

Absolute Zero of Temperature

1 Object

To measure the pressure and temperature of fixed volumes of gas in order to determine the temperature at which the pressure is expected to become zero.

2 Apparatus

Absolute zero apparatus, 1 gal insulated beverage cooler, accurate fast-response digital probe thermometer with 0.1°C resolution, source of tap water, hot plate, metal-bottomed coffee pot, source of ice, plastic water pitcher with straining lid, towel, bucket.

3 Theory

The temperature of a substance is due to the random microscopic motions of its atoms or molecules. More specifically, temperature is a measure of the average kinetic energies of the individual particles. Substances with higher temperatures have more energetic molecules than those with lower temperatures, and when two objects having different temperatures are brought into contact, collisions between the molecules transfer energy from the “hotter” substance to the “colder” one. This continues until both objects have the same temperature and their individual molecules have the same average kinetic energy.

It is reasonable to expect that the lowest temperature possible is one where all of this motion either ceases or becomes as small as possible. We can define a temperature scale such that $T = 0$ at this minimum, and we refer to this as the **absolute zero** of temperature. Higher temperatures on this scale have to be defined according to some reference standard, and the internationally accepted standard is to let $T = 273.15$ at the freezing point of water at atmospheric pressure. The units for this scale are Kelvin, abbreviated as K. This choice was made so that a change of temperature of 1 degree on this absolute scale would be equal to a change of temperature of 1 degree on the Celsius scale. By setting *changes* in each temperature scale to be the same, it becomes easy to convert between temperatures on both scales:

$$T_K = T_C - 273.15 \qquad \Delta T_K = \Delta T_C. \qquad (1)$$

One way to investigate the relationship between absolute temperature and the kinetic energies of molecules to consider the behavior of an ideal gas. An ideal gas is one comprised of a number of randomly moving, non-interacting, point-like particles. When n moles of these particles are confined within a container of volume V , they bounce around, colliding with the walls of the container. Because the particles have mass and carry momentum, each time one collides with the container wall, it exerts a force on the wall. Due to the immense number of particles in a typical sample of gas, these collisions generate a uniform net force per unit area, or pressure P . Consequently, the pressure is related to the kinetic energies of the particles, and therefore to the temperature. If we use the absolute Kelvin temperature scale as defined above, then we find that an ideal gas obeys the *ideal gas law*,

$$PV = nRT. \qquad (2)$$

Notice that this equation implies that the pressure of the gas would drop to zero when the temperature drops to absolute zero. The value of R in this equation is a constant, but it depends on the units used for pressure and volume. If pressure is measured in Pascals ($1 \text{ Pa} = 1 \text{ N/m}^2$) and volume in m^3 , then R is

equal to $8.314 \text{ J/mol}\cdot\text{K}$. This constant would also be different if the freezing point of water on the Kelvin scale were chosen to be something other than 273.15 .

At pressures close to atmospheric pressure ($1 \text{ atm} = 1.013 \times 10^5 \text{ Pa} = 14.7 \text{ lb/in}^2$) and temperatures similar to those in our environment, real gases and mixtures of such gases, like air, behave very much like ideal gases. If you use a fixed amount of air, and enclose it in a container of constant volume, then any change in the temperature of the gas will be directly proportional to the change in pressure of the gas:

$$\Delta T = \left(\frac{V}{nR} \right) \Delta P. \quad (3)$$

Since a *change* in temperature on the absolute scale is equivalent to the same change on the Celsius scale, if you use a fixed amount of gas in a container of constant volume, and make a number of measurements of pressure at a variety of different Celsius temperatures, then you can plot your Celsius temperature versus pressure and fit the data to a straight line. If you imagine that this straight line goes from the Celsius temperature at which $P = 0$ as well as through your data, then your fitting equation should have the form

$$T_C = \left(\frac{V}{nR} \right) P + T_0. \quad (4)$$

The slope of the line is related to the volume and the number of moles, and the y-intercept should be the temperature (in Celsius) at which the pressure theoretically becomes zero.

During this experiment, you will use a special “absolute zero” apparatus, shown in Fig. 1, consisting of a spherical metal bulb which is connected to a thin tubular metal stem. On the other end of the stem is a pressure gauge. On the side of the tube is a pressure release valve. If you press in the pin on the pressure release valve, the pressure inside the apparatus will equalize with the external atmospheric pressure. The apparatus will seal closed again when you let go of the pin. By pressing the release valve when the gas inside is at different temperatures, you can vary the number of moles of gas particles inside.

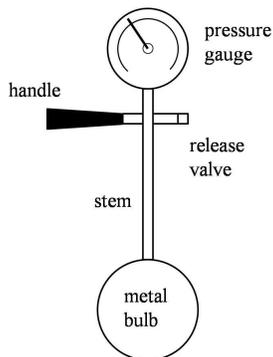


Figure 1: The absolute zero apparatus.

