Chapter 1

Thermal Physics: Thermal Expansion & the Heat Engine

Most materials expand when heated (Can you think of one that doesn't?). A typical metal expands by less than 1% even when heated by hundreds of degrees. This small change, however, has to be taken into account when designing instruments or structures exposed to large temperature changes. Quantitative study of thermal expansion became possible only after scientists were able to measure temperature. Today a variety of thermometers are available and we use them on many occasions in everyday life.

Heat engines were at the heart of the Industrial Revolution and they continue to play a very important role. The theoretical foundation of the operation of the heat engine was laid down by Nicholas Carnot in 1824. A heat engine can be defined as a cyclic device that converts thermal energy into work. It operates as long as we provide energy (fuel) to the engine. Various thermodynamic processes are involved in each cycle. Volume, pressure and temperature of the gas change in these processes.

Objective

1. To study thermal expansion of different metals.

2. To study the thermodynamic processes involved in the operation of a heat engine

Apparatus Thermal expansion apparatus, digital multi-meter, Vernier temperature probe, steam generator, cylinder/piston system, air chamber, hot plate, beakers, weights, LabQuest Mini interface

1.1 Thermal Expansion

1.1.1 Introduction

We will limit our consideration of the thermal expansion to long tubes made of metals. For such tubes the change in length (ΔL) varies linearly with the change in temperature (ΔT) it experiences; that is, ΔL is proportional to ΔT. For the same change of temperature, a long tube will change its length more than a short one. Thus, we expect that ΔL is also proportional to L, where L is the original length of the tube. The two proportionalities can be made into an equation by introducing a constant of proportionality, in this case called α, so we have $\Delta L = \alpha L \Delta T$. The constant, α, is called the temperature coefficient of linear expansion and ΔT here can be in either degrees Celsius or Kelvins, since the change in temperature is numerically the same for both.

From a microscopic point of view, thermal expansion is explained in the following way. Heating the material causes its atoms to vibrate with greater amplitudes. As thermal energy is added to the material, the equilibrium positions of the rapidly oscillating atoms separate and the solid gradually expands. The weaker the inter-atomic cohesive forces, the greater are the displacements from their equilibrium separations.

Nearly all materials have positive values of the temperature coefficient of linear expansion α. A few important materials are listed in the table below.

Material	Coefficient $\alpha(K^{-1})$
Aluminum	23.4×10^{-6}
Brass	18.9×10^{-6}
Copper	16.6×10^{-6}
Lead	29.0×10^{-6}
Steel (structural)	12.0×10^{-6}
Concrete	12.0×10^{-6}
Water	69.0×10^{-6}
Glass (pyrex)	3.2×10^{-6}

Note that the values in the table above are for *linear expansion*. Generally, the *volume* will expand at a rate of 3 times the linear rate.

Some ceramics have values of temperature coefficient of linear expansion α near zero or even negative.

1.1.2 Prelab exercise 1

1. The roadway of the Golden Gate Bridge is 1320 m long and it is supported by a steel structure. If the temperature varies from -30 °C to 39 °C, how much does the length change? The result indicates the size of the thermal expansion joints (shown below) that must be built into the structure. Without the joints the surfaces would buckle on very hot days or crack due to contraction on very cold days.
2. Give at least two additional examples where the thermal expansion must be taken into account when designing structures or devices.

Figure 1.1: Thermal expansion joints in a roadway.

1.1.3 Experimental

The thermal expansion apparatus is shown below. It consists of a base with built-in dial gauge and a thermistor, which is a small piece of semiconductor material.

