Physics 157 Homework 6: due Wed, Oct 31st by 5pm

In this homework set, you'll get more practice analyzing thermodynamic processes, with a focus on calculating the efficiency of heat engines. In addition to the goals from last week, we want you to be able:

- To calculate the net work done in a cyclic process
- To identify which in which parts of a cyclic thermodynamic process heat is flowing in to the system, and in which parts heat is flowing out.
- To calculate the efficiency of a heat engine, given a description of the thermodynamics processes associated with it, or a depiction of the cycle on a PV-diagram

A summary of the formulae you may need:

Ideal gas law: $PV = nRT$ or $P_1 V_1 / T_1 = P_2 V_2 / T_2$ if n is constant.

Work: $W = P \Delta V$ (constant pressure) or area under curve on P-V diagram. Positive for expansion, negative for compression.

Internal energy: $\Delta U = n C_v \Delta T$

Heat: $Q = \Delta U + W$ (First Law of Thermodynamics)

Constant volume: T/P is constant, $W = 0$ so $Q = \Delta U$

Constant pressure: T/V is constant, $W = P \Delta V$, $Q = n C_p \Delta T$ where $C_p = C_v + R$

Constant temperature: PV is constant, $\Delta U = 0$, so $Q = W$. $W = n R T \ln(V_f/V_i)$,

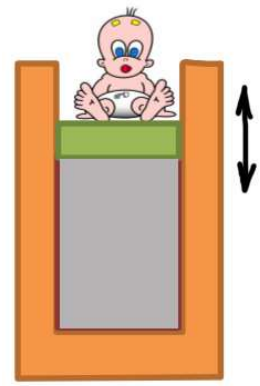
Adiabatic: $Q = 0$, $P V^{\gamma}$ = constant, $T V^{\gamma-1}$ = constant where $\gamma = C_p/C_V$, $W = -\Delta U$

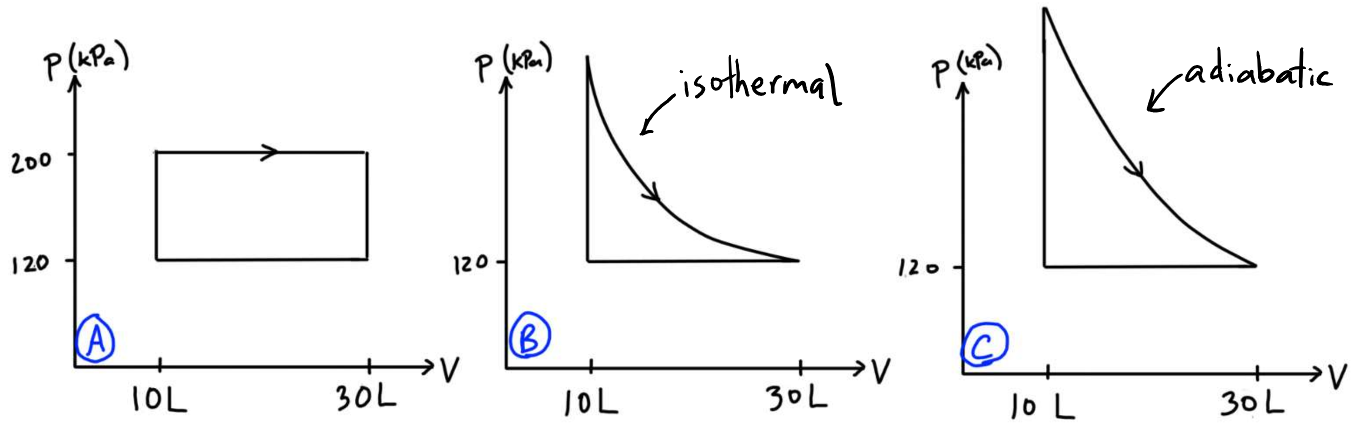
Efficiency of an engine: $e = W_{net} / Q_{in}$ where Q_{in} is the sum of all positive contributions to Q

Part 1: Do the mastering physics assignment

Part 2: Do the written question on the next page and hand it in in the homework box.