Suppose that you first press the pressure release value when the Celsius temperature of the gas inside the apparatus is T_1 . Then you make a number of measurements of pressure at different temperatures. Then, at some other Celsius temperature T_2 , you press the pressure release valve again. Then you make another set of measurements of pressure at different temperatures. After performing a linear regression on both data sets, you can use the ratio of the two slopes to determine the ratio n_1/n_2 of the number of moles of gas in the apparatus for each data set. Once you determine this ratio, you can use the ideal gas law

again to infer the value of a constant C we need to add to our Celsius temperatures to convert them into absolute temperatures:

$$\frac{n_1}{n_2} = \left[\frac{PV}{R(T_1 + C)} \right] \left[\frac{R(T_2 + C)}{PV} \right] = \frac{T_2 + C}{T_1 + C}. \quad (5)$$

4 Procedure

1. Fill the coffee pot with tap water and set it on the hot plate and turn the hot plate on high at first. During this experiment, you should not rest the empty coffee pot on the hot plate. Always make sure that there is some water in the pot when it is on the hot plate. You may have to add water to the coffee pot as the experiment progresses and may have to adjust the setting on the hot plate. Remove all papers and other items from the area immediately surrounding the hot plate. Be careful not to touch the hot plate as you can burn yourself.
2. Add enough ice to half-fill the plastic water pitcher. Then add tap water to the ice to nearly fill the pitcher. Put the straining lid on the pitcher. Turn on the digital thermometer and set it for 0.1°C resolution. Record the room temperature.
3. Press in the pressure release valve pin on the absolute zero apparatus so as to make the pressure inside of the apparatus equal to the outside atmospheric pressure. **Carefully** lower the absolute zero apparatus into the insulated cooler with the spherical metal bulb at the bottom. Do NOT drop the apparatus into the cooler, as the pressure gauge at the top is sensitive to shock and could be damaged permanently.
4. Add enough of the ice-water from the pitcher to the cooler to completely cover the metal bulb and come about half-way up the metal stem that connects the bulb to the pressure gauge. Do not let any ice get into the cooler – just the cold water. Turn on the digital thermometer and insert the probe into the water in the cooler. Gently move the absolute zero apparatus up and down to stir the water a little bit.
5. Hold the apparatus in a vertical position, and read off the pressure in units of lb/in^2 to the nearest $0.1 \text{ lb}/\text{in}^2$ if you can. Give the gauge a slight tap to make sure that the needle is not sticking. Record the pressure. Record the temperature of the water in $^\circ\text{C}$ to the nearest 0.1°C .
6. You will next raise the temperature of the water in the cooler about 5°C by removing some water from the cooler and adding some warmer water to replace it. Have your lab partner remove the absolute zero apparatus from the water and hold it while you pour about $1/4$ of the water from the cooler into the bucket. Then gently place the absolute zero apparatus back into the cooler. Add enough warmer water to bring the liquid level back to where it was before. You may have to use a mixture of hot water from the coffee pot, water from your bucket, and/or ice water from your pitcher to obtain the desired increase of about 5°C . Gently move the apparatus up and down a bit to stir the water a bit as before. Read off the pressure and temperature as you did before and record both values.
7. Continue to increase the temperature of the water in the cooler and make pressure and temperature measurements roughly every 5°C until you have at least 15 pairs of pressure and temperature values for temperatures between from 0°C and 75°C . Try to get them evenly spaced if possible. Do not go above 75°C as the cooler is not designed for these higher temperatures.

- While the absolute zero apparatus is still in the cooler with water that is close to 75°C , press the pressure release valve pin on the absolute zero apparatus to change the amount of gas inside the apparatus. The pressure should come back down to atmospheric pressure. Record the temperature and pressure as you did before.
- Using the same pour-and-refill technique, you will now *reduce* the temperature of the water in the cooler by about 5°C using tap water, water from your bucket, water from a fountain, or ice water from your plastic pitcher. Measure the pressure and temperature at this lower temperature as you did before. Continue to reduce the temperature incrementally in this fashion until you have at least 15 pairs of pressure and temperature values between 75°C and 0°C .

5 Calculations

- Make a plot of temperature versus pressure for your first set of 15 (or more) measurements where you were increasing the temperature. Perform a linear regression and report your first result for T_0 and its associated error δT_0 in 4-line summary.
- Make a plot of temperature versus pressure for your second set of 15 (or more) measurements where you were decreasing the temperature. Perform a linear regression and report your first result for T_0 and its associated error δT_0 in 4-line summary.
- Compute the average of your two results for T_0 , and estimate the associated error in this average as $\delta T_0 = \frac{1}{2}\sqrt{(\delta T_{01})^2 + (\delta T_{02})^2}$. Report your average for T_0 along with this associated error.
- Estimate the ratio n_1/n_2 of the number of moles of gas that were in the apparatus when you were raising the water temperature (n_1) to the number of moles of gas when you were decreasing the temperature (n_2).
- Take the room temperature value at which you released the pressure valve, and the higher temperature at which you released the valve again, and combine them with the ratio n_1/n_2 you just determined to find what constant must be added to your Celsius temperature values so that Eq. 5 is satisfied. Report your value for this constant and comment how it compares to your earlier results for the value of absolute zero in Celsius units.

6 Questions

- Suppose we had two identical absolute zero apparatus set-ups which read the same pressure, but one of them has twice as many moles of gas in it as the other. How are their temperature readings in $^{\circ}\text{C}$ related? Come up with an expression that lets you calculate the $^{\circ}\text{C}$ temperature of one if we know the $^{\circ}\text{C}$ temperature of the other.
- Suppose that when you did this experiment, you only covered the lower metal bulb portion of the apparatus with water while the metal stem going up to the gauge was not in the water. Would this introduce a systematic error in your measurement of the gas pressure or the gas temperature?
- Should the slopes of the two plots you made be the same or should they be different? Explain your answer.