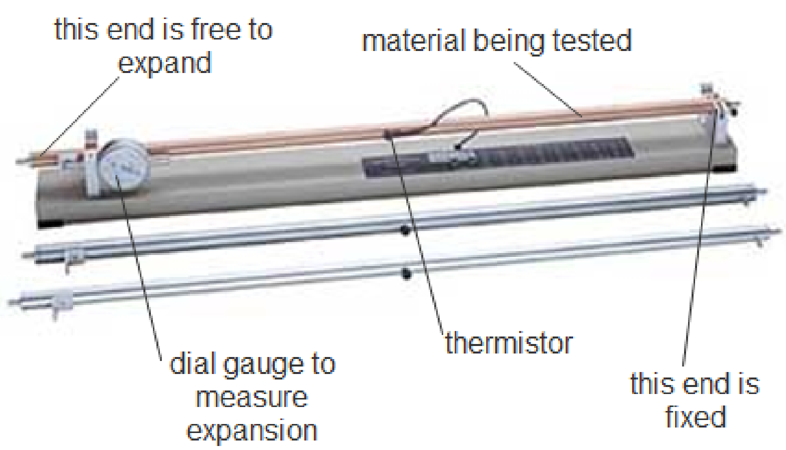


Figure 1.2: Thermal expansion apparatus.

The resistance of the thermistor varies strongly with temperature. The resistance can be measured with a digital ohmmeter and converted to a temperature using the conversion table affixed to the base of the apparatus. Hot steam can be fed directly through the tube to increase the temperature of the tube.

1.1.4 Measurements and Calculations

1. Measure the length of the tube L from the steel pin to the inner edge of the angle bracket, as shown below.

2. Mount the tube in the base. The steel pin on the tube fits into the slot on the slotted mounting block and the bracket on the tube presses against the spring arm of the dial gauge. Drive the thumbscrew against the pin until the tube can no longer be moved.

3. Attach the themistor lug to the threaded hole in the middle of the tube (the themistor is embedded in the thermistor lug). Align the lug with the tube to maximize the contact between the lug and the tube. Place the foam insulator over the thermistor lug.

4. Turn on the digital gauge and zero the scale. Ensure the scale is in units of mm.

5. Plug the leads of the digital ohmmeter into the banana connectors in the center of the base. Measure the resistance of the thermistor at room temperature R_{RT} and convert it to temperature T_{RT}.

6. Carefully attach the flexible tubing of the steam generator to the end of the metal tube. (Use the heat-resistant gloves provided incase the tubing is hot.) Raise the end of the base at which the steam enters the tube. This will allow any water that condenses in the tube to drain out. Place a container under the other end of the tube to catch the draining water.

7. Ensure there is about 150 mL of water in the flask, plug in the hot plate and turn on the hot plate (set the temperature knob to 3/4). This is the steam generator for the heat engine.

8. Monitor the gauge and ohmmeter. When the thermistor resistance and gauge stabilize, record the resistance R_{hot} and convert it to temperature T_{hot}. Include an error for your T_{hot} measurement. Record the expansion of the tube $\Delta L \pm \delta\Delta L$ displayed on the digital gauge.

9. **TURN OFF HOT PLATE AND UNPLUG.**

10. Using the equation $\Delta L = \alpha L \Delta T$, calculate α, its uncertainty and the percentage difference.

1.1.5 Questions

1. Discuss possible sources of uncertainty in the experiment. How might you improve the accuracy of the experiment?

2. Small gaps are left between railroad tracks sections. Explain why. Estimate a reasonable size of the gap.

1.2 The Heat Engine

1.2.1 Introduction

The operation of the heat engine involves three thermodynamic process characterized by the volume of gas V, the pressure p and the temperature T can change. For an ideal gas (the air can be approximately treated as one), V, p and T, were found to be inter-related. In 1662 Robert Boyle discovered that keeping the temperature constant, the volume of a gas varies inversely with pressure: that is, $pV = b$, where b is a constant. In approximately 1787 Jacques Alexandre Cesar Charles of Paris, France, discovered that for constant pressure, all gases increase in volume when the temperature increases: i.e., $V = cT$, where c is a constant. Finally, in 1802, Joseph Loius Gay-Lussac observed that when the volume is kept constant, the absolute pressure of a given amount of any gas varies with temperature: i.e., $p = aT$, where a is a constant.