Written Question: You have just taken up a job in the R&D office of Fuel-n-Fun, a company that specializes in fossil-fuel based children's products. Your first assignment is to evaluate three proposals for the design of a gasoline powered device to entertain babies. Each design is based around air (use $C_V = 5/2R$) in a cylinder with a piston that moves up and down in response to heating/cooling. All added heat for the various processes comes from burning gasoline (35MJ/L). The thermodynamic cycles associated with the three designs (for a fixed baby-weight) can be modeled by the following PV diagrams, where in all cases, the temperature at the bottom-left corner of the cycle is 300K.





Psychologists have determined the happiness of a baby on such a device is directly proportional to the net work performed on them per time (up to a limit), regardless of the design. If we want to produce a certain amount of net work by burning the least amount of fuel, which is the most efficient design, and what is its efficiency? For this design, how much gasoline do we have to burn per hour if we want the baby to move up and down 10 times per minute?

See next page for old midterm problems (not to be handed in). You can ignore the parts about entropy for now.

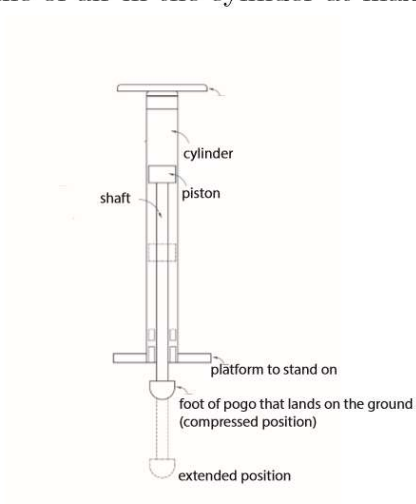
1. The photograph below shows a person jumping on a pneumatic pogo stick. In case you have not seen one before, a person on a pogo stick bounces up and down as the stick absorbs the energy and releases it again like a spring. Many pogo sticks do use springs, but in this problem the "bounce" comes from compression of a cylinder of gas as the person hits the minimum height of their bounce. The cross section of a pneumatic pogo stick is shown on the right: the cylinder of gas, with a piston that is connected by a shaft to the foot of the pogo that hits the ground.

When a pogo stick is up in the air, the cylinder is expanded to its maximum volume of V_i = 1.3 l, the pressure in the cylinder is p_i =200 kPa, and the temperature T_i is 20°C. At the top of a jump, the center of gravity of the person and pogo stick together (mass 60 kg) are h_1= 2.1 m above the ground. At the lowest point, the air in the cylinder of the pogo stick is maximally compressed and the center of gravity is h_2=1.2m above the ground.

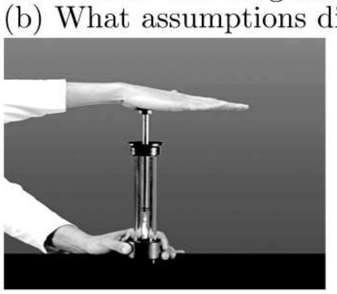
a) How many moles of gas are there in the cylinder?

b) What is the temperature inside the cylinder at maximal compression?

c) What is the volume of air in the cylinder at maximal compression?

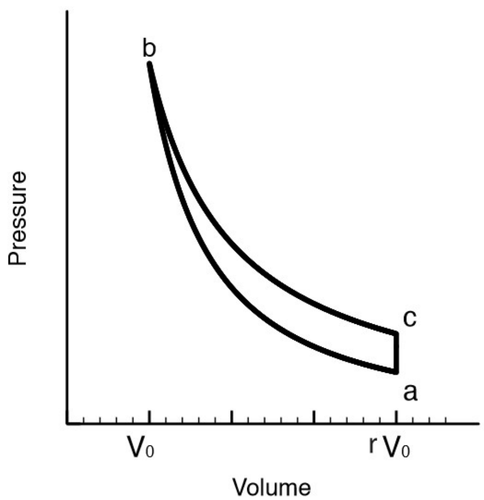


1. In class, you saw the experiment of burning some paper by compressing air in a glass cylinder. Instead on pushing on the piston as in class (left-hand figure), we rotate the cylinder by 180° (upside down) and drop it on the floor so that the piston strikes the floor (right-hand figure).
(a) From what minimum height we have to drop it to burn the paper? The apparatus weights 0.35 kg; the inside diameter of glass tube is 0.797 cm; the paper will ignite at 240°C; the initial position of the piston is 18.308 cm above the bottom of the tube. Ignore the friction and drag forces.
(b) What assumptions did you make? Write a brief sentence justifying each assumption.



