions are given in the analysis section.

In our setup, the pressure sensor replaces the measurement of the height used in the original Clément Desormes experiment to determine γ of three different gases. Before starting the experiment, one must flush the system using the appropriate gas to ensure there are no other gases inside. Once flushed, connect the pressure sensor to the aperture near the opening of the apparatus. Turn on the PASCO interface and open the file *Clement_Desormes*.

The first page consists of a table with columns for the apparatuses internal pressure P_0 and P_1 and the other is for the ambient air pressure. On the right hand side there is a graph showing internal pressure as a function of time. You can get a visual sense of when the apparatus is in thermal equilibrium using this display. Before beginning the experiment make sure that the pressure sensor is calibrated. This is performed after the initial flushing of the system. Make sure that the internal pressure is not above the room's pressure. If the internal pressure does not change at the release of the lever then it is at atmospheric pressure. Otherwise open and close the top until it is.

Procedure

- Once at atmospheric pressure, click Calibration on the left hand tool bar and click *next*. You will then be asked for the types of probes to calibrate, choose Dual Pressure Sensor, Ch P1 then select *One Standard (1 point offset)* to perform a one point calibration in order to determine the offset, not the slope. Press *next*.
- The current atmospheric air pressure H can be found online at www.weather.gc.ca. One enters the ambient pressure H as the standard value and click Set Current Value to Standard Value. Now the sensor has been calibrated. Press *Finish*. Also note H in your lab book for the calculation of γ .

- The apparatus can hold an internal pressure of up to roughly 115-120 kPa before leaking; the experiment will be performed with P_0 values ranging between 105 kPa and 115-120 kPa. Fill the chamber with a certain amount of gas so that the internal pressure rises above room pressure.
- Wait until thermal equilibrium has been reached (when the internal pressure vs. time plot levels off). **Note that the pressure may be constantly dropping because some of the flasks are leaking slightly. If you encounter a leaking flask, keep the value once the dropping rate is slowed down; do not wait for the values of pressure to stabilize. But only do this if your flask is leaking!** When thermal equilibrium is reached press to log the pressure value in the table. This is your P_0 value.
- Release the lever for a second to allow the internal pressure to drop to atmospheric pressure and wait for equilibrium **in this case, wait until the value of pressure becomes fully stabilized**; then type the value as your P_1 in the corresponding column.
- Perform this 10 times for P_0 values ranging between 105 kPa and 115-120 kPa recording the P_0 and P_1 values each time. Once you are finished export the data as a csv file.

In-Class Analysis

For each gas, calculate the mean value for γ and the standard deviation σ for all your data points. Before leaving class, copy these values to the spreadsheet on the main computer. This file will be copied to myCourses and is available to the whole class.

After-Class Analysis

- Plot $\ln(\frac{P_0}{H})$ vs. $\ln(\frac{P_0}{P_1})$ for your data set for each gas. Find γ , which is the slope, using a least squares fit. This line should pass through the origin, so as a first approximation you can assume $b = 0$ and $a = \frac{\sum xy}{\sum x^2}$. However, you should confirm that the data is consistent with having a zero intercept, i.e., compare your fit results for fixed and variable b .
- Determine the uncertainty of your measurement.
- Calculate the mean and σ of the class data and compare it to the value of γ that you extracted from the fit.
- Compare your results of γ to literature values. What conclusions can you draw?

Rüchardt's Method of Measuring the Ratio of Specific Heats of a Gas

Apparatus

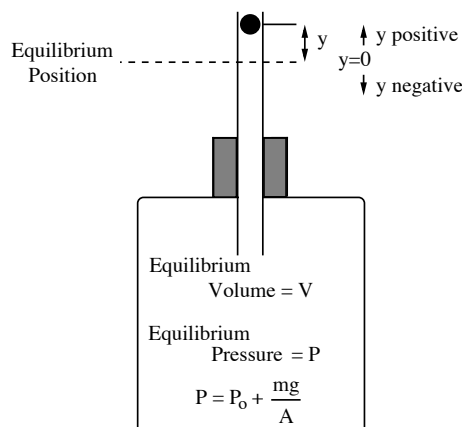


Figure 4: Rüchardt's Apparatus for the Measurement of γ

Theory

An ingenious method of measuring γ developed by Rüchardt in 1929, although no more accurate than the method of Clément and Desormes, will appeal to students who have a liking for mechanics. The gas is contained in a large jar of volume V . Fitted to the jar is a glass tube with an accurate bore of cross-sectional area A , in which a graphite cylinder of mass m fits snugly, like a piston. Since the gas is slightly compressed by the weight of the graphite cylinder, the pressure P is slightly larger than atmospheric pressure P_0 . Thus, neglecting friction,

$$P = P_0 + \frac{mg}{A}. \quad (6)$$

If the graphite cylinder is given a slight upward displacement and then let go, it will oscillate with a period τ . Friction will cause the cylinder to come to rest eventually. Let the displacement of the cylinder from its equilibrium position at any moment be denoted by y , where y is positive when the cylinder is above the equilibrium position and negative below. A small positive displacement causes an increase in volume that is very small compared with the equilibrium volume V and that therefore can be denoted by ΔV , where

$$\Delta V = yA.$$

Similarly, a small positive displacement causes a decrease in pressure that is very small compared with the equilibrium pressure P and that therefore can be denoted by ΔP , where

