GEOS 24705 / ENST 24705
Problem set #4
Due: Tues Apr. 13

Problem 1: Making steam / latent heat

This problem asks you to consider how large the latent heat of vaporization is relative to some other energy densities you have encountered in this class.

The latent heat of vaporization, as you remember, is the "extra" heat you need to add to liquid water to get its molecules to switch from the liquid phase to the gas phase. When you boil water to make steam, you have to not only heat up the water so that its temperature rises the boiling point, but you also have to add additional heat to get the molecules of water to leave the liquid phase and enter the gas phase. (See the handout on steam for much more detail).

As a side note, the latent heat of vaporization is also the reason why you evolved the ability to sweat. On hot days, your body produces liquid water in the form of sweat; as that water evaporates it takes up heat to drive the evaporation, leaving you cooler.

What happens to that latent heat if the water vapor re-condenses? We know from the First Law of Thermodynamics that energy is conserved, so if you condense water again, you have to somehow get that latent heat back again. How? When water vapor condenses, it dumps its latent heat out again and raises the temperature of its surroundings.

Latent heat is then a kind of energy density – it is an additional store of energy that water vapor "carries" with it. It is given in units of J/kg or J/m3.

A. We estimated the value of L_v n the first lecture (from thinking about a microwave). Give that value, in J/kg (which for water is the same as J/liter)

B. Just by intuition alone for now (i.e. make a guess), if you burned a kg of gasoline (about a liter) could you use that heat to evaporate a liter of water? Would you have not enough, just enough, or extra? (This won't be graded, it's just for fun).

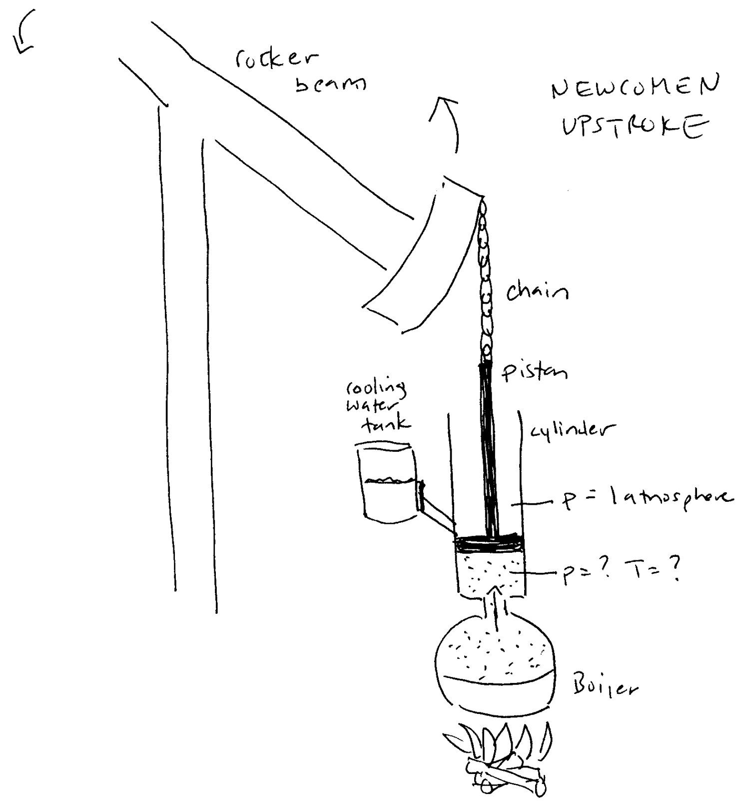
C. Make a guess (don't even bother estimating, just give a gut feel) of how much gasoline you'd need to burn to make heat to evaporate that water. (Again, this is just for fun, no grading of your guess).

D. Now consider the energy density of gasoline (which you looked up in PS2), and actually compute how much gasoline you would need to evaporate that liter of water.

E. Explain how this relates to the fact that burning yourself on steam in the kitchen is really painful.

Problem 2: The Newcomen Engine

Upstroke



In the first part of the Newcomen engine cycle, its cylinder is filled with pure steam (think: no air, or at least minimal air - just water molecules).

We mentioned in class that the Newcomen engine doesn't run at very high pressure - the pressure in the cylinder is about the same as the in the surrounding atmosphere.

A. *What temperature is the steam at?*

(We'll call this T_{steam} in the problem)

You might get the bright idea that you could inject pressurized steam into the cylinder to push the piston up.

