Lab 8

Constant Volume Gas Thermometer and Absolute Zero

Continuing Objectives

3. Be able to write an experimental result (including correct number of significant digits, uncertainty, units).

4. Be able to make careful measurements to ensure reproducible results.

7. Know how to make comparisons: are two measured quantities equal? Is a measured quantity statistically equivalent to a theoretical value?

Lab-specific Objectives

1. Learn to recognize and account for "systematic uncertainty" in an experiment.

Introduction

The method used in this lab to determine absolute zero is based on the Ideal Gas Law:

$$PV = NkT. \tag{8.1}$$

If the volume V of a sample of gas is kept constant, it follows that there is a linear relationship between T and P given by

$$T = \frac{V}{Nk} P = \text{constant} \times P. \tag{8.2}$$

In this lab, a sample of gas (air from the room) is contained in a glass bulb and kept at constant volume. You will collect data on the pressure as you change the temperature of the gas from about 90 °C to 10 °C. A graph of the experimental points (P_i, T_i) should be a straight line according to the Ideal Gas Law. We **define** absolute zero to be the temperature at which the pressure of an ideal gas will go to zero, and you can estimate this temperature by extrapolating your graph back to zero pressure.

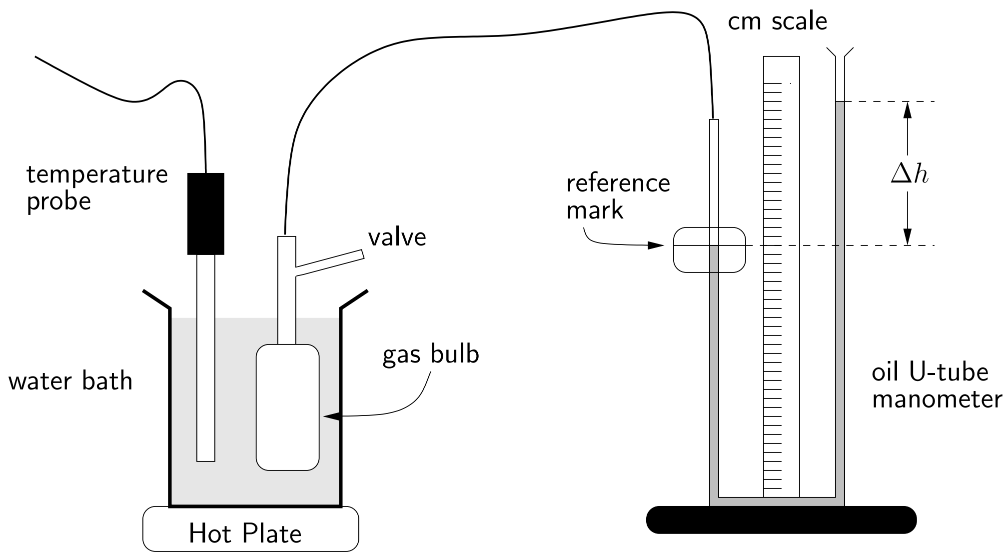


Figure 8.1: The constant volume gas thermometer.

Experiment

Note: your instructor may have you start this lab by taking data. If this is the case, turn to page 4 and begin with the *Procedure* section. Return to this section when you have collected all data for this lab.

The temperature of a gas sample in this experiment is determined from a temperature probe placed in the water bath. The temperature probe is connected to the computer through the LabPro interface. The absolute pressure of the gas sample is measured using a U-tube manometer as shown in Figure 8.1. The gas sample exerts a pressure P on the left side of the oil tube while the right side of the tube is open to atmosphere, which exerts a pressure P_{atm} on the right side of the oil column. If these two pressures were equal, the heights of the two oil columns would be the same. If $P > P_{\text{atm}}$, the height of the oil on the right, h_R, is higher than that on the left, h_L, by an amount $\Delta h = h_R - h_L$. This indicates that the pressure of the gas sample is the sum of atmospheric pressure P_{atm} and the pressure due to the difference in oil levels, P_{oil}:

$$P = P_{\text{atm}} + P_{\text{oil}}. \tag{8.3}$$

In the actual experiment, P_{atm} is obtained by checking the local barometric pressure at (`https://www.wunderground.com/weather/us/pa/lewisburg`). Note that the pressure at this site will be given in units of inches of mercury (inHg). There are several units for pressure, including millibars (mb), atmospheres, and the SI unit, N/m^2 also known as Pascal (Pa). A handy conversion is:

$$1\,\text{atm} = 101\ 325\,\text{N/m}^2 = 1013.25\,\text{mb} = 29.93\,\text{inHg}$$

The value for P_{oil} is obtained by measuring Δh, where Δh is read directly as a height difference on a scale.

