Virtual Lab Manual

Ideal Gas Law:
Build your own temperature scale

Synopsis

Just because Celsius, Fahrenheit and Kelvin defined their own temperature scales and named them after themselves, it doesn't mean that you can't create your own! In the Ideal Gas Law simulation, you will define the physical concept of temperature and absolute zero. You will observe how ideal gas molecules behave according to the Ideal Gas Law, and you'll learn about the relationship between pressure, volume and temperature in gases using gas thermometry.

Define your temperature scale
Your first mission in the Ideal Gas Law simulation will be to define a unique temperature scale. In order to complete this task, you will assign the correct temperature to various reference points. You will discover at which temperature water freezes and nitrogen boils. At the end of this mission, you will be able to calculate a new value of the Boltzmann's constant.

Formulate the Ideal Gas Law
Imagine how easy it would be to understand the behavior of an ideal gas if the gas molecules were so big that they could be seen with the naked eye. Well, in this simulation they can! The gas molecules are magnified, so you can see what is otherwise invisible. Your next mission is to define the relationship between the pressure, temperature and volume of an ideal gas sealed in a glass jar.

Experiment with gas thermometry
Handling extreme temperatures is not a hazard as long as you're a part of this simulation! Observe the changes in the pressure of an ideal gas as you cool it down from the temperature of boiling water to the temperature of boiling nitrogen. You will have complete freedom to repeat the experiment with any amount of gas and to define the absolute zero temperature.

Are you ready to apply the Ideal Gas Law and everything you learned in gas thermometry in order to assist the transfer of an organ for a transplant surgery?

Learning Objectives

At the end of this simulation, you will be able to...

- Explain the physical concepts of temperature and absolute zero
- Define the relationship between pressure, volume and temperature in gases using gas thermometry
- Apply the Ideal Gas Law

Techniques in Lab

- Gas thermometry

Theory

Phase transitions
Phase transitions play an important role in the study of Thermodynamics. The evaporation of a fluid or the melting of a solid, are examples of phase transitions. The phase of a given substance depends on the pressure and temperature. As an example of this water will boil at a lower temperature on the top of Everest than at sea level as there due to the differences in altitude there is a large pressure difference.

At ambient pressure and temperature, one would assume that the water in a glass would be in a liquid form. If we keep increasing the temperature of the water eventually it will boil, this is when the water will transition from the liquid phase to the gas phase. If you transfer the glass of water to the North Pole, most likely the water will transition from the liquid phase to solid phase as it freezes.

The kinetic theory of gases
Gases, liquids or solid phases are composed of an extremely large number of microscopic particles each possessing a certain amount of kinetic energy. This kinetic energy is divided among the particles that comprise the substance.

When referring to a gas, the molecules use this energy in order to move or to rotate. Even though the velocity, rotation or vibration of a single molecule can be measured, it is impossible in practice to directly measure the total kinetic energies of all the particles which make up some macroscopic material like the total amount of gas in a tank.

That's why temperature is typically used to measure or define the average microscopic kinetic energy of the particles in some material.

In ideal gases, the Ideal Gas Law describes the relationship between the pressure and temperature of a gas.

Boltzmann constant

The Boltzmann constant, k_R, is a physical constant that relates the average kinetic energy of particles in a gas with the temperature of the gas. The constant is commonly used in the Ideal Gas Law.

If the temperature is measured in Kelvin and the energy in Joules the constant gets the following value in SI units:

$k_R = 1.38 \times 10^{-23}$ J/K.

The value of the constant has to be adjusted to the temperature scale selected.

Thermometers

A very precise way to measure the temperature of an object would be by summing the kinetic energy of its constituent particles. Unfortunately, this method is not feasible in the real world as even tiny objects contain billions of particles. Therefore, to obtain a quantitative measurement of temperature we always measure temperature through some other proxy.

This can, for example, be the expansion of the length of a column of mercury in a glass capillary, the bending of a bimetallic strip or a change in the electrical resistivity of a material or some other physical change. An instrument that measures the temperature of a material by measuring some other physical change is called a thermometer and since the measurement is dependent on some physical change, each type of thermometer is limited to functioning over a limited temperature range.