3. A new heat engine cycle can be described by an adiabatic compression ($a \to b$), an isothermal expansion ($b \to c$), and an isochoric cooling process ($c \to a$), as shown in the graph. The compression ratio is r. For a diatomic ideal gas: $c_V = \frac{5}{2}R$, $c_P = \frac{7}{2}R$, $\gamma = 1.4$ Assume the processes are reversible.

(a) Write down the expression for the heat transferred during each process.
(b) Find an expression for the efficiency of this cycle in terms of only the compression ratio, assuming the process is running with a diatomic ideal gas.
(c) If point a is at room temperature (300K) and atmospheric pressure (100kPa), and the compression ratio is 4, what is the efficiency for this heat engine? How does this compare to the Carnot efficiency running between the same two temperatures?
(d) What is the entropy change for each process if V_0 is 1L (0.001m^3), and as above, point a is at room temperature (300K) and atmospheric pressure (100kPa)?



Problem 2. You have been asked to design a combustion chamber based on adiabatic compression of a gas for graphitizing polymers to produce high tensile strength carbon fibre. For the particular process you are using you need to heat the polymer in air (mixture of mostly N_2 and O_2 gas) to a temperature of $1700°C$. The adiabatic compression chamber you are using to test the concept has an air inlet which opens to exchange the gas in the cylinder with the atmosphere ($20°C$ and 101kPa) when the piston is at the top of the cylinder where it has a volume of 0.500L (1L=$0.001m^3$).

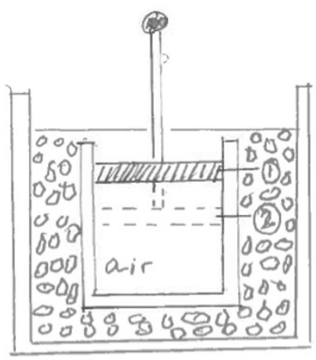
(a) What compression ratio is needed to reach the necessary temperature for this process?

(b) Calculate the total work done *on the gas* in compressing it to reach the necessary temperature.

(c) Normally, the process is done by heating the polymer in air in a furnace. How much energy is required to reach the same temperature by heating at constant pressure assuming the same starting conditions and how does this compare with the adiabatic compression method described above?

(d) Since you want to scale up this process for industrial production, how does the energy required change with the volume of gas? Which process is better for large volumes or does it matter?

2. A cylinder containing 0.5kg of air and a moveable piston is submerged in an ice-water bath (shown in the sketch below). The air in the cylinder is initially in equilibrium with the bath temperature. The piston is very quickly (adiabatically) pushed down from position 1 to position 2 compressing the air to 2/3 of its original volume. The piston is held at position 2 until the air is again in equilibrium with the bath temperature. Finally, the piston is very slowly raised back to position 1.
(a) Draw approximate p-V and T-S diagrams for the cycle indicating those parts of the cycle in which heat flows into or out of the air cylinder.
(b) On the basis of either of your diagrams, explain whether the amount of ice in the ice-water mixture is increased or decreased over a complete cycle.
(c) Calculate the per cycle change in the mass of ice in the mixture.
Useful information: molar mass of air: 28.97g/mol, latent heat of fusion of ice is: 334 kJ/kg



Problem 1. A truck, driven in the winter, when the temperature was -5°C, hit the curb with its right front tire, which suddenly decreased the volume of this tire by 20%.

a) What was the temperature of the air in the tire immediately after the hit?
b) What was the pressure at this moment, if the initial pressure in the tire was 3 atmospheres?

The same truck was outside for few days in the same temperature and its loading area was slowly filling with snow. The weight of snow deformed the tire so its volume was reduced by 20%.

c) What was the resulting pressure in the tire?