The three laws described above are specific cases of the Ideal Gas Law.

$$pV = nRT$$

where n is the number of moles and R, the Universal Gas Constant, is equal to 8.31 J/mol °K

A thermodynamic process occurs when a system (air in our experiment) changes from one state (one set of p, V and T) to another state (a different set of p, V and T). The system can be changed in a variety of ways. Four basic processes are: isothermal (T constant), isobaric (p constant), isochoric (V constant) and adiabatic (no heat is transferred from or to the system; processes which occur suddenly tend to be adiabatic because heat takes a fair amount of time to flow). The thermodynamic processes involving vapours and gases are particularly important, for example, in the operation of engines: steam, automobile, jet, etc..

The work done by a heat engine can be evaluated in a particularly simple way for the situation when the system (cylinder of gas) expands against an external pressure – thus changing its volume and doing work. Let's assume that a piston of cross-sectional area A is frictionless and weightless. The downward force F (for example, weight mg of a mass m put on top of the piston) is exactly opposed by an upward force produced by the gas: $F = pA$. If the gas is heated, as shown below, the volume increases but the pressure remains the same (isobaric process).

If the displacement of the piston is ΔL, the work done on the surrounding (the atmosphere) by the expanding gas is

$$W = F\Delta L = pA\Delta L = p\Delta V$$

where $\Delta V = A\Delta L$ is the change in volume.

When the gas expands, ΔV is positive and the work W is positive. When the gas contracts, ΔV and W are both negative.

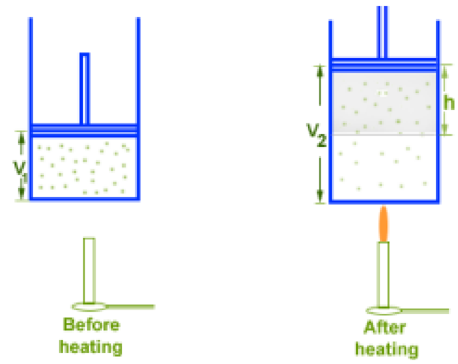


Figure 1.3: An example of an isobaric process.

The pressure versus volume (or pV) diagram for an isobaric expansion is shown below.

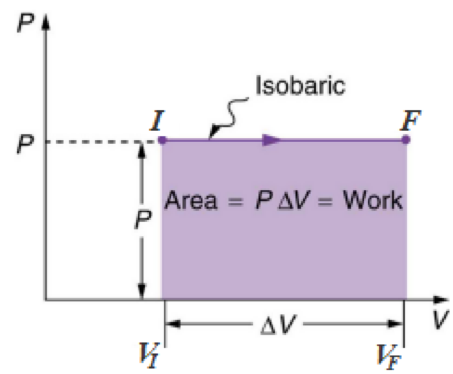


Figure 1.4: Pressure vs Volume plot for an isobaric expansion.

From an initial state "I", the system was transformed at a constant pressure to a different final state "F". Notice that the work done, $p\Delta V$, is the area under the curve. If the pressure varies as the volume changes, the area under the pV curve will still correspond to the work done.

Real engines use so called cyclic thermodynamic processes. After several processes the system returns to the original state and then the process is repeated over and over again. The cyclic process corresponds to a closed figure on the pV diagram. The heat engine transforms the substance (air) through a cycle in which heat is absorbed from a source at high temperature, then work is done by the engine and finally heat is expelled by the engine to a source at lower temperature.

An important characteristic of a heat engine is its efficiency e defined in the following way.

$$e = W/Q$$

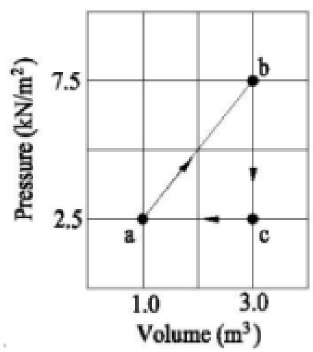
where W is the work done by the engine and Q is the heat delivered to the engine (the ratio of what we get out to what we put in). In practice, heat engines convert only a fraction of the absorbed heat into work (e = 20 - 40%). It can be shown that the maximum efficiency of a heat engine can be expressed in terms of temperatures.

$$e_{\text{max}} = \frac{T_H - T_L}{T_H}$$

where T_H is the temperature of the hot reservoir and T_L is the temperature of low temperature reservoir (all temperatures are in °K). This expression is independent of the engine's working fluid and hence applies for everything from an airplane jet engine to a steam engine.