ΔP is a negative quantity. The resultant force F acting on the cylinder is equal to $A \cdot \Delta P$ if we neglect friction, or

$$\Delta P = \frac{F}{A}.$$

Notice that, when y is positive, ΔP is negative and therefore F is negative, that is, F is a restoring force. Hence

$$\frac{\Delta P}{\Delta V} = \frac{F}{yA^2}.$$

Now, as the cylinder oscillates fairly rapidly, the variations of P and V are adiabatic. Since the variations are also quite small, the states through which the gas passes can be considered to be approximately states of equilibrium. We may therefore assume that the changes of P and V represent an approximately quasi-static adiabatic process, and we may write

$$PV^\gamma = \text{const.}$$

and

$$P_\gamma V^{\gamma-1} \Delta V + V^\gamma \Delta P = 0.$$

Substituting for ΔV and ΔP , we get

$$F = -\frac{\gamma PA^2}{V}y.$$

The above equation expresses the fact that the restoring force is directly proportional to the displacement and in the opposite direction. This is precisely the condition for simple harmonic motion, for which the period τ is

$$\begin{aligned} \tau &= 2\pi \sqrt{\frac{m}{-F/y}} \\ \text{Consequently, } \tau &= 2\pi \sqrt{\frac{mV}{\gamma PA^2}} \\ \text{and } \gamma &= \frac{4\pi^2 mV}{A^2 P \tau^2}. \end{aligned} \tag{7}$$

The mass of the cylindrical bob, the cross-sectional area of the tube, the pressure, and the volume are all known beforehand, and only the period has to be measured to obtain γ .

Experiment

In our experiment we will use a motion sensor to measure τ . On the laptop open up the PASCO Capstone file *Ruchhardt*. Turn the PASCO Interface on. On the left side of the program is a **Calculator** tool where the equations and constants are located. Look up the current atmospheric pressure and dimensions of your apparatus and enter them in the appropriate spot. The dimensions of your apparatus can be found on page **4** of the Capstone program. Make sure the tube of the Ruchhardt's apparatus is perpendicular to the table in order to minimize friction, and that the motion sensor is located a few inches above the top facing downwards. Wedging a piece of paper under the jar may straighten the apparatus. The motion sensor for this experiment measures the position of the graphite cylinder inside the tube and the program plots its position as a function of time.

Procedure

- When ready press the **Record** button and with the hand pump, bring the graphite cylinder up from its rest position to just above the cork at the lower end of the tube. Then quickly (but carefully) increase the pressure with the hand pump (one hard squeeze usually works); the cylinder will rise about $\frac{2}{3}$ of the way up the tube and oscillate. Do not wait too long after pressing **Record** before starting the experiment as the PASCO program is set up to record for 10 seconds.
- The sample rate is set to 100Hz, but it can be adjusted with the **Sampling Rate** control icon located at the bottom of the page, if needed be. If no nice oscillation plot is recorded, the proximity sensor needs adjustment. Ask the TA for help.
- Clicking the **Show coordinates and access Delta Tool** icon and right clicking on the coordinate tool on the graph you can access the **Delta Tool**. Place the first movable box on the first peak, and place the second box on the last peak. Enter the number of cycle between the 2 peaks in the table below as well as the time of all oscillations.
- Repeat this measurement 10 times.
- Click on “page 2” to see the values of γ and τ that are calculated for you.

Warning: This experiment relies on there being enough clearance between the graphite cylinder and the glass tube for the cylinder to slide freely with minimum losses, but not so much clearance that the air leaks past the cylinder causing it to fall to the bottom of the tube before you can complete the measurement. If you operate the equipment roughly, you could drive the cylinder into the end stop and damage it. Making a replacement can take significant time, depending on one's machining skills.

Analysis

- Equation 7 provides a value for γ , with the only experimental measurement being that of τ , the period of oscillation of the cylinder. The values of m , the mass of the cylinder; A , the cross-sectional area of the glass tube; and V , the volume of the jar, are given to you.
- You will need to obtain the atmospheric pressure P_0 , in order to determine P .
- Estimate the uncertainty on τ and propagate this error and uncertainties in the other measured quantities in the calculation of γ .
- Find γ . Make sure you convert all units to the SI system.
- Compare your value of γ with that obtained for nitrogen by the method of Clément and Desormes, and discuss. What conclusions can you draw about the degree of freedom n of the content of air?