Note: The quantity Δh starts out positive but becomes negative during the experiment. Also, when the air sample is at atmospheric pressure, the oil levels are equal, $\Delta h = 0$.

Converting height difference to pressure difference

During your experiment, you will obtain a reading of the bulb pressure in terms of the atmospheric pressure (measured in N/m^2) and the height difference in the oil levels (measured in cm). To combine these two quantities, you will need to convert the height difference to a pressure difference. To do this, we will need to establish a relationship between the two quantities.

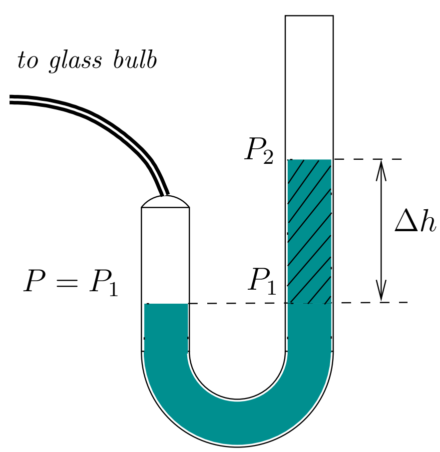


Figure 8.2: Measured pressure difference in oil manometer.

Based on Figures 8.1 and 8.2, perform the following steps to determine the conversion from height difference to pressure.

Step 1: Convince yourself of the following: on either side of the manometer, the pressures of the gas just above the oil levels are

$$P_2 = P_{\text{atm}} \tag{8.4}$$

and

$$P_1 = P_2 + P_{\text{oil}}, \tag{8.5}$$

where P_{oil} is the extra pressure due to the weight of the column of oil shown cross-hatched in the sketch.

If you have any questions, discuss them with your instructor or TA.

Step 2: We can now use the same Newton's second law step-by-step approach that you learned in your problem session to obtain an expression for P_{oil}. Consider the volume of oil cross-hatched in Figure 8.2. Assume that the cross-sectional area of the U-tube is A. Draw a force diagram for this section of oil in this equilibrium state. Be sure to label all the forces.

Step 3: Show that the gravitational force felt by the oil column F_{grav} is given by $F_{\text{grav}} = \rho_{\text{oil}}\, gA\, \Delta h$, where ρ_{oil} is the mass density of the oil in the manometer.

Step 4: Using Newton's 2^{nd} Law, show that

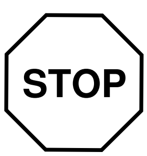
$$(P_1 - P_2)\, A = F_{\text{grav}} = \rho_{\text{oil}}\, gA\, \Delta h. \tag{8.6}$$

Step 5: Show that the relationship between P_{oil} and Δh is given by

$$P_{\text{oil}} = \rho_{\text{oil}}\, g\, \Delta h. \tag{8.7}$$

From this expression, calculate the conversion factor from Δh (measured in m) to P_{oil} (measured in N/m^2). Note that for the Krytox oil that we use, $\rho_{\text{oil}} = 1.88\,\text{g/cm}^3$. You will use this conversion factor throughout your experiment.

Step 6: Use Eq. (8.3) and Eq. (8.7) to derive an equation for the gas pressure P (measured in N/m^2).



Have your lab instructor or TA check your result for P.

Procedure

1. With the temperature probe connected to the analog input port labeled `CH 1` on the LabPro interface, turn on power to the interface and start the Logger *Pro*software from the windows desktop. Use the file `TempC.cmbl` which is in the `PHYS211_212 Lab` → `211Lab` → `Lab 08 - Const V Gas Term and Abs Zero` folder. There is also an Excel template in the same folder that you should use to record your measurements.

2. Place the bulb in the water with the valve open. Turn on the stirrer and the heater. The heater should be set to 250 °C MAXIMUM and the stirrer to 8.

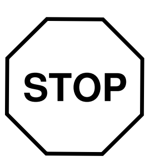
3. When the temperature of the water reaches 45 °C, close off the valve by folding and then clamping the valve tube. Continue to heat the water.

4. Now as a result of the expansion of the air in the bulb, the oil in the left tube tends to be pushed down and that in the right tube tends to be pushed up. As you continue heating *keep the oil at the reference mark by moving the left tube down and/or the right tube up* until you run out of room. This should occur at approximately 85 °C, but stop heating about 5 °C before you get there since the temperature will continue to rise for a time after the heat is turned off.