1.2.2 Prelab Exercise 2

A sample of an ideal gas is taken through the cyclic process $a - b - c - a$, as shown below. The temperature of the gas at point a T_a = 298 °K.



- How many moles of gas are in the sample?
- What is the temperature of the gas at point b?
- What is the work done by the gas during the complete cycle?
- How much heat was added to the gas during the cycle?

1.2.3 Experimental

A cylinder/piston system used in this experiment is shown in Figure 1.5. The graphite piston is nearly frictionless and the leakage of air around it is negligible. Air from the air chamber (the metal can) flows through flexible tubing and a valve to the cylinder. The pressure of gas can be changed by placing a mass on the platform on the top of the piston. The temperature of the gas is changed by submerging the air chamber in a beaker containing hot or cold water.

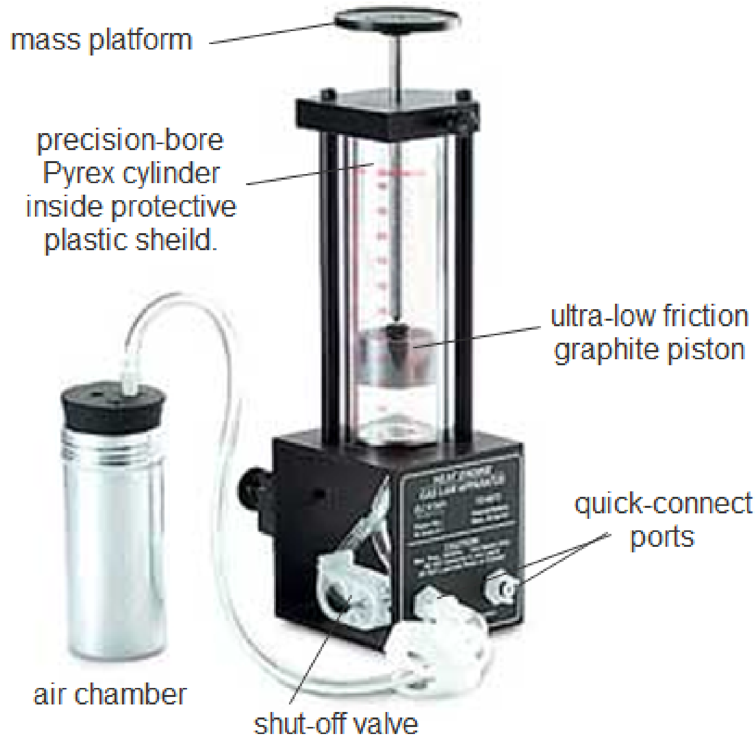


Figure 1.5: Heat Engine Apparatus.

1.2.4 Measurements and Calculations

Experiment 1

This activity is related to the operation of a **heat engine**. The closed cycle will be formed by four thermodynamic processes: two isobaric and two isothermic. The area of the closed loop on the pV graph is equal to work done by the engine.

1. Raise the piston approximately 50 mm and then connect the flexible tubing to a shut off valve (the other valve is in the shut off position as it is not needed). The engine cycle is much easier to describe if you begin with the piston resting above the bottom of the cylinder.

2. Prepare two beakers; One with ice cold water and one with hot water. (The electric kettle will be used for hot water.)

3. The sequence of operations to follow to complete one engine cycle is illustrated below. These operations, described in words below, *should be completed very quickly to avoid air leakage around the piston.* **After each operation, record the position of the piston.**

   (a) Put the air chamber into the cold water.