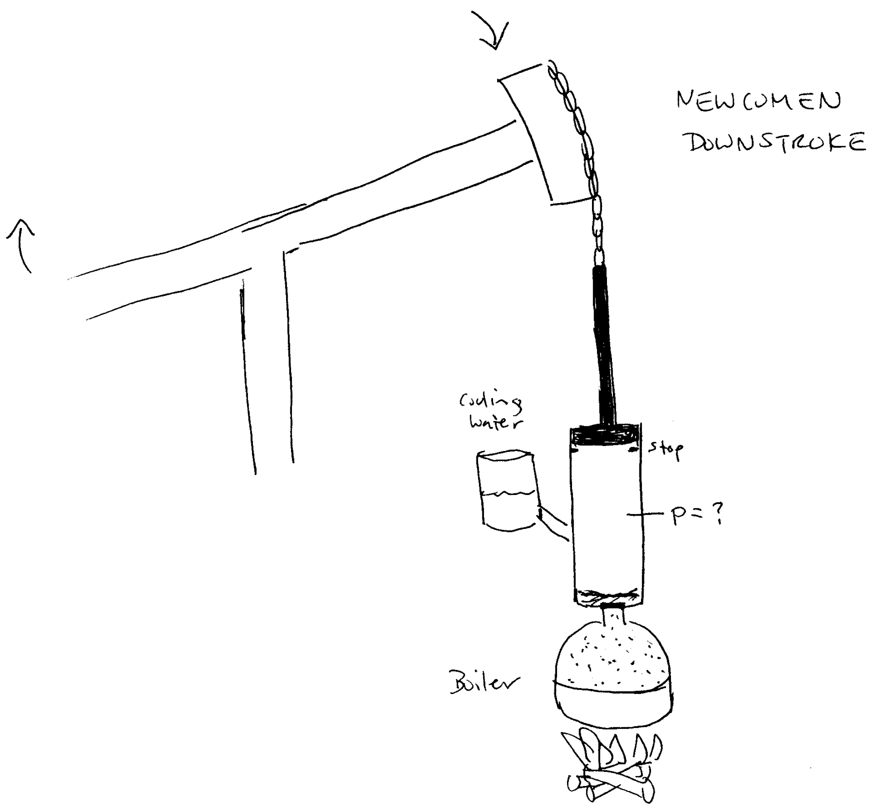
B. *If you do this, will the piston in turn push on the rocker beam? Can you transfer force to the rocker bar by pushing on the piston? Explain*

If the piston can't push on the rocker beam, the engine can do no work on the upstroke. So we'll have to hope it can do some work on the downstroke or the engine would be useless.

For the questions below, you'll need some size for the engine. I guessed from the drawings that the cylinder might be 1 m long and it looked like the diameter of the cylinder was 1/3 the length. Those are fine numbers to use

Downstroke

In the second part of the Newcomen engine cycle, cooling water is injected into the cylinder, quickly condensing the steam.



Imagine that you insert a “stop" in the cylinder at the top of the piston stroke and keep the piston from moving. Then you squirt in the cooling water and condense the steam.

- *C. Is there force on the piston now? Draw an arrow showing the direction of this force.*
- *D. What is the pressure inside the cylinder? (Assume the mechanic who made it did a good job.)*
- *E. What is the pressure differential that the cylinder has to support? (The difference between outside pressure and inside pressure).*
- *F. What is the force pressing on the piston?*
- *G. If you now let the piston go, can the piston do work? Explain.*
- *H. How much work could the engine do in one piston-stroke?*

I. *Newcomen advertised his engine as being able to make 12 strokes per minute. What power does the engine put out? (Rate of work done). Give your answer both in W and in horsepower. (Self-check: make sure your answer is reasonable).*

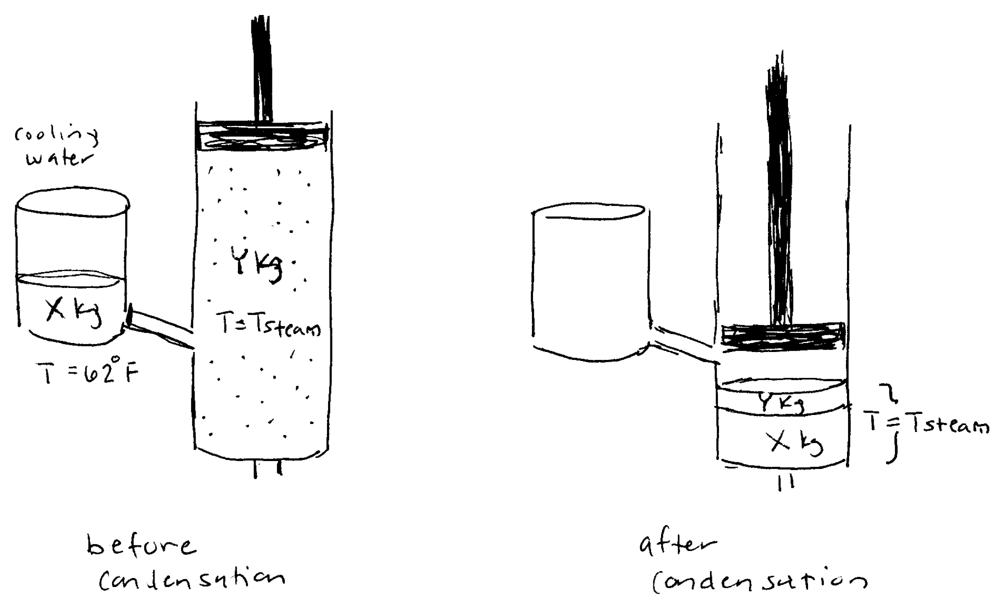
What you calculated above was the maximum rate of work possible, the actual may be considerably smaller. The pressure differential is likely smaller, since the steam can’t condense instantaneously and the piston is moving down as the steam condenses. And there are many losses to friction.