5. Now begin your measurements. As the water cools, take measurements of the height difference Δh at different temperatures. To do this, record the height of the oil level on the left side of the tube (h_L) and the right side of the tube (h_R) at temperatures about $4 - 5\,^{\circ}$C. (You may make a measurement every 3-4 minutes instead.) **Remember, for each measurement, the left oil level must be at the reference mark because the volume must be kept constant.**

6. To speed up the cooling process, you may, from time to time, remove a couple hundred milliliters of hot water with the syringe and replace it with cool water or ice. Be sure to allow enough time after adding ice for T to stabilize before taking a measurement. Continue until you run out of room, at around 20 °C.

7. You have now collected all the data you will need. **Get your instructor of lab TA to help you with this step.** While you wait for a TA or instructor, begin bringing the bulb temperature back up to 45 °C while adjusting the oil levels. **Important: To ensure that the oil does not overflow into the small connecting tube, keep adjusting the oil levels. Only, once the oil levels are about equal on either side (usually happens around 45 °C), you may unclamp the valve.**



Show your data to your instructor or TA. Get help unclamping the valve if you need to.

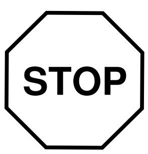
Note: If your instructor had you skip pages 2—4 and start with the Procedure section, you should now work through pages 2—4.

Analysis

1. Plot a graph of T (°C) vs. P (N/m^2), remembering to add atmospheric pressure to each measured pressure difference. (Note: Temperature T should be on the y-axis.) Extend your temperature axis from $-300\,°\text{C}$ to $100\,°\text{C}$, and your pressure axis from 0 to $150,000\,\text{N/m}^2$.

2. The temperature at zero pressure is absolute zero in °C. If we assume that the points determine a straight line, we can find the "best-fit" straight line and extrapolate it to zero pressure. To add a best-fit line to your data, click on your plot and click the green plus-sign that appears on the side. You will see an option to add a trendline. After adding it, double-click the trendline and look through the options for "Forecast". Set "backwards" to 100,000. Also check off the option for "Display equation on chart". Follow these steps and record the results in your lab notebook. How close is your result to the accepted value of absolute zero, $T_0 = -273.15\,°\text{C}$?

3. You can use the `linest` feature of Excel to obtain the uncertainty in the intercept of your plot. The output of linest is provided in your Excel template. (You find a description of `linest` in Appendix C.8.) Report your final result for absolute zero with uncertainty in standard form. Given your uncertainty, is your result consistent with the accepted value for absolute zero?



Write your result and its uncertainty on the board. Is there anything you notice about your result and the rest of the lab's results? Are they consistent with the known value of absolute zero? If not, why not? Discuss your thoughts with your lab instructor or TA.

You have likely noticed that not only is your measurement of absolute zero inconsistent with the accepted value, even taking into account uncertainty, but the entire *class* has results that are inconsistent with the accepted value. Not only that, but the class results all seem to be "off" in a similar way. When this sort of pattern occurs in a set of data, it is likely the cause of a "systematic error."

A systematic error is, simply, an error which consistently affects a result in the same way. For example, in using a thermometer, you could imagine random errors in reading the scale, sometimes reading it too high, other times too low - this would NOT be considered "systematic." But a mislabeled thermometer might give measurements which are always ("systematically") too low.

Often, working out the limitations of our experiment and any systemic errors it imparts to the data is an important part of calibration and data interpretation.

If we characterize the effects of the systematic errors, we can account for it in our data and results, thereby allowing for better comparison with the expected value.

4. Consider your apparatus carefully, and attempt to identify sources of systematic errors. First of all, consider possible systematic effects that would affect your temperature measurement. Discuss how this systematic effect would change the line fitted to your data. Would including this systematic error shift your experimental value for absolute zero closer to the accepted value of $-273.15\,°C$?
5. Consider a systematic error similar to that in step 4 but that would affect your pressure measurement. Discuss how this systematic error would change the line fitted to your data. Would including this systematic error shift your experimental value for absolute zero closer to the accepted value?

STOP

Discuss your answers to steps 4 and 5 with your lab instructor or TA.

Reflection

Please reflect on today's lab in your notebook.

Look back at today's lab-specific objectives (beginning of the lab).

1. How has your understanding of those topics changed through today's lab?
2. You have now learned about three different types of uncertainty: uncertainty from measurement propagation, statistical uncertainty, and systematic uncertainty. What are the main differences between these sources of uncertainty? When is it appropriate to account for each of these uncertainties? Can you imagine a case where you might have contributions from all three?