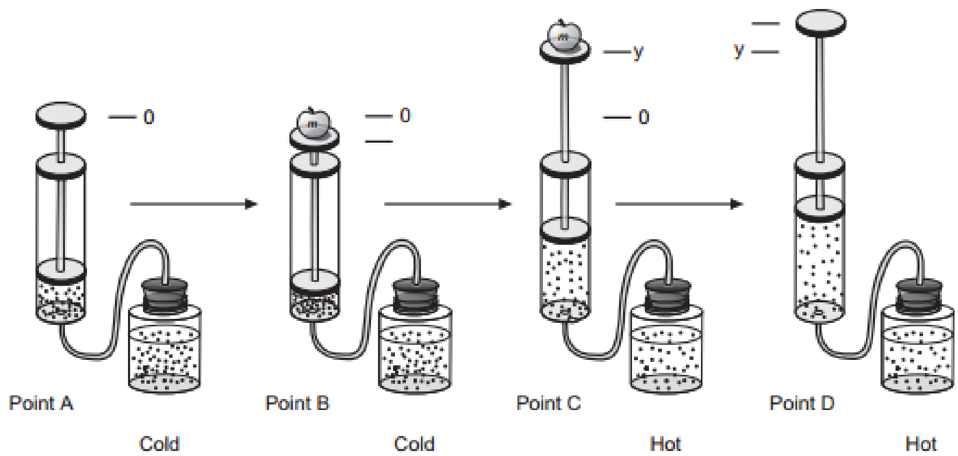


Figure 1.6: A simplified diagram of the mass lifter heat engine at different stages of its cycle.

(b) Add mass $M = 200$ g to the platform (on top of the piston).

(c) Place the air chamber in the hot water. The piston should move upward. **This is the engine power stroke**. The engine did work equal to the increase of potential energy $U = (m + M)gh$, where h is the distance moved by the piston.

(d) Remove the mass M from the platform and record the new position of the piston. The pressure is now smaller and the piston probably moved higher.

4. Now place the air chamber back in the cold water. The piston should return to the original position (the cycle is completed).

5. Measure the temperature of the hot and cold water using the Vernier temperatur probe.

   For each of the steps (a –d), calculate volume $V = \pi r^2 h$, where $r = d/2$ (diameter of the piston $d = 0.0325$ m) and h is the position of the piston and pressure $p = (m + M)g/A$, m is the mass of the piston (m= 0.035 kg), M is the additional mass on the platform and $A = \pi r^2$ is the cross-sectional area of the piston.

   Your four points on the pV graph should look as shown below.

   Connect the points by straight lines. The area enclosed is then approximately a parallelogram. The thermodynamic process a-b and c-d are isothermal (performed at constant temperature), while processes b-c and d-a are isobaric (at constant pressure due to constant mass M on the platform). By connecting the four points by straight lines we are making an approximation (for small changes of V and p this approximation is quite acceptable).

6. Calculate the thermodynamic work done by the engine. It is equal to the area of the parallelogram. In order to obtain work in joules (J) the units of pressure p should be

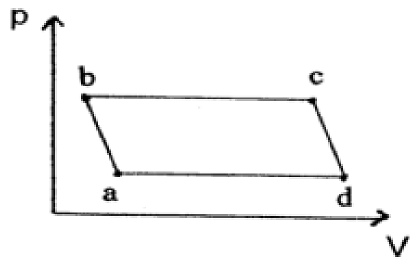


Figure 1.7: Expected pV graph.

in Pa (N/m^2) and volume V in m^3. How does this work compare to the increase of the potential energy $U = Mgh$?

7. Determine the efficiency of your heat engine. It depends only on the temperature of the hot and cold water reservoirs.

Experiment 2

In this next lab activity, you will observe a particular application of the process you were just investigating.