Problem 3: Design problems with the Newcomen Engine

James Watt's interest in steam engines started when he was asked to work on a Newcomen engine - he was a mechanic working for Glasgow University - and he was surprised by how much water had to be squirted in on each engine cycle to condense the steam. After some experimenting with the engine, he found that the minimum amount of water he could add was 24 kg of liquid water from his reservoir tank (which was at 62 Fahrenheit) to condense only one kg of water in the form of steam.

That seemed excessive to him, and he started investigating in a more controlled way.

The picture below shows how condensation should be working in the cylinder. Some mass of cold liquid water (X kg) is added to hot steam (Y kg). If the cylinder is well insulated and no heat is lost, then the only transfer of energy is between the steam and the liquid water. The end result (if you add *just* enough cool water to condense the steam) is X + Y kg of liquid water at T_{steam}. The cylinder walls stay at the same temperature.



A. What happened to the latent heat that was dumped out as steam condensed?

Watt did some careful experiments to determine how much energy he could derive from condensing steam, and basically made a pretty good estimate of L_v.

Watt then thought about the energy going to heat the cooling water. All material has a characteristic "specific heat", i.e. a characteristic amount of energy required to raise the temperature of a given mass of water. (The specific heat, or c_p, actually varies a little with temperature, but for the purpose of this class we'll consider it a constant). Watt did enough experiments to effectively derive the specific heat of water vapor. Fifty years later, the heating of water formed the basis for one of the first definitions of units of energy: a "calorie" is the amount of energy required to raise 1 gram of liquid water by 1 degree Celsius (or Kelvin). Use this information along with the conversion we discussed in class (1 calorie ~ 4.2 J).

B. How much cooling water (in kg) should ideally be needed to condense 1 kg of steam? It might help to think of the cooling water as "soaking up" the heat released by the condensing steam.

Watt concluded from his numbers that the Newcomen cylinder wastefully designed. Some of his cooling water must be cooling the cylinder walls themselves, i.e. pulling energy from them on each stroke. That means the cylinder is cooling, then heating up again on every stroke when steam is re-introduced – very wasteful. Watt estimated the wastefulness of this process by asking

C. What is the ratio

kg cooling water actually used in condensing part of cycle
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kg cooling water that should be used in ideal engine

That ratio should give approximately the energy wastefulness of the condensing part of the Newcomen cycle, and so the potential improvement if Watt could design an external condenser.

D. From lecture, what was the actual efficiency improvement that Watt achieved? Is that consistent (even in a rough way) with your answer above?

WARNING – for the problems below, don't forget that temperatures must be given in a scale that starts with absolute zero, so Kelvin, not Celsius.

Problem 4: Engines and Carnot efficiency

Were Watt's improvements on Newcomen's engine all that could be achieved?

A *By Carnot's theory, what was the maximum efficiency that Newcomen's or Watt's early heat engines could have achieved?*

B *How close did Watt actually get to the Carnot limit? (use number from lecture)*

C By the end of the steam era (early 1900s), engine efficiency approached 25%, but in practice, steam engines never actually achieved their Carnot limits. Assume that each engine's efficiency (at 25%) was only 1/2 its own Carnot limit. *What temperature did the early 1900s engines then have to run at to achieve 25% efficiency? What are the implications for 20th century steam engines? Explain your assumptions about T_{cold} (T_2 in the class notation) as well as T_{hot} for the heat engine.*

D *If you want to achieve an engine efficiency of 75%, what temperature would you have to run the engine at if were otherwise ideal?*

E Steel loses 90% of its strength above 800 C (~ 1000 K). *Can you make a 75% efficient engine out of steel?*

There is a lot of research into ceramics in engine design at present, for good reason.

Optional problems for those wanting to go further...these are aimed at eliciting some deeper insight into steam engines.

F *For the 25% efficient, ½-way-to-Carnot limit engine, what is the steam pressure, compared to atmospheric pressure?*

NOTE: you may need to turn to the handout on steam for this one.

G Someone comes to you and offers to show you a new steam engine whose steam supply system line has a valve that shuts off contact with the liquid water in the boiler at 100 C and then continues heating the steam (so that it's superheated). *What are the advantages to this design? If you want to achieve the performance of part F above, what pressure does your engine have to be rated at now?*

H *Why didn't people design steam engines like this?*

I *The big question of this section: Why did the steam engine disappear relatively quickly after the invention of the internal combustion engine? The above questions should lead you to one plausible answer.*