Temperature scale

Thermometers measure temperature according to well-defined scales of measurement. The three most common temperature scales are Fahrenheit, Celsius, and Kelvin. Temperature scales are created by identifying at least two reproducible temperatures. The freezing and boiling temperatures of water at standard atmospheric pressure are commonly used as reference points to these scales.

The table below shows the most common temperature reference points at all three scales:

Reference point	Kelvin (K)	Celcius (°C)	Fahrenheit (°F)
Boiling water	373.15	100	212
Ice water	273.15	0	32
Boiling nitrogen	77	−195.79	-320

And the equations below show how to convert from one temperature scale to another:

T (in °C) + 273.15 = T (in K)

T (in °F) = T(in °C) × 9/5 + 32

Absolute zero

Experiments have confirmed the existence of the lowest possible temperature, or the minimum allowed by quantum mechanics. This temperature is called absolute zero. At this point, the average kinetic energy of molecules is zero.

Ideal Gases

It is known experimentally that for gases at low density (such that their molecules occupy a negligible fraction of the total volume) and at temperatures well above the boiling point, pressure is proportional to temperature.

This proportionality is the basis of the constant-volume gas thermometer. When temperature is held constant, either pressure or volume is proportional to the number of molecules.

When the proportionalities are combined into a single equation, the constant of proportionality is independent of the composition of the gas. The resulting equation for all gases applies in the limit of low density and high temperature. A gas at that limit is called an Ideal Gas; it obeys the Ideal Gas Law, which is also called the equation of state of an Ideal Gas.

Ideal Gas Law

The Ideal Gas Law describes the behavior of a real gas with a density low enough or temperature high enough that it is far from liquefaction. The Ideal Gas Law can be expressed for Ideal Gases as follows:

$pV = Nk_RT$

where p is the absolute pressure of a gas,

V is the volume it occupies,

N is the number of molecules in the gas,

T is its absolute temperature,

and k_R is the Boltzmann constant.

Gas Thermometry

The purpose of the Gas Thermometry experiment is to construct a temperature scale and determine the absolute zero temperature. This experiment demonstrates the temperature dependency of the pressure of a constant gas volume. In addition, the absolute temperature scale is determined by extrapolation towards low temperatures. The temperature readings given by a gas thermometer are nearly independent of the substance used in the thermometer. Generally, gases used in gas thermometry are Ideal Gases.

The apparatus consists of a table with three reservoirs beneath. The left reservoir contains boiling water and is connected to a variac that controls the power. The middle reservoir contains a polypropylene cylinder placed into a large Styrofoam block for insulation and contains a near equilibrium mixture of ice and water. The right reservoir is also a polypropylene tube in a Styrofoam block but this tube contains liquid nitrogen. Each of these reservoirs acts as a stable temperature reference and are accessible through a flange covering a hole in the table.

The main piece of the apparatus is a *dipper* which consists of a steel gas vessel attached to valves and tubing and mounted to a Lexan sheet (to prevent splashing/steam/vapor and to protect the manometer), a digital manometer and a handle. The dipper is designed to fit into each reservoir and rest on the flange on the lexan sheet.

The manometer has a digital readout screen. It is suggested you use Torr or mmHg as your unit of measurement, but it is not necessary if you make the appropriate conversions. Note that like most pressure gauges, the manometer reads in gauge pressure. This means pressure relative to the outside atmosphere.

Gas thermometry safety rules

Before starting the experiment, there are some key safety issues to aware of:

- Safety glasses must be worn at all times.
- Move the “dipper” from each reservoir slowly since the temperature changes involved in this lab are extremely large. The dipper is fragile.
- Wear gloves while handling cold and hot items, and do not handle any hot or cryogenic items directly.
- The power to the hot plates which boil water is controlled by a variac. Do not exceed 120V on the variac.
- If you or your partner are uncomfortable moving the cylinder/container from each of the reservoirs, ask the teaching assistant or the technician for help.
- Liquid nitrogen is extremely cold. Handle liquid nitrogen with respect.