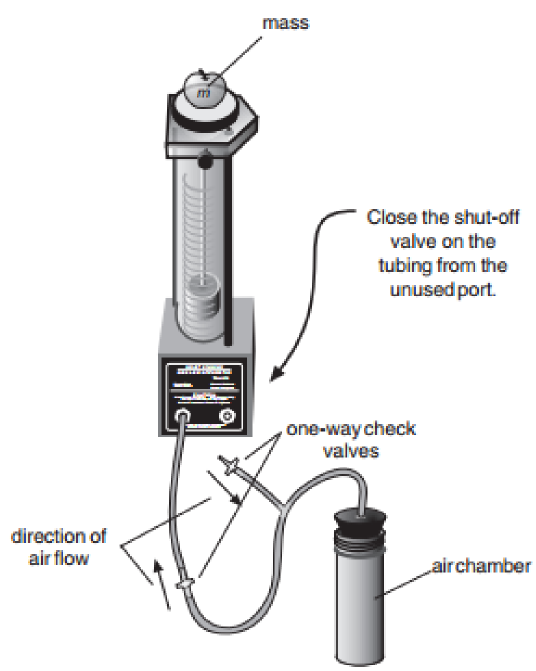


Figure 1.8: Experiment 2 apparatus.

1. Connect the heat engine to the air chamber as shown in figure 1.8. Note the two

one-way valves inserted in the tubing. Observe that one of the two one-way valves allows air to flow from the air chamber to the cylinder, while the other one-way valve prevents air from leaving through the branched tubing.

2. Move the air chamber from cold water to hot water a few times. Describe what happens with the piston and the flow or air through both one-way valves. Explain your observations!

1.2.5 Questions

1. Several factors contributed to the uncertainty in your heat engine measurements. List these factors and discuss their importance.

END OF LAB

Was this lab useful, instructive, and did it work well? If not, send an email to thatlabsucked@gmail.com and tell us your issues. In the subject line, be sure to reference the your course, the experiment, and session. example subject: *PHYS1010 Linear Motion monday 2:30.* We won't promise a response, but we will promise to read and consider all feedback.

Table 1.1: Linear Thermal expansion of a metal tube.

Tube 1 Material:		
Original Length: $L_1 \pm \delta L_1 =$		
Condition	**Thermistor Resistance $\pm$ uncertainty (units)**	**Temperature $\pm$ uncertainty (units)**
Room Temperature	$R_{RT,1} =$	$T_{RT,1} =$
Hot	$R_{H,1} =$	$T_{H,1} =$
–	–	$\Delta T = T_{H,1} - T_{RT,1} =$
Expansion: $\Delta L_1 \pm \delta(\Delta L_1)$		
$\alpha_1 = \frac{\Delta L_1}{L_1(T_{H,1} - T_{RT,1})}$		
Uncertainty: $\frac{\delta \alpha_1}{\alpha_1} = \frac{\delta L_1}{L_1} + \frac{\delta(\Delta L_1)}{\Delta L_1} + \frac{(\delta(\Delta T))}{\Delta T}$		
Percentage Difference of $\alpha_1 =$		

Table 1.2: Parameters of a heat engine during a complete cycle.

Step	**Condition**	**Temperature of water ± uncertainty**	**Height of piston ± uncertainty**	**Volume** $V_i = A_{piston} \times H_i$	**Pressure** $P = F/A$
Initial	Room temperature	$T_0 =$	$H_0 =$	–	–
(a)	Cold water	$T_1 =$	$H_1 =$	$V_1 =$	$P_1 = \frac{mg}{A_{piston}} =$
(b)	Cold water + 200g	$T_2 =$	$H_2 =$	$V_2 =$	$P_2 = \frac{(m+M)g}{A_{piston}} =$
(c)	Hot water + 200g	$T_3 =$	$H_3 =$	$V_3 =$	$P_3 = \frac{(m+M)g}{A_{piston}} =$
(d)	Hot water remove 200g	$T_4 =$	$H_4 =$	$V_4 =$	$P_4 = \frac{mg}{A_{piston}} =$
(a)	Cold Water	$T_5 =$	$H_5 =$	$V_5 =$	$P_5 = \frac{mg}{A_{piston}} =$

- The area of the piston $A_{piston} = \pi(d/2)^2$ where the diameter d of the piston is 0.0325 m.
- The mass of the piston m is 0.035 kg.
- The acceleration due to gravity g is $9.81 